The performance of small scale multi-generation technologies in achieving cost-optimal and zero-energy office building solutions

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Abstract: This study investigates the economic viability of small-scale, multi-generation systems (combined heat and power (CHP), combined cooling, heating, and power (CCHP)), along with conventional heating and cooling systems combining sixteen heating/cooling energy generation systems (H/C-EGSs). The Energy Performance of Buildings Directive (EPBD) comparative framework methodology is followed. The local cost-optimal solution for an office building, in Helsinki, Finland is determined for each H/C-EGS as well as the global cost-optimum. The suggested energy efficiency measures get 144 building combinations, and alongside the H/C-EGSs, altogether 2304 cases. The results show that the global cost-optimum belongs to the ground source heat pump with free ground cooling. The investigated biomass-based CHPs are economically viable only with high overall efficiency and low power-to-heat ratio due to both low investment and operational costs. The biomass-based CCHPs do not have economic or environmental benefits over the biomass-based CHPs due to the significant increase entailed of both investment and operational costs. The fossil fuel-based CHPs with high operational costs are the worst solutions economically and environmentally. Extending the cost optimal solutions by a photovoltaic panels system yields the net zero-energy office building with minimum life-cycle costs as well.

Highlights

- The cost-optimal solutions for a new office building in Finland are obtained.
- The EBPD comparative framework methodology is followed.
- Biomass CHPs with high overall efficiency and low P/H ratio are economically viable.
- Biomass CCHPs do not have economic or environmental benefits over biomass CHPs.
- Extending the cost-optimal solutions by PV system yields NZEB with minimum LCC.

The performance of small scale multi-generation technologies in achieving cost-optimal and zero-energy office building solutions

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Abstract

This study investigates the economic viability of small-scale, multi-generation systems (combined heat and power (CHP), combined cooling, heating, and power (CCHP)), along with conventional heating and cooling systems combining sixteen heating/cooling energy generation systems (H/C-EGSs). The Energy Performance of Buildings Directive (EPBD) comparative framework methodology is followed. The local cost-optimal solution for an office building, in Helsinki, Finland is determined for each H/C-EGS as well as the global cost-optimum. The suggested energy efficiency measures get 144 building combinations, and alongside the H/C-EGSs, altogether 2304 cases. The results show that the global cost-optimum belongs to the ground source heat pump with free ground cooling. The investigated biomass-based CHPs are economically viable only with high overall efficiency and low power-to-heat ratio due to both low investment and operational costs. The biomass-based CCHPs do not have economic or environmental benefits over the biomass-based CHPs due to the significant increase entailed of both investment and operational costs. The fossil fuel-based CHPs with high operational costs are the worst solutions economically and environmentally. Extending the cost optimal solutions by a photovoltaic panels system yields the net zero-energy office building with minimum life-cycle costs as well.

Keywords

EPBD recast; life-cycle cost; biomass; combined heating and power (CHP); combined cooling heating and power (CCHP); zero-energy office building

26 Nomenclature

27 Abbreviations:

AC	Absorption chiller
BSSP	Building service system package
CAV	Constant air volume
CCHP	Combined cooling, heating and power
CHP	Combined heat and power
CO ₂ -eq	CO ₂ equivalent emissions
COP	Coefficient of performance [-]
DC	District cooling
DH	District heating
dLCC	Incremental life-cycle cost [€/m ²]
EEM	Energy efficiency measure
EGS	Energy Generation system
EPBD	Energy Performance of Building Directive
GC	Ground cooling
GHG	Greenhouse gases
GSHP	Ground source heat pump
H/C	Heating/cooling
HVAC	Heating ventilation and air conditioning
ICE	Internal combustion engine
IFGT	Indirect fire gas turbine
LCC	life-cycle cost [€/m ²]
MS	Member states
mT	Micro-turbine
NG	Natural gas
nZEB	Nearly zero-energy building
NZEB	Net zero-energy building
O&M	Operation and maintenance
ORC	Organic Rankine cycle
P/H	Power to heat ratio
PB	Pellet boiler
PE	Primary energy
PV	Photovoltaic panels
Q _c	thermal cooling capacity [kW]
Q _h	thermal heating capacity [kW]
RET	Renewable energy technology
SE	Stirling engine
SFP	Specific fan power [kW/(m ³ /s)]
SHGC	Solar heat gain coefficient
SPC	Space cooling demand [kWh/m ² a]
SPH	Space heating demand [kWh/m ² a]
VAV	Variable air volume
VCR	Vapor compression refrigeration cooling system

28

29 1 Introduction

30 In order to reach the EU target of 20-20-20 (20% GHG emissions reduction, 20% increase of renewable energy and 20%
 31 increase in energy efficiency by 2020 from 1990 levels), the building sector has to be looked into, since the building energy

needs in the European Union represent 40% of the overall energy consumption [1]. The Energy Performance of Building Directive 2010/31/EU, (EPBD) recast [2] specified that by the end of 2020, all new buildings shall be “nearly zero-energy buildings” (nZEB). As stipulated in this directive, all Member States (MS) shall ensure that minimum energy performance requirement achieving cost-optimal levels has to be set using a comparative methodology framework. The methodology framework was published as EU supplementary EPBD recast in 2012 as “Guidelines accompanying Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012 supplementing Directive 2010/31/EU “ [3]. In May 2012, Finland submitted the minimum energy performance requirements for calculating cost-optimal levels report to the EU [4]. This report shows the cost-optimal of the minimum energy performance of new residential and commercial buildings built in accordance with the current Finnish building regulations D3-2012 [5] and D5 2012 [6] as well as existing buildings. The multi-generation systems including cogeneration heat and power (CHP) and tri-generation system (which is also defined as combined cooling, heating, and power (CCHP)) were not implemented in the Finnish report [4].

Several researches in Europe focused on a combination of building energy performance and cost analysis. Since the EPBD recast has been raised recently, a limited number of current studies refer directly to the objectives of the EPBD recast and related concepts. The implementation of the EPBD recast to determine the energy performance requirement under national perspectives is conducted and submitted by EU Member States as well as in some articles. Before publishing the EU supplementary EPBD recast [3], several studies tried to investigate the cost-optimal levels of minimum energy performance requirements such as [7]. Regarding the calculation method used to evaluate the minimum energy requirements achieving the cost-optimal levels within the comparative methodology framework, the developed optimization techniques were presented by [8] applied to new single family house and [9] applied to the retrofitting of existing office buildings. Regarding the national policies and perspectives comparing with the EPBD requirements, Turkey as an EU Member Candidate, the adaptation of cost-optimal calculations under national circumstances and Mediterranean climates of Turkey using an existing office building is presented in [10]. Most of the aforementioned and similar studies investigated the building elements without changing the supply systems or with limited conventional systems.

The CHP as a proven and reliable form of technology provides various energetic, economic, and environmental advantages compared to the separate production of heat and power at the large and district levels. Various fuels can be supplied to the CHP systems such as natural gas (NG), diesel, peats, biogas, and biomass (wood). The biomass and biogas are considered renewable energy sources. Implementing small scale (in the 30 - 2000 kW_e range [11]) biomass-based CHP as a supply system in the residential and commercial buildings was carried out from different perspectives. Techno-economic

60 investigation of implementing biomass-based CHPs was carried out by [12,13]. Some studies investigated the biomass-
61 based CCHP where the biomass-based CHP was coupled with thermally-activated cooling technology [14,15]. Meanwhile
62 the net zero energy building (NZEB) definition is raised, the biomass-based CHP systems were investigated as a main
63 energy supply system in [16,17]. Moreover, the energy matching capability of the micro-scale bio-syngas- and natural gas
64 (NG)-based CHP systems operated under thermal and electrical tracking strategies, fulfilling NZEB balance are
65 investigated in [18,19]. None of these studies looked at the cost-optimal levels for the minimum energy performance as a
66 primary objective of the EBPD recast for multi-generation systems.

67 The main objective of this study is to find the local cost-optimal level for each heating/cooling energy generation system
68 package (H/C-EGS) implemented on a representative new office building in Finland using the comparative methodology
69 framework as well as the global cost-optimal level which is the minimum cost-optimal level among all H/C-EGSs. The
70 H/C-EGSs are illustrated in Section 3.2, consisting of five conventional systems, four different biomass-based CHPs with a
71 vapor compression refrigeration (VCR) system, four biomass-based CCHP with same technologies of the biomass-based
72 CHP but coupled with absorption chiller (AC), and three fossil fuel-based CHPs with a VCR. The new office building is the
73 same reference office building used in the Finnish report [4], selected as a representative office building built in accordance
74 with the current Finnish building regulations D3 and D5-2012 [5, 6]. Moreover, the other objective is to find an economical
75 solution along with the economic viability of achieving the nZEB and NZEB when a photovoltaic panels system (PV) as a
76 renewable energy technology (RET) is implemented either to the obtained local cost-optimal or the minimum energy
77 performance solutions. The minimum energy performance solution refers to the solution that has minimum energy
78 consumption.

79 **2 Methodology**

80 In this study, to find the local cost-optimal levels, as well as the global cost-optimal level for the implemented
81 heating/cooling energy generation system packages (H/C-EGSs) serving all considered building energy efficiency measure
82 (EEM) combinations, the steps of cost-optimal framework methodology explained in the EU supplementary EPBD recast
83 [3] are followed. Fig. 1 shows in detail the layout of the methodology used to achieve the objectives of this study. In step 1,
84 the reference office building is defined. In step 2, the proposed building EEM are defined and all building EEM
85 combinations are simulated. In step 3, the delivered energies for all combinations are calculated using post-processing of
86 the annual heating, cooling and electrical demands considering the distribution efficiencies, as well as the annual heating

87 and cooling average efficiencies. In step 4, the primary energy (PE) consumption is calculated based on a national
88 conversion of primary factors. Additionally in this study, the CO₂ equivalent emissions (CO₂-eq) is evaluated based on CO₂
89 emission factors. The associated costs of delivered energies, of a building's EEM investment, heating and cooling systems,
90 replacement, operation and maintenance (O&M), and finally, the total incremental life-cycle cost (dLCC) are calculated. In
91 step 5, the cost-optimal solution and the minimum energy performance solution regarding each H/C-EGS, as well as the
92 global cost-optimal solution are determined.

93 According to the EPBD comparative methodology framework, the life-cycle cost (LCC) calculation is the method used to
94 assess the viability of the building performance. The LCC is the sum of the present value of the investment and discounted
95 operational costs of the building and services systems, including those related to maintenance and replacement, including
96 taxes, over a specified calculation period. In this study, the total incremental life-cycle cost (dLCC) is calculated and
97 presented as a difference cost between each H/C-EGS and a defined reference case which consists of the reference building
98 served by certain H/C- EGS, as given by Eq. (1). The LCC calculation follows a financial cost calculation concerning
99 individual owner perspective [3]. The life-span for office buildings is 20 years as recommended by the EU supplementary
100 EPBD recast [3]. The LCC calculation is illustrated in ANNEX 1 of the supplementary EPBD recast [3].

$$dLCC(\tau) = LCC - LCC_{ref}$$

101 (1)

102 It should be mentioned that steps 3-5 are carried out for all considered building EEM combinations and H/C-EGSs. For
103 each H/C-EGS, all considered building EEM combinations drawn in imported PE (or imported CO₂-eq emissions) vs life-
104 cycle cost figure create a "cloud" as shown as output in Fig. 1. The imported PE is calculated for the cost-optimal
105 calculations for the imported energies excluding any exported energy following the energy performance calculation method
106 in the Finnish building code D3-2015 [5].

107 The cost-optimal curves can be derived from the "cloud" of each H/C-EGS separately as well as the two important
108 associated solutions located on the cost-optimal curves, which are the local cost-optimal and minimum energy performance
109 solutions. These two solutions are analyzed with imported PE and the imported CO₂-eq emissions. The imported CO₂-eq
110 emissions mean that the released CO₂-eq emissions associated with the imported energies.

111 The EPBD recast [2] defines a nearly zero-energy building (nZEB) as a building that has a very high energy performance
 112 and should be covered to a very significant extent by energy from renewable sources, including energy from renewable
 113 sources produced onsite or nearby. Finland has not yet announced an official nZEB definition. Nevertheless, it can be assumed
 114 that the nZEB requirement is the highest energy efficient class according to the current Finnish regulations building energy
 115 certificate [20]. Therefore, for office buildings, the highest energy efficient class is “A” where the imported PE has to be
 116 less than 80 KWh/m²a. Similarly to the cost-optimal calculation, the nZEB performance is addressed by the imported PE
 117 following the energy performance calculation method in [20].

118 The net zero-energy building (NZEB) is defined as a building with greatly reduced energy needs through efficiency gains
 119 such that the balance of energy demand can be supplied with onsite or nearby renewable technologies on a yearly level
 120 [21]. However, the NZEB definition and related aspects have to be identified consistently. In this study, the NZEB building
 121 boundary is defined to include all H/C-EGSs as the onsite supply option and the necessary space required to install any
 122 additional onsite or nearby renewable energy technology (RET). However, the imported fuel has to be taken into account in
 123 the NZEB balance. The typical operating energy uses are considered for the balance, including heating, cooling, ventilation,
 124 domestic hot water, lighting, HVAC equipment, and appliances. The import/export is the balancing type. Symmetrical non-
 125 renewable PE factors are used for importing and exporting the electricity. Typically, the balance period is a year. The net
 126 PE is the metric balance. The NZEB balance is fulfilled when the net PE is equal to or less than zero as shown by Eq. (1).

$$127 \quad net \, PE = \sum_i^n PE_{imp_i} - PE_{exp, Ele}$$

128 (2)

129 where PE_{imp} is the annual imported primary energy of an energy carrier, i refers to a given imported energy carrier, n is the
 130 number of the imported energy carriers crossing the building boundary, and $PE_{exp, Ele}$ is the annual primary energy
 131 associated with the exported electricity.

132 Reaching the nZEB and NZEB, the photovoltaic panels (PV) are chosen as RET to be implemented in the office building
 133 (step 6-Fig. 1). Therefore, the electricity produced via PV can be utilized for the electrical demand to reduce the energy cost
 134 of electricity and the surplus electricity can be exported to the grid for compensating the imported energies and to make
 135 financial profits. As shown in step 6 in Fig. 1, the PV panels are installed in both the cost-optimal and minimum energy
 136 performance solutions for each H/C-EGS. The aim is to investigate the economic viability of achieving the nZEB and
 137 NZEB based on both solutions and comparing them.

138 Sensitivity analysis is conducted with different discount rates by repeating steps 4 and 5 in Fig. 1. The effect of using
139 different discount rates on the local and global cost-optimal solutions is analyzed.

140

141 Fig. 1

142

143 **3 Computational case study**

144 **3.1 Reference building description**

145 The office building is the same representative office building identified in [4]. It is a six-story office building with a narrow
146 shape (an approximately 50 m x 22 m footprint) with the short sides oriented to the east and the west. The room height is
147 3.6 m. Each floor is 936 m² and the net heated floor area is 5615 m². Envelope properties, operation schedule, and set point
148 temperatures of the reference office building are shown in Table 1. More detailed descriptions are presented in [4]. The
149 reference building and all building EEM combinations are simulated using IDA-ICE simulation software [22] using
150 reference year weather data (Vantaa TRY2012) [23] used as well in [4]. Fig. 2 shows a plan for the typical floor and
151 building model in a simulation program. The simulation results indicate that the reference building's demands (excluding
152 any distributed systems' and supply systems' efficiencies.) are 21.7 kWh/m²a annual space heating (SPH), 39.3 kWh/m²a
153 ventilation heating, 4.6 kWh/m²a space cooling (SPC), 4.3 kWh/m²a ventilation cooling, and 6.0 kWh/m²a DHW. The
154 electrical demands are 22.3 kWh/m²a lighting, 22.3 kWh/m²a appliances, and 13.3 kWh/m²a HVAC auxiliaries (which
155 includes the fan power, but not the electricity used for direct or indirect heating and cooling).

156

157 Fig. 2

158 Table 1

159

160 **3.2 Energy efficiency measures (EEMs) and packages**

161 In this study, 143 building EEM combinations are proposed to improve the energy performance of the pre-defined reference
162 office building. The proposed building EEMs are categorized into building envelope measures, building service system

package (BSSP), and heating/cooling energy generation supply packages (H/C-EGS). The building envelope measures include (i) insulation level of external wall, (ii) window type, (iii) infiltration level. The BSSP includes different options of ventilation system and daylight control. Other EEMs such as roof /ground additional insulation, heavy thermal mass, optimal orientation, and solar shading are not considered in this study because they showed low energy-saving potential in [24]. Additionally, the optimal range of the external wall insulation and optimal window parameters and sizes were investigated based on the cost-optimal solutions for office buildings in [25], [26]. The building alternatives of EEMs and their associated costs are obtained from [4], [8], [27], [28] and illustrated in details in Appendix A, including three levels of wall insulation, four different window types, four levels of infiltration, and three options of BSSP. All 144 building EEM combinations including both building envelope measures and BSSP options are integrated into the simulation software to find out the annual heating, cooling and electrical demands.

In this study, sixteen H/C-EGSs (Table 2) investigated with the 144 building EEM combinations yield altogether 2304 cases. The H/C-EGSs are selected to compare between the conventional systems and the other systems based on small-scale CHP and CCHP technologies. Appendix B shows the technical and economic characteristics of all H/C-EGS.

176

177 Table 2.

178

It should be noticed that the thermal heating and cooling capacities of all heating and cooling systems vary from building combination to another to cover the peak thermal heat demands for each. Also, the capacities of biomass-based CCHP are sized to cover the total peak thermal heating demand required for heating and cooling purposes [29]. The cost of the conventional heating and cooling systems are from [30], [31], [32], [33]. For the GSHP-GC, the borehole lengths required for both heating and free ground cooling purposes of the 144 building combinations are calculated and optimized using EED 3 (Earth Energy Designer) software [34]. The average annual efficiencies of the conventional systems are obtained from the Finnish building codes [5, 6]. The biomass- and fossil fuel-based CHPs' efficiencies, not mentioned in the Finnish building codes are assumed constant and equal to the nominal efficiencies. The costs and performance of the CHPs are from [12], [35], [36], [37] as shown in details in Table B. 5 - Appendix B. Some of the suggested biomass-based CCHP were investigated before, for example, the ORC-AC and SE-AC as biomass CCHP are investigated in [38] and [39]. For the electrical connection fee, the installation cost for 380 V with electrical current higher than 200 A is 60 € multiplied by the

190 peak ampere [30] which vary according to the peak electrical load of the building EEM combinations. All heating and
191 cooling systems have a life span of 20 years. Therefore, there is no replacement for any heating or cooling system. All
192 CHPs are operated to track the thermal demands with ON/OFF operation using the dead band of a water storage system
193 with a capacity of 3.0 cubic meters [16, 11]. In this study, there is only one value for the annual costs including the
194 subscription costs, as well as operation and maintenance (O&M) costs.

195 The reference office building has EEMs of wall 1, win 1, inf 1, BSSP 1. The reference case consists of the reference
196 building served by DH-VCR as H/C-EGS. The DH-VCR is selected because in the urban area of the Helsinki region, the
197 DH utilized in the building stock has the highest percentage of 85% [40]. In [4], only the VCR system was investigated as a
198 cooling option for the new office buildings. The DC option has been growing rapidly in the Helsinki region but it is still not
199 a common cooling option [41].

200 **3.3 *Energy performance factors***

201 The energy performance is commonly defined by the PE consumption, but additionally in this study, is also defined by the
202 CO₂-eq emissions as long as the EU target is to reduce the GHG emission by 20%, nevertheless it is not stated in the EPBD
203 recast. The aim is to compare between the PE consumption and the CO₂-eq emission as energy performance metrics. The
204 national Finnish conversion PE factors and CO₂-eq emission factors are given in Table 3. The national Finnish conversion
205 PE factors are from Finnish building code D5-2012 [6], while the CO₂-eq emission factors are from [16, 42].

206

207 Table 3.

208

209 **3.4 *Life-cycle cost parameters***

210 In this study, the starting year of the cost calculation is 2013. All cost taken from references before 2013 are updated based
211 on building cost indices and inflation rates from [28]. The calculation period is 20 years as recommended for the office
212 building in EU regulation supplementary Directive 2010/31/EU [3]. For the basic calculations, a 3% real discount rate is
213 used [3]. The sensitivity analysis is carried out with three different real discount rates of 1%, 6%, and 10%. All building
214 EEMs have a life span equal to the calculation period, therefore the residual value will equal zero for all EEMs and

215 packages. No disposal costs for building elements and EEMs are taken into consideration. Table 4 shows the fuel and
216 energy prices, and their escalation rates obtained from [43]. All energy prices include taxes and transportation costs.

217 Regarding the exported electricity produced by the multi-generation systems, the current Finnish energy policy for the feed-
218 in tariff states that the exported electricity produced via new small scale biomass- and biogas-based CHP has a target price
219 of 83.5 €/MWh [44] where the Energy Market Authority will pay the difference between the target price and the average
220 spot market price every three months. This feed-in tariff scheme is applied for twelve years. In light of that, it is assumed
221 that for all CHP technologies including the fossil fuel-based, the exported electricity price is 83.5 €/MWh without taking
222 into consideration any inflation rate over the calculation period.

223

224 Table 4.

225

226 **3.5 Implementing PV panels to achieve nZEB and NZEB**

227 According to the offer provided by local energy distribution companies Fortum Company [30], Helsingin Energia [45] in
228 the Helsinki region, the PV system is installed completely by those companies and they give fees for purchasing the surplus
229 electricity. Based on the offered PV system by [30], the installation price of the whole PV system is 427.6 €/m² (including
230 VAT) with a 20-year guarantee. The annual service fee is 46.70 €. In this study, the hourly electricity produced by the PV
231 system is calculated by TRNSYS 17.1 software [46] according to its specifications [47] shown in Appendix C using the
232 same reference year's weather data (Vantaa TRY2012) [23]. The orientation of the PV modules is selected to be horizontal
233 to utilize the maximum roof area without losing in-between areas when the PV modules are tilted to avoid the shading
234 effect on each other. Therefore, the maximum collected solar energy can be yielded. The calculated electricity production
235 after the inverter of a one square meter of PV is 119.6 kWh/a. The hourly matching between the electrical demand and the
236 electricity produced via the PV system is carried out using Matlab software.

237 The exported price of the electricity produced via the PV system varies hourly depending on the spot market price. It is
238 assumed to be equal to the spot market price minus a 0.24 c/kWh margin fee and a 0.07 c/kWh online service fee [30]. The
239 hourly and annual average spot market price of 2013 are from Nord pool [48], and shown in Appendix C. The average price

240 of 41.16 €/MWh is used. The effect of using the average price instead of hourly prices is investigated in Section (4.3.2). It
241 is assumed that the electricity produced via PV has the same escalation rate as the imported electricity.

242 **4 Results and discussion**

243 **4.1 Energy demands**

244 The impact of implementing the separate aforementioned building EEMs to the reference office building is shown in Fig. 3.
245 The reference building has the main EEMs of wall 1, win 1, inf 1, and BSSP 1. The options of EEMs are two wall options
246 (wall 2 and 3), three window types (win 2, 3, and 4), three infiltration levels (inf 2, 3 and 4), and two options of building a
247 service system package (BSSP 2, and 3), see Appendix A, added separately to the reference building. The simulated annual
248 demands are 67 kWh/m²a for heating, 9 kWh/m²a for cooling, and 58 kWh/m²a for electrical demands. The most efficient
249 package among the separate EEM packages is the BSSP including a variable-air volume (VAV) ventilation system with
250 airflows depending on the CO₂ levels and daylight control. The energy saving potential are 24% for the SPH, 80% for
251 ventilation heating, 55% for ventilation cooling, 54% for HVAC auxiliary electrical demands with SFP of 1.8 kW/(m³s)
252 (BSSP 1) and 62% with SFP of 1.4 kW/(m³s) (BSSP 2), while the SPC demand increases by 185%. The explanation of the
253 increase of the SPC is related to withdrawing the heat released by the internal heat and solar gains at night time in the
254 summer (unoccupied time) where the daytime is too long at higher latitudes. Also, the HVAC auxiliary systems and the
255 lighting electrical demand decrease by 62% and 8% respectively. Generally speaking, the external wall with low U-value
256 and lower infiltration level than the reference one has a lower heating demand and a higher cooling demand. The window
257 types 2 and 3 reduce the SPC demand by 52 % and increase the SPH demand slightly with respect to the reference building.

258

259 Fig. 3.

260

261 The total annual heating (including DHW, SPH and ventilation heating), cooling (including SPC and ventilation cooling),
262 electrical (including lighting, appliances, and HVAC auxiliaries) demands of the 144 building EEM combinations including
263 the reference building are shown in Fig. 4. From this figure, the gap on the X-axis (heating demand) between the two
264 groups of building EEM combinations with BSSP 1 and the other group with BSSP 2 is due to the large reduction of the
265 SPH demands when the BSSP 2 and 3 are implemented instead of BSSP 1. All building EEM combinations of the BSSP 1

266 have constant electrical demand of 57.9 kWh/m²a, while those of BSSP 2 and 3 have approximately the electrical demand
267 of 48.8 kWh/m²a where it varies between 47.8 kWh/m²a and 49.7 kWh/m²a in accordance with the fan power of the
268 ventilation system and the daylight control. As shown in Fig. 4, some cases have total heating demand higher than the
269 reference case due to the implementing of window types 2 and 3. It can be concluded that not only for new, but also for
270 retrofitted office buildings that replacing the CAV system with a VAV system is the most efficient EEM with formidable
271 saving potential.

272

273 Fig. 4.

274

275 4.2 Cost-optimality calculation

276 Depending on the simulation results of all building EEM combinations, the annual imported PE and CO₂.eq emissions are
277 evaluated using post-processing of the annual heating, cooling and electrical demands obtained from the simulation of 144
278 building cases using the annual average efficiencies of distribution systems and the H/C-EGSs.

279 Using the financial calculation method, the incremental life-cycle cost is calculated for all cases taking into account the paid
280 costs by the customer including all applicable taxes. The DH-VCR system package serving the reference building is the
281 reference case which has dLCC equal to 0 €/m² as indicated in Section (3.2). The dLCC of all cases are presented with two
282 metrics; imported PE and imported CO₂-eq emissions to evaluate the energy performance of the office building.

283 4.2.1 Imported Primary energy (PE) consumption versus incremental life-cycle cost (dLCC)

284 Fig. 5 shows the imported PE versus the dLCC of all building EEM combinations served by each H/C-EGS. As shown, for
285 each H/C-EGS, the building EEM combinations are categorized into two groups according to the BSSP options (BSSP 1
286 and BSSP 2 &3) presented by the filled and unfilled markers, respectively. The solution space has an imported PE range of
287 99 kWh/m²a and 323 kWh/m²a. The dLCC range is -83 €/m² and 477 €/m². According to the Finnish building code D3-
288 2012 [5], the imported PE has to be limited by 170 kWh/m²a for office buildings. Therefore, the fossil fuel-based CHPs
289 including NG-ICE-VCR, NG-mT-VCR, and D-ICE-VCR with all building combinations of BSSP 1 are not appropriate to
290 be a heating system option due to either high PE factors of NG. Moreover, the biomass-based CHP (ICE-VCR) and CCHP

291 (ICE-AC) in with some building combinations of BSSP 1 are not appropriate to be a heating system option as well, due in
292 large part to the high amount of imported pellet fuel as a result of low thermal efficiency of the biomass-based ICE.

293 Fig. 5 shows that the building combinations of BSSP 2&3 group show not only imported PE savings, but also economic
294 savings over those of the BSSP1 group. This is due to reducing both the investment cost of H/C-EGSs and the energy cost
295 through the building's life span. The cases of building combinations of BSSP 2&3 with DH-VCR, DH-DC, PB-VCR, and
296 GSHP-GC as conventional H/C-EGSs, PB-AC, ORC-VCR, and SE-VCR have negative dLCC showing the economic
297 savings with respect to the reference cases. Additionally, the cases of BSSP 1 group with PB-VCR and GSHP-GC have
298 also dLCC less than the reference case. The pellet boiler technology, which is a mature product with the advantage of
299 running on an abundance of biomass fuels, requires relatively low investment and annual costs. The pellet fuel price and its
300 escalation rate are the lowest among all energy carriers. The GSHP-GC is a low-operating-cost, environmentally friendly
301 H/C-EGS.

302 Regarding the multi-generation systems shown in Fig. 5, it can be noticed that biomass-based CHP technologies with high
303 P/H ratio (such as IFGT and ICE) cannot compete with the conventional systems due to the following reasons. The first one
304 is the high investment cost relating to high heating and electrical capacities as well (Table 5.B - Appendix B). The second
305 reason is that high P/H ratio, which means low thermal efficiency yields to high operational cost since the CHP operational
306 strategy is the thermal tracking. On the contrary, the biomass-based CHP technologies with low P/H ratio (such as SE and
307 ORC) can compete with the conventional systems. Also, for the same building EEM combination, it is found that the
308 imported PE increases for the PB and biomass-based CHPs when the VCR is replaced by AC as a cooling system. From the
309 imported PE point of view, the increase of the imported PE varies from one building EEM combination to another,
310 depending on the thermal performance of the PB and biomass-based CHPs. The PB-AC has the imported PE increase by a
311 range of 3 kWh/m²a and 7 kWh/m²a while the ICE-AC, for example, undergoes an increase of the imported PE in range of
312 6 kWh/m²a and 14 kWh/m²a. From the net PE consumption point of view, the net PE consumption records increase for the
313 PB and reduction for biomass-based CHPs due to the associated electricity production. The net PE consumption of the PB-
314 AC increases in range of 3 kWh/m²a and 7 kWh/m²a, while the IFGT-AC, for example, undergoes a reduction of the net PE
315 consumption in the range of 4 kWh/m²a and 10 kWh/m²a. Therefore, it can be concluded that the biomass-based CCHP
316 does not have an environmental advantage with respect to the imported PE according to the current Finnish energy
317 calculation regulations in [5] and [20], while it will be feasible with respect to the net PE consumption. From an economic
318 point of view, the dLCC increases significantly as a result of increase in the investment cost of both biomass-based CHP

319 and the AC as well as the purchased fuel. The same conclusion of the lack of economic viability of a small scale biomass-
320 based CCHP was reached by [29] and [49].

321

322 Fig. 5

323

324 Table 5 shows the cost-optimal and minimum energy performance solutions regarding the imported PE for all H/C-EGSs.
325 The reference case has imported PE of 162.4 kWh/m²a. The global cost-optimal solution belonging to the GSHP-GC has
326 dLCC of -83 €/m² and an imported PE of 107 kWh/m²a, with an overall savings of 34% with respect to the reference case.
327 Its building EEM combinations are wall 1, win 1, and inf 1 and BSSP 2. The GSHP-GC is a low-operating-cost,
328 environmentally friendly H/C-EGS with high thermal performance (COP coefficient of performance). The PB-VCR has an
329 imported PE of 117 kWh/m²a and dLCC of -82 €/m² due to the abovementioned features of PB technology and low pellet
330 fuels price and escalation rate. The H/C-EGSs based on the district heating; the DH-VCR and DH-DC, are the second and
331 fifth cost-optimal solutions which have dLCC of -73 €/m² and -36 €/m², respectively. The VCR has an advantage over the
332 DC because it has lower annual costs where the O&M cost of the VCR is less than the sum of the annual subscription and
333 the O&M costs of the DC system (Table B. 1 and Table B. 4 - Appendix B).

334 Regarding the multi-generation systems, the ORC-VCR and SE-VCR have the lowest dLCC among all CHP and CCHP
335 systems of -55 €/m² and -49 €/m² corresponding to an imported PE of 113 kWh/m²a and 112 kWh/m²a, respectively. Table
336 5 shows that, the IFGT-AC has the highest exported PE of 34 kWh/m²a. Therefore, it has the minimum net PE of 92
337 kWh/m²a but high additional dLCC due to high thermal capacity as well as the operational cost corresponding to high
338 imported fuel. The fossil fuel-based CHP systems record the highest imported PE as well as relatively high dLCC.

339 The difference between the dLCC of the global cost-optimal solution of GSHP-GC and that of GH-DC (which has
340 maximum negative incremental life-cycle cost of -36 €/m²) is 47 €/m². Comparing this value with the global cost-optimal
341 (1889 €/m²) given by [4], even though the difference between the life span used in this study (20 years) and that used in [4]
342 (40 years), it is found that it yields less than 2.5 %. Therefore, due to inputs data uncertainty, each of these system
343 combinations GSHP-GC, PB-VCR, DH-VCR, ORC-VCR, SE-VCR, and DH-DC could be the global cost-optimal solution.

344

345 Table 5.

346

347 As shown in Table 5, the local cost-optimal solutions for all biomass-based CHPs, and NG-ICE-VCR have building EEM
348 combinations of wall 2, win 2, inf 4, and BSSP 2 as the cost effective EEMs from both heating and cooling demands. Once
349 the AC and DC cooling systems are implemented, there is no need to invest more in the infiltration level due to dependency
350 on the lowest energy carriers' costs. Therefore, the DH-DC and all CCHPs have building EEM combinations of wall 2, win
351 2, inf 1, and BSSP 2. However, for the GSHP-GC, PB-VCR, and DH-VCR which have the lowest dLCC and the highest
352 heating efficiency and/or COP, there is no need to invest more in the building EEMs, only implementing the most efficient
353 EEM (i.e., BSSP 2) in the reference building. Due to high energy prices of the fossil fuel supplied to the fossil fuel-based
354 CHPs, the local cost-optimal solutions have high levels of the building EEM combinations of wall 2, win 4, inf 4, and
355 BSSP 3 except the NG-ICE-VCR with relatively low P/H. The minimum energy performance solutions for all H/C-EGSs
356 have the highest EEM levels of wall 3, win 4, inf 4, and BSSP 3.

357 Fig. 6 shows the breakdown of the cost-optimal solutions of all H/C-EGSs with respect to the reference case costs. It can be
358 noticed that all local cost-optimal solutions bring with them additional investment costs due to the implementation of the
359 EEMs. Because all local cost optimal solutions have either BSSP 2 or BSSP3, which consist of VAV system and daylight
360 control, all cost-optimal solutions have energy cost savings by way of reduced electrical demands. The highest electrical
361 demand cost saving is recorded by biomass- and fossil fuel-based CHPs having high P/H ratios and all biomass-based
362 CCHPs. The GSHP-GC is the only system that has investment and operational cost savings covering the cooling demand
363 with respect to the VCR of the reference case as a result of free ground cooling, which mainly needs a pumping system.
364 The DC has high investment and operational cost over the VCR of the reference case by 43 €/m². The high investment and
365 operational cost increase of the AC for PB-AC and all biomass-based CCHPs over the VCR of reference case is not only
366 due to the difference of the cooling system itself, but also includes the investment and operational cost difference of the
367 heating system supplying the AC system.

368 The investor or the decision maker might not depend only on the results of the comparative framework methodology, where
369 other factors are not reflected in the comparative framework methodology and/or excluded in this study. For example, the
370 heating/cooling system package's reliability, social acceptance, local emission, additional space required depending on the
371 footprint, fuel procurement and storage, etc. have a strong influence on the decision making.

372

373 Fig. 6

374 4.2.2 *Imported CO₂-eq emissions versus incremental life-cycle cost*

375 Fig. 7 shows the imported CO₂-eq emissions versus the dLCC for all building EEM combinations for each H/C-EGS. The
376 imported CO₂-eq emissions mean the released CO₂-eq emissions associated with the imported energies, whereas the
377 exported CO₂-eq emissions mean the displaced CO₂-eq emissions in the grid associated with the exported energies from
378 renewable energy sources, using the symmetric CO₂-eq emission factors. The imported CO₂-eq emissions are in range of
379 13.1 kg_{CO2}/m²a and 76.2 kg_{CO2}/m²a. It can be noted that for biomass-based CHP and CCHP systems, the difference between
380 the imported CO₂-eq emissions between the building EEM combinations of BSSP 1 and BSSP 2&3 is very small. The
381 building EEM combinations with BSSP 2&3 have always imported CO₂-eq emissions lower than ones with BSSP 1. The
382 net CO₂-eq emissions can be defined as the difference between the imported and exported CO₂-eq emissions. From the net
383 CO₂-eq emissions point of view, the building EEM combinations with BSSP 2&3 have lower net CO₂-eq emissions than
384 ones with BSSP 1, except the ORC. The reason is mainly related to the very low CO₂-eq emission factor of pellet fuel
385 compared to other energy carriers. As concluded in [16] for net CO₂-eq emissions, as long as the biomass-based CHP
386 systems are operated under a thermal tracking strategy, the possibility of producing electricity which can be utilized by the
387 electrical demand or exported to the grid, is decreased with highly efficient thermal demands, leading to an increase in the
388 net CO₂-eq emissions. Replacing the VCR by AC with the PB and all biomass-based CHP achieves reduction in the
389 imported CO₂-eq emissions and net CO₂-eq emissions as well. Significant reductions of the imported CO₂-eq emissions of
390 17%, 16%, 15%, and 14% are obtained when the AC is implemented instead of VCR as a cooling system with SE, ORC,
391 IFGT, and ICE, respectively. Once the displaced CO₂-eq emissions in the grid associated with the exported electricity is
392 taken into account, the net CO₂-eq emissions reduces by 41%, 39%, 23%, and 20% with IFCT, ICE, ORC, and SE,
393 respectively, when the AC is implemented instead of the VCR.

394

395 Fig. 7

396

397 The global cost-optimal solution, as well as the cost-optimal solutions for each H/C-EGS, is the GSHP-GC the same as the
398 one illustrated with the imported PE results. As shown in Table 6, the global cost-optimal solution has imported CO₂-eq

emissions of 16.9 kg_{CO2}/m²a, with a savings of 50% with respect to the reference case which has imported CO₂-eq emissions of 33.8 kg_{CO2}/m²a. The imported CO₂-eq emissions savings are higher than the imported PE savings of the local cost-optimal solutions for each H/C-EGS with respect to the reference case except the NG-mT-VCR and the D-ICE-VCR. The reason is primarily related to the PE factors and CO₂-eq emission factors. It can be concluded that, under Finnish conditions, the imported CO₂-eq emissions as an energy performance metric is a straightforward way to achieve the EU target of reducing the GHG emissions by 20%. However, the argument of evaluating the energy performance using either the PE consumption or the CO₂-eq emissions primarily depends on the national factors where the results obtained by this study cannot be generalized.

The minimum imported CO₂-eq emission solutions of all biomass-based systems except the ORC-AC do not have the most efficient EEMs as shown in the minimum imported PE solutions. This is primarily related to a very low pellet fuel CO₂-eq emission factor with respect to other energy carriers. However, the difference between the minimum imported CO₂-eq emission solutions and the cases with the most efficient EEMs is less than 0.02 kg_{CO2}/m²a.

411

Table 6.

413

4.3 *nZEB and NZEB calculations*

4.3.1 *Implementing PV to reach nZEB and NZEB levels*

In the context of the aforementioned nZEB and NZEB definitions, PV as a RET is implemented to reach nZEB and NZEB. As shown in Fig. 8, the PV system in a 200 m² module step is installed “onsite” reaching 1000 m², which is approximately equal to the roof area of the office building while over 1000 m²; it has to be installed “nearby.” The local cost-optimal solutions for all H/C-EGSs are extended by installing a PV area equal to the maximum PV area determined to achieve the NZEB balance between the imported and exported PE as given in Table 5. Meanwhile, the minimum energy performance (min imported PE) solutions are extended only for the GSHP-GC with imported PE of 75 kWh/m²a and dLCC of -30 €/m², where the proposed nZEB imported PE limit is reached by installing the PV system onsite (i.e., PV area ≤ 1000 m²). It can be noticed that the PV area ≤ 1000 m² has a small increase in the dLCC. The reason is primarily related to the high correlation between the PV electricity production and the electrical demand. The percentage of the onsite utilized electricity varies between 65% and 72% depending on the H/C-EGS. However, small addition LCC is observed as the difference

between both the investment cost of a PV system and the exported electricity and the annual cost saving of the imported electricity. Over a 1000 m² PV area, where the PV area has to be installed nearby, the percentage of the onsite utilized electricity produced by the PV system is decreased and the dLCC increases rapidly due to the low feed-in tariff of the exported electricity. The dLCC of the extended local cost-optimal solutions by PV system are less than those of the extended minimum energy performance solutions as presented by the GSHP-GC. Therefore, the NZEB balance is fulfilled and presented by the local cost-optimal solutions of each H/C-EGS.

The NZEB balance is fulfilled when the maximum PV area is implemented for the local cost-optimal solution each H/C-EGS given in Table 5. The additional cost required for the cost-optimal solutions of the NZEB varies from H/C-EGS to another. The minimum and maximum additional costs are 104 €/m² and 165 €/m² with respect to the IFGT-VCR and NG-ICE-VCR, respectively. Using the PV systems, the NZEB has always dLCC higher than the reference case. The extension of the global cost optimal (GSHP-GC) to reach NZEB balance has dLCC of 39 €/m². However, the extended local cost optimal solutions of PB-VCR, DH-VCR, ORC-VCR, and SE-VCR all have dLCC less than 64 €/m². The minimum imported/exported PE belongs to the global cost optimal solution (GSHP-GC) extended by 2946 m² of 63 kWh/m²a followed by the local cost optimal solutions of ORC-VCR and SE-VCR with 64 kWh/m²a. However, as concluded in [19], the low imported PE does not necessarily indicate the high-energy-matching situation, especially when different imported energies (i.e., fuels) are imported beside the electricity and thermal heat.

442

443 Fig. 8

444

445

446 4.3.2 *The effect of using the hourly spot price as a feed-in tariff instead of using the annual average value*

447 In the base calculation, the prices of exported electricity produced by the PV system are calculated using the annual average value of the spot market price for 2013. Repeating the nZEB and NZEB cost calculation using the hourly spot price as a feed-in tariff instead of the annual average value for 2013; it is found that the difference is negligible. The maximum dLCC variation when the hourly spot price used with the global cost optimal solution (i.e., GSHP-GC extended by 2946 m² PV area as an example) is equal to 1.6 €/m² more the dLCC when the average annual value is used.

4.4 Sensitivity analysis

The sensitivity analysis is carried out to show the effect of different real discount rates on the local cost-optimal solutions for all H/C-EGSs. The basic real discount rate used as aforementioned is 3%. Other three real different discount rates are selected: 1%, 6%, and 10%. Fig. 9 shows the imported PE and dLCC of the local cost-optimal solutions where the H/C-EGSs are in ascending order based on their dLCC of the base calculation of 3% of the real discount rate. The dLCC is calculated relative to its reference case cost with the same real discount rate, therefore the costs of reference cases with all real discount rates are drawn on zero value. The change of the imported PE for the same H/C-EGSs with different real discount rates means a change in its cost-optimal solutions' building EEM combinations. It can be concluded that, the GSHP-GC is a global cost optimal solution with low real discount rates of 1% and 3%. The DH-VCR and PB-VCR become the global cost-optimal solutions, with 6% and 10% real discount rates, respectively. The DH-VCR and DH-DC become more economic than the ORC-VCR and SE-VCR with high real discount rates of 6% and 10%. All biomass-based CCHPs are the most expensive system packages with high real discount rates of 6% and 10%. Natural gas and diesel oil have high energy costs and high escalation rates. Therefore the discounted annual costs of the fossil fuel are decreased significantly compared to other energies when the real discount factors increases. Additionally, increasing the imported PE of 6% and 10% real discount rates cases yields that the dLCCs are close together for all studied real discount rates.

Fig. 9

5 Conclusion

This study aims to find the local cost-optimal solutions for the minimum energy performance building for a representative office building located in Helsinki, Finland. The Energy Performance of Building Directive (EPBD) comparative framework methodology is used. Four building energy efficiency measures (EEMs); external wall insulation, window type, infiltration level, and building service system package (BSSP) options consisting of the ventilation system and daylight control are included to address the building EEM combinations. Sixteen heating/cooling energy generation packages (H/C-EGS) consisting of small-scale multi-generation systems along with conventional heating and cooling systems are investigated. These multi-generation systems are biomass- and fossil fuel-based combined heat and power (CHP), as well

478 as biomass-based combined cooling, heating, and power (CCHP). The energy performance is presented by two metrics;
479 imported primary energy (PE) and imported CO₂ equivalent (CO₂-eq) emissions. The lifecycle cost is presented by the
480 incremental life-cycle cost (dLCC) over the reference case integrating the reference building built in compliance with the
481 prevailing Finnish building codes (D3 and D5-2012) served by the district heating and vapor compression refrigeration
482 (DH-VCR) system package. As a further step, the photovoltaic panels (PV) as a renewable energy technology (RET) are
483 implemented, aiming to reach nearly zero-energy building (nZEB) and net zero-energy building (NZEB). The nZEB
484 imported PE is proposed to be limited by the Finnish energy class “A” of 80 kWh/m²a for office buildings. The nZEB and
485 NZEB costs for each H/C-EGS, extended based on the cost-optimal and the minimum energy performance solutions are
486 compared. The following findings are obtained:

- 487 • The solution space has an imported PE in the range of 99 kWh/m²a and 323 kWh/m²a, and imported CO₂-eq in the
488 range of 13.1 kg_{CO2}/m²a and 76.2 kg_{CO2}/m²a. The dLCC range is 477 €/m² and -83 €/m². The reference case has an
489 imported PE of 162.4 kWh/m²a, and imported CO₂-eq emissions of 33.8 kg_{CO2}/m²a. All fossil fuel-based CHPs and the
490 biomass-based CCHP with high power-to-heat (P/H) ratio and low overall efficiency (Indirect fire gas turbine (IFGT)
491 and internal combustion engine (ICE)) with all building EEM combinations of BSSP options consisting of a constant
492 air volume (CAV) ventilation system without daylight control have imported PE higher than the Finnish building code
493 limit value of 170 kWh/m²a.
- 494 • The fossil fuel-based CHPs recorded the worst economic and environmental solutions due to high PE factors and high
495 energy prices with high escalation rates as well.
- 496 • The global cost-optimal solution relates to a GSHP-GC with dLCC of -83 €/m², an imported PE of 107 kWh/m²a (34
497 % lower than the reference case), and CO₂-eq emissions of 16.9 kg_{CO2}/m²a (50% lower than the reference case).
- 498 • Since the investigated CHPs operate under a thermal tracking strategy, the Organic Rankine Cycle (ORC) and the
499 Stirling Engine (SE) technologies, the ORC-VCR and SE-VCR with high overall efficiency and low P/H ratios,
500 resulting low investment and low operational costs, have the lowest dLCC among all CHP and CCHP systems in the
501 range of -55 €/m² and -49 €/m² and imported PE of 113 kWh/m²a and 112 kWh/m²a, respectively.
- 502 • The biomass-based CCHPs do not have economic or environmental benefits over the biomass-based CHPs due to
503 significant increase of the investment cost of biomass-based CHP and the absorption chiller (AC), as well as the
504 purchased pellets fuel.

- 505 • Regarding the proposed nZEB, the local cost-optimal solutions extended by onsite PV area ($\leq 1000 \text{ m}^2$, equal to the
506 office roof area) cannot fulfill the proposed limit of $80 \text{ kWh/m}^2\text{a}$, while the extended minimum energy performance
507 solutions can fulfill the nZEB limit only for the GSHP-GC with imported PE of $75 \text{ kWh/m}^2\text{a}$ and dLCC of -30 €/m^2 .
- 508 • The NZEB solutions extended based on the cost-optimal solutions for all H/C-EGSs have lower dLCC than that of the
509 extended based minimum energy performance solutions.
- 510 • The NZEB achieved by extending the global cost optimal (GSHP-GC) has a dLCC of 39 €/m^2 . However, the extended
511 local cost optimal solutions of PB-VCR, DH-VCR, ORC-VCR, and SE-VCR have dLCC less than 64 €/m^2 .

512 As shown, since the EEMs and H/C-EGSs are applicable to be implemented in either new or existing buildings, the results
513 of this study can help the designers throughout the design process of nearly and net ZEB for new construction of, and the
514 retrofitting of existing office buildings. Additionally, the results will be also useful to the policy makers since the
515 legislation of Finnish nearly ZEB will be set in the coming years.

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521 performance requirements for calculating the cost-optimal levels in Finland.

522 **Appendix A Energy efficiency measures and their costs**

523 The proposed energy efficiency measures (EEM) included the computational case study; external wall insulation levels,
524 window types, infiltration levels, and building service system package (BSSP) (ventilation system and daylight control) are
525 listed in Table A. 1, Table A. 2, Table A. 3, Table A. 4, respectively.

526 Table A. 1

527 Table A. 2

528

529 Table A. 3

530 Table A. 4

531 **Appendix B Heating/cooling energy generation system packages' (H/C-EGS) performance and cost**

532 The H/C-EGSs' performance and costs are shown in Table B. 1-Table B. 5.

533 Table B. 1

534

535 Table B. 2

536

537 Table B. 3

538

539 Table B. 4

540

541 Table B. 5

542

543 **Appendix C Spot market price and photovoltaic panels specifications**

544 Finnish spot market price for 2013 and specifications of the PV modules are shown in Fig. C. 1, and Table C. 1,

545 respectively

546

547 Fig. C. 1

548 Table C. 1

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Fig. 1 Schematic diagram for the layout of the methodology.

Fig. 2 Typical floor plan and the 3D model in IDA ICE of the simulated reference office building.

Fig. 3. Annual energy demands of the reference building (consists of wall 1, win 1, inf 1, and BSSP 1) and the effect of changing one EEM on the reference building (indicated by EEM changed from the reference case).

Fig. 4. Heating, Cooling, and electrical demands of the 144 building EEM combinations.

Fig. 5 Incremental life-cycle cost (dLCC) versus imported primary energy (PE) for all building EEM combinations integrated with H/C-EGSs. Filled and unfilled markers refer to BSSP 1 and BSSP 2&3 combinations, respectively. The dashed lines link visually between the two groups for each H/C-EGS. For interpretation of each marker's color, the reader is referred to the web version of the article.

Fig. 6 Breakdown of the local cost-optimal solutions of all H/C-EGSs with respect to the reference case costs. For interpretation of each marker's color, the reader is referred to the web version of the article.

Fig. 7 Incremental lifecycle costs versus imported CO₂-eq emissions for all building EEM combinations integrated with H/C-EGSs. Filled and unfilled markers refer to BSSP 1 and BSSP 2&3, respectively. The dashed lines link visually between the two groups of each H/C-EGS. For interpretation of each marker's color, the reader is referred to the web version of the article.

Fig. 8 The incremental life-cycle cost of implementing a PV system in 200 m² modules versus the imported PE for the local cost-optimal solutions of each H/C-EGS. The GSHP-GC has two extensions based on local cost-optimal (filled marker) and minimum energy performance solutions (unfilled marker). The IFGT-AC and ICE-AC are out of the dLCC range. The EEM combinations and maximum PV area achieving the NZEB are given in Table 5. For interpretation of each marker's color, the reader is referred to the web version of the article.

Fig. 9 The cost-optimal solutions versus the imported PE consumption for each heating/cooling system package at different discount rates. The H/C-EGSs are in ascending order according to the cost-optimal solutions obtained from base calculation with a 3% discount rate. For interpretation of each marker's color, the reader is referred to the web version of the article.

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Table 1 Envelope properties, operation schedules, and set points of the reference office building [4].

Property description	Value
U-value of walls	0.17 W/m ² K
U-value of roof	0.09 W/m ² K
U-value of ground floor	0.16 W/m ² K
U-value of windows	1.0 W/m ² K
SHGC of Glazing factor	0.68 (-)
Overall window to wall ratio	27.2 %
Infiltration rate (air change per hour)	0.94 (50 Pa) 1/h
Occupancy schedule	Weekdays 07:00 - 18:00 ^a
Lighting schedule and control	Weekdays 07:00 - 18:00 ^a
Appliances schedule and control	Weekdays 07:00 - 18:00 ^a
Ventilation schedules and control	Weekdays 06:00 - 19:00 ^a at other times 0.15 l/sm ²
Heating set point temperature	21 °C
Cooling set point temperature	25 °C
Heating system	Always On
Cooling system	Always On

^a All detailed profiles depend on the zones utilization, for example, offices, meeting rooms, etc. [4].

Table 2. Heating/cooling energy generation system packages (H/C-EGSs).

Heating/cooling energy generation system package (H/C-EGS) description	Abbreviation
District heating and vapor compression refrigeration system	DH-VCR
District heating and district cooling systems	DH-DC
Pellet boiler and vapor compression refrigeration system	PB-VCR
Ground source heat pump and free ground cooling	GSHP-GC
Biomass-based organic Rankine cycle and vapor compression refrigeration system	ORC-VCR
Biomass-based internal combustion engine with gasifier and vapor compression refrigeration system	ICE-VCR
Biomass-based indirect fire gas turbine and vapor compression refrigeration system	IFGT-VCR
Biomass-based updraft gasifier with stirling engine and vapor compression refrigeration system	SE-VCR
Pellet boiler and absorption chiller system	PB-AC
Biomass-based organic Rankine cycle and absorption chiller system	ORC-AC
Biomass-based internal combustion engine with gasifier and absorption chiller system	ICE-AC
Biomass-based indirect fire gas turbine and absorption chiller system	IFGT-AC
Biomass-based updraft gasifier with stirling engine and absorption chiller system	SE-AC
Natural gas-based internal combustion engine and vapor compression refrigeration system	NG-ICE-VCR
Natural gas-based micro-turbine and vapor compression refrigeration system	NG-mT-VCR
Diesel-based internal combustion engine and vapor compression refrigeration system	D-ICE-VCR

Table 3. Energy carriers' primary energy and CO₂-equivalent emission factors.

Energy carrier	Electricity	DH	DC	Pellets	NG	Diesel oil	Ref
Primary energy factor kWh _{pe} /kWh	1.7	0.7	0.4	0.5	1	1	[6]

CO _{2-eq} emission factor kgCO ₂ /kWh	0.269	0.216	0.12	0.01	0.267 ^a	0.267 ^a	[16,42]
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^a NG and Diesel oil CO₂ emission factors are based on [16], otherwise [42].

Table 4. Energy and fuel prices, and their escalation rates

Energy carrier	Price (c/kWh) ^a	escalation rate (%) ^b
Electricity	15.480	2.74%
DH	7.967	1.78%
DC ^c	2.600	1.78%
Pellets	5.600	1.54%
NG	6.597	6.50%
Diesel	11.290	4.42%

^a All prices are annual average prices based on 2013 and obtained from [43].

^b The escalation rate is calculated based on the energy price evolution for last 10 years.

^c Since the district cooling historical data are not available, it is assumed that it has same escalation rate as DH.

Table 5. Local cost-optimal and minimum energy performance solutions (imported PE) and their building EEM combinations for each H/C-EGS, as well as the reference case. The H/C-EGSs are in ascending order according to the dLCC of the cost-optimal solutions.

	Local cost-optimal solutions					Minimum energy performance solutions				
	dLCC €/m ²	PE _{imp} kWh/ m ² a	PE _{Exp} kWh/ m ² a	EEM [wall, win, inf, BSSP]	PV area to reach NZEB m ²	dLCC €/m ²	PE _{imp} kWh/ m ² a	PE _{Exp} kWh/ m ² a	EEM [wall, win, inf, BSSP]	PV area to reach NZEB m ²
Ref. case	0	162	0	[1, 1, 1, 1]	4484	-	-	-	-	-
GSHP-GC	-83	107	0	[1, 1, 1, 2]	2946	-59	99	0	[3, 4, 4, 3]	2733
PB-VCR	-82	117	0	[1, 1, 1, 2]	3233	-62	108	0	[3, 4, 4, 3]	2971
DH-VCR	-73	121	0	[1, 1, 1, 2]	3347	-58	110	0	[3, 4, 4, 3]	3047
ORC-VCR	-55	113	6	[2, 2, 4, 2]	3127	-37	109	5	[3, 4, 4, 3]	3000
SE-VCR	-49	112	8	[2, 2, 4, 2]	3101	-32	108	6	[3, 4, 4, 3]	2977
PB-AC	-39	121	0	[2, 2, 1, 2]	3330	-19	113	0	[3, 4, 4, 3]	3116
DH-DC	-36	119	0	[2, 2, 1, 2]	3280	-22	109	0	[3, 4, 4, 3]	3016
NG-ICE-VCR	7	153	20	[2, 2, 4, 2]	4212	12	140	16	[3, 4, 4, 3]	3870
IFGT-VCR	16	115	17	[2, 2, 4, 2]	3183	33	110	14	[3, 4, 4, 3]	3033
ICE-VCR	22	121	17	[2, 2, 4, 2]	3332	49	114	14	[3, 4, 4, 3]	3154
ORC-AC	45	119	10	[2, 2, 1, 2]	3283	65	110	7	[3, 4, 4, 3]	3036
NG-mT-VCR	59	157	31	[2, 4, 4, 3]	4321	62	156	30	[3, 4, 4, 3]	4297
SE-AC	59	117	12	[2, 2, 1, 2]	3224	79	108	9	[3, 4, 4, 3]	2981
D-ICE-VCR	74	157	26	[2, 4, 4, 3]	4322	77	156	25	[3, 4, 4, 3]	4297

IFGT-AC	232	126	34	[2, 2, 1, 2]	3474	251	115	26	[3, 4, 4, 3]	3183
ICE-AC	237	136	34	[2, 2, 1, 2]	3755	252	124	26	[3, 4, 4, 3]	3416

Table 6. The local cost-optimal and minimum imported CO₂-eq emission solutions and their building EEM combinations for each H/C-EGS, as well as the reference case. The H/C-EGSs are in ascending order according to the dLCC of the cost-optimal solutions.

	Local cost-optimal solutions				Minimum energy performance solutions			
	dLCC €/m ²	CO ₂ -eq _{imp} kg/m ² a	CO ₂ -eq _{Exp} kg/m ² a	EEM [wall, win, inf, BSSP]	dLCC €/m ²	CO ₂ -eq _{imp} kg/m ² a	CO ₂ -eq _{Exp} kg/m ² a	EEM [wall, win, inf, BSSP]
Ref. case	0	33.8	0	[1, 1, 1, 1]	-	-	-	-
GSHP-GC	-83	16.9	0.0	[1, 1, 1, 2]	-59	15.7	0.0	[3, 4, 4, 3]
PB-VCR	-82	15.8	0.0	[1, 1, 1, 2]	-68	15.0	0.0	[2, 4, 2, 3]
DH-VCR	-73	22.8	0.0	[1, 1, 1, 2]	-58	19.9	0.0	[3, 4, 4, 3]
ORC-VCR	-55	15.2	1.0	[2, 2, 4, 2]	-44	14.7	1.0	[2, 4, 2, 3]
SE-VCR	-49	15.1	1.2	[2, 2, 4, 2]	-39	14.7	1.2	[2, 4, 2, 3]
PB-AC	-39	14.8	0.0	[2, 2, 1, 2]	-27	14.2	0.0	[2, 4, 2, 3]
DH-DC	-36	23.1	0.0	[2, 2, 1, 2]	-22	20.6	0.0	[3, 4, 4, 3]
NG-ICE-VCR	7	30.9	3.2	[2, 2, 4, 2]	12	27.7	2.5	[3, 4, 4, 3]
IFGT-VCR	16	14.8	2.8	[2, 2, 4, 2]	27	14.4	2.8	[2, 4, 2, 3]
ICE-VCR	22	14.9	2.8	[2, 2, 4, 2]	32	14.5	2.8	[2, 4, 2, 3]
ORC-AC	45	13.6	1.6	[2, 2, 1, 2]	65	13.1	1.1	[3, 4, 4, 3]
NG-mT-VCR	59	32.2	4.8	[2, 4, 4, 3]	62	32.0	4.7	[3, 4, 4, 3]
SE-AC	59	13.4	2.0	[2, 2, 1, 2]	84	12.9	1.7	[3, 1, 4, 3]
D-ICE-VCR	74	32.2	4.1	[2, 4, 4, 3]	77	32.0	4.0	[3, 4, 4, 3]
IFGT-AC	232	13.4	5.4	[2, 2, 1, 2]	247	12.8	4.2	[2, 4, 4, 3]
ICE-AC	237	13.6	5.4	[2, 2, 1, 2]	248	13.0	4.2	[2, 4, 4, 3]

Table A. 1 External wall insulation levels and its cost

Wall insulation	Material	Insulation thickness (m)	U-values (W/m ² K)	Investment cost (€/m ³)	Ref.
Wall 1 Wall 2 Wall 3	Mineral wool	0.24, 0.35, 0.54	0.17, 0.12, 0.09	64	[27]

Table A. 2 Window types

Window no	U-value (W/m ² K)	T-value	SHGC	Cost (€/m ²)	Description	Ref.
Win 1 ^a	1.0	0.56	0.68	250	Triple-laminated glass wood aluminum (Argon gas)	[4]

Win 2 ^a	1.0	0.34	0.46	258	Triple-laminated glass wood aluminum (Argon gas)	[8]
Win 3 ^a	0.85	0.29	0.42	290	Quadruple-laminated glass wood aluminum (Krypton gas)	[4]
Win 4 ^a	0.7	0.2	0.3	350	Quadruple-laminated glass wood aluminum (Krypton gas)	[4]

^a In all windows, the blinds are between the outer panels.

The worker cost is subtracted from the total cost of windows taken from [4] to be only the investment cost.

Table A. 3 Infiltration levels

Infiltration level	Specification n50 (1/h)	Additional labor cost (€/m ² of envelope)
Inf 1	1.0	0.0
Inf 2	0.74	4.15
Inf 3	0.49	8.3
Inf 4	0.37	9.6

Costs are taken from [7] and updated to 2013 ones by using 3.2 % inflation rate [28]

Table A. 4 Building service system packages of ventilation system, daylight control [4]

System packages	BSSP 1	BSSP 2	BSSP 3
AHU #1			
Heat recovery effectiveness ^a	0.6	0.8	0.8
Maximum allowable exhaust air temperature	4.0	1.0	1.0
Ventilation control	CAV	VAV ^c	VAV ^c
Air flow rates of L/s,m ²	1.85	min 0.07 max 1.85	min 0.07 max 1.85
Specific fan power (SFP) kW/(m ³ /s)	2	1.8	1.4
AHU #2			
Heat recovery effectiveness ^{a,b}	-	0.55	0.55
Maximum allowable exhaust air temperature	4.0	1.0	1.0
Air flow rate (constant flow), L/(s.m ²)	0.15	0.15	0.15
Ventilation control	CAV	CAV	CAV
Specific fan power (SFP)	2	1.8	1.4
Total ventilation system cost (€/m ²)	90	110	115
Daylight control (Yes/No)	No	Yes ^d	Yes ^d
Building automation cost (€/m ²)	10	15	15

^a Supply air heat recovery ratio

^b AHU #2 serves services zones, corridors, toilets, atrium, etc.

^c The ventilation control of VAV limits: minimum <600 ppm and up to > 900 ppm.

^d Daylight control limits: <500 lx illumination a fully enabled, >700 lx lighting off completely.

Table B. 1 District heating and district cooling costs for business customer

System	Thermal capacity (kW)	Installation cost (€)	annual subscription fees (€)	Ref.
DH	61 > Q _h > 190	15500	22.7 Q _h + 2753.73	[30]
	191 > Q _h > 350	24800	22.7 Q _h + 2753.73	

DC	$220 > Q_c > 315$	$372 \times Q_c$	$58.28 Q_c$	
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Q_h is thermal heating capacity.

Q_c is thermal cooling capacity.

The fixed annual fees are service and subscription cost.

Table B. 2 Pellet boiler costs

Thermal heating capacity (kW)	Thermal efficiency (%)	Installation cost (€)	Annual operation and maintenance (O&M) (€)	Ref.
$100 < Q_h < 200$	84.0 ^a	85,000	2,100	[31]
$200 < Q_h < 350$	84.0 ^a	100,000	2,100	
$350 < Q_h < 600$	84.0 ^a	130,000	2,100	

^a annual average efficiency based on Finnish building code D5-2012 [6]

Table B. 3 GSHP performance and costs

Item	cost	unit	Ref.
Boreholes drilling	33.45	€/m	[32]
Piping of the ground heat exchanger	15	€/m ² of gross building area	
Heat pump equipment	325	€/kW	

- Annual average COP of the GSHP for space and ventilation heating is 3.0 and for DHW is 2.3 based on Finnish building code D5-2012 [6]
- The annual O&M costs are assumed to be 1.5% of installation cost.
- The optimal borehole lengths required for both heating and free ground cooling purposes of the 144 building combinations are obtained using EED 3 (Earth Energy Designer) software [34].

Table B. 4 Vapor compression refrigeration (VCR) cooling system and absorption chiller system performance and costs

System	COP	Installation cost (€)	Annual O&M (€)	Ref.
Vapor compression refrigeration (VCR) cooling system	3.0 ^a	72020	620	[33]
Absorption chiller (AC) system	0.7 ^a	133578	Every year = 3000 ^b Every 3 years = 50000 ^c After 10 years = 15000 ^d	[33]

^a Annual average coefficients of performance are based on [6]

^b The annual O&M includes checks and solution sample analysis.

^c Every 3 years O&M includes change rupture disc.

^d After 10 years O&M includes change the solution pump and refrigerant pump, (the price is assumed).

Table B. 5 CHPs technologies' characteristics and costs

Technologies	Fuel	Electrical efficiency η_e %	Thermal efficiency η_{th} %	Overall efficiency η_{ov} %	Power to heat ratio P_e/H_{th}	Life-time (year)	Inv. cost (€/kW _e)	Variable O&M (€/kWh _e)	Fixed O&M (€/kW _e a)	Ref.	Electrical capacity range
ORC	Pellets	14 ^a	70 ^a	85 ^a	0.2 ^a	20 ^b	6696 ^c	0.0072 ^d	135 ^d	^{a, c} [12], ^b [36], ^d [36]	with VCR 30 – 90 kW _e with AC 78 – 114 kW _e
Gasifier, ICE	Pellets	23 ^e	46 ^e	70 ^e	0.5 ^e	20 ^f	5987 ^g	0.037 ^h	147 ^h	^e [12], ^f [36] ^{g, h} [37]	with VCR 75 – 225 kW _e with AC 195 – 285 kW _e
Direct combustion IFGT	Pellets	28 ⁱ	56 ⁱ	84 ⁱ	0.5 ⁱ	20 ^j	6800 ^k	0.024 ^l	131 ^l	ⁱ [35], ^j [12], ^{k, l} [37]	with VCR 75 – 225 kW _e with AC 195 – 285 kW _e
Updraft gasifier SE	Pellets	18 ^m	72 ^m	90 ^m	0.24 ^m	20 ⁿ	7652 ^m	0.032 ⁿ	33 ⁿ	^m [12], ⁿ [35]	with VCR 36 – 108 kW _e with AC 94 – 137 kW _e
Natural Gas ICE	NG	25.1	44.4	69.5	0.56	20	1436	0.016	20+37.3 ^p	[37]	with VCR 85 – 254 kW _e
Micro-turbine	NG	31	34	65	0.97	20	1946	0.005	60+37.3 ^p	[37]	with VCR 146 – 427 kW _e
Diesel ICE	Diesel	28.4	33.4	61.8	0.85	20	1439	0.016	7	[37]	with VCR 129 – 385 kW _e

^{a-n} The references of all data are identified separately using superscripts.

^p The first value is the unit fixed annual O&M, while the second one is the annual gas grid subscription fee [30].

Table C. 1 Specifications of the PV module “210 P2 PBW” [46] inputted into TRNSYS software to get the hourly electricity production

<i>Parameter</i>	<i>Value</i>
Area (m ²)	1.444
Cell type	polycrystalline
<i>Performance at STC</i>	
Maximum power (W/Pmax)	210
Maximum power tolerance (W)	+5/-0
Current (typical at max power) (A/I _p)	8.16
Voltage (typical at max power) (V/V _p)	25.8
Short circuit current (typical) (A/I _{sc})	8.77
Open circuit voltage (typical) (V/V _{oc})	33.3
Module efficiency (minimum) (%)	14.5
Module efficiency (maximum) (%)	14.9
<i>Performance at NOCT</i>	
Maximum power (W/Pmax)	151.3
Current (typical at max power) (A/I _p)	6.46
Voltage (typical at max power) (V/V _p)	23.4
Short circuit current (typical) (A/I _{sc})	7.09
Open circuit voltage (typical) (V/V _{oc})	30.5
<i>Temperature Coefficients at STC type</i>	
Open circuit voltage (V/K)	-0.117
Short circuit current (A/K)	0.0040
Maximum power (%/K)	-0.54
Efficiency Reduction from STC Reduction (approximately) (%)	5

STC = Standard Test Conditions; cell temperature = 25 °C, irradiation = 1000 W/m², air mass = 1.5.

NOCT = Normal operating cell temperature; cell temperature = 46 °C, irradiation = 800 W/m², ambient temperature = 20 °C, wind speed ≤ 1.0.