Cost optimal and net zero energy office buildings solutions using small scale biomass-based cogeneration technologies

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Abstract

In this study, four different small-scale biomass-based cogeneration heat and power (CHP) technologies along with three conventional energy generation systems serving an office building in Helsinki, Finland are investigated to find the local cost-optimal solutions for minimum energy performance for each as well as the global cost optimal solution. The Energy Performance of Building Directive (EPBD) comparative framework methodology is followed. All building combinations are simulated by IDA-ICE 4.5 software including building energy efficiency measures/packages; external wall insulation, window type, and envelope air-tightness, and building service system packages including ventilation system, and daylight control. The reference case is defined consisting of a reference building built in accordance with the current building code served by district heating and vapor compression cycle cooling system (DH-VCR). The results show that the pellet boiler with vapor compression refrigeration system (PB-VCR) has global cost-optimal solution. When the CHP capacities are sized to cover the peak thermal demands, the low power-to-heat (P/H) ratio CHP technologies have life cycle cost (LCC) less than the reference case, while the CHP technologies with high P/H have higher LCC. The reason for that is the high investment cost relating to higher associated electrical capacities as well as high operational energy costs due to lower thermal efficiency. However, optimizing the CHP capacity and installing an auxiliary pellet boiler means that all investigated CHP technologies have LCC less than the reference case. Furthermore, the net zero energy building (NZEB) solutions extended - by implementing photovoltaic system (PV) - for the cost-optimal solutions have lower LCC than those extended based minimum energy performance solutions.

1. Introduction

According to the Energy Performance of Building Directive 2010/31/EU, (EPBD) recast (Directive, 2010), 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 EBPD recast No 244/2012 (Supplementing-Directive, 2012). In the submitted Finnish report (Ministry-of-the-Environment, 2012), the cogeneration heat and power (CHP) was not investigated as an energy supply system. However, the CHP technologies have various energetic, economic, and environmental advantages over the separate production heat and power in large and district level (Salomón et al., 2011). In Finland, 115,882 GWh biomass fuel was consumed by the CHP plants in 2012 (Statistics-Finland, 2013) Moreover, biomass has the highest renewable energy source share (23% in 2011) which is considered a promising source alongside wind power to replace fossil fuels. This encourages the investigation of installing the small-scale biomass-based CHP systems as an energy generation system (EGS).

The objective of this study is to find the local cost-optimal solutions for four small-scale biomass-based CHP technologies along with three conventional systems as well as the global cost-optimal solution serving an office building in Helsinki, Finland. Furthermore, the cost-optimal and the minimum energy performance solutions are extended by installing a photovoltaic system (PV) to reach the NZEB balance. The aim of that is to answer the question as to which solution has the lower NZEB life-cycle cost (LCC).

2. Methodology

2.1 Cost optimality calculation

The steps of cost-optimal framework methodology explained in (Supplementing-Directive, 2012) are followed. Step 1, the reference building is defined. It is a six-storey office building with a narrow shape (Fig. 1). The room height is 3.6 m. Each floor is 936 m^2 and the net heated floor area is 5615 m^2. The reference office building is built in compliance with the standards of the Finnish building codes (D3, 2012; D5, 2012). Its envelope properties, operation schedule, and set point temperatures are shown in Table 1. More detailed descriptions are presented in (Ministry-of-the-Environment, 2012). Step 2, the building energy efficiency measures (EEM) and all their combinations are identified and simulated using IDA-ICE 4.5 software. The simulation uses reference year weather data (Vantaa TRY2012) (Kalamees et al., 2012). The proposed EEM and packages are categorized into three groups; building structure measures, building service system packages (BSSP), and heating/cooling energy generation systems (EGS). The building structure packages are three wall insulation levels, four window types, and four air-tightness levels. Other EEMs related to the building structure such as roof /ground additional insulation, heavy thermal mass, optimal orientation, solar shading are not considered in this study, because they showed low energy-saving potential in a previous study (Flodberg et al., 2012). The BSSPs are three packages consisting of ventilation system and daylight control. All the suggested combinations of building structure measures and BSSPs (3 x 4 x 4 x 3 = 144 building combinations) are simulated to get the heating, cooling, and electrical energy demands. The heating/cooling EGSs include three conventional systems, district heating and vapor compression refrigeration cooling system (DH-VCR), district heating and district cooling systems (DH-DC), pellet boiler and vapor compression refrigeration cooling system (PB-VCR), and four biomass-based CHPs with VCR; organic Rankine cycle (ORC-VCR), internal combustion engine with gasifier (ICE-VCR), indirect fire gas turbine (IFGT-VCR), updraft gasifier with stirling engine (SE-VCR). Thereafter, in step 3, the delivered energies, the imported primary energy (PE), of 1008 cases (144 x 7) are calculated. The characteristics and costs of the building structure packages, BSSPs and EGSs are illustrated in Appendix A.

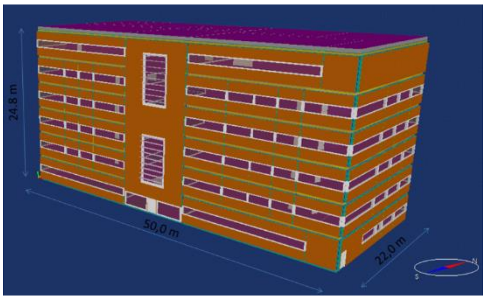

Fig. 1 – The 3D model of the simulated office building in IDA ICE.

Table 1 – Envelope properties, operation schedules, and set points of the reference office building (Ministry-of-the-Environment, 2012)

Property description	value
U-value of walls	0.17 Wm^{-2}K^{-1}
U-value of roof	0.09 Wm^{-2}K^{-1}
U-value of ground floor	0.16 Wm^{-2}K^{-1}
U-value of windows	1.0 Wm^{-2}K^{-1}
SHGC of Glazing factor	0.68 (-)
Overall window to wall ratio	27.2 %
Infiltration rate (air change/hour)	0.94 (50 Pa) h^{-1}
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 ls^{-1}m^{-2}
Winter set point temperature	21 °C
Summer set point temperature	25 °C
Heating system	Always On
Cooling system	Always On

[a] All detailed profiles depend on the zone's utilization, for example, office, meeting rooms, etc.

The delivered energy is calculated by post-processing the annual energy demands taking into consideration the distributed and system efficiencies based on (D5, 2012). For the CHPs, it is assumed that the efficiencies are constant and equal to the nominal values obtained from different sources (Table A. 8, Appendix A). All CHPs are operated to track the thermal demands with ON/OFF operation using the dead band of a water storage system with a capacity of 3.0 cubic meters (Mohamed et al., 2014b).

The conventional systems are sized to cover the peak thermal demands. As a preliminary step, the CHPs are sized to cover the peak thermal demands as well. Thereafter, the CHP capacities are optimized.

Step 4, the imported PE is calculated for the cost-optimal calculations for the imported energies excluding any exported energy following the energy performance calculation method in the Finnish code (D3, 2012). The PE factors are given in Fig. 2. The life-cycle cost (LCC) calculation is the method used to assess the economic viability of the building performance (Supplementing-Directive, 2012). The LCC is the sum of the present value of the investment and discounted operational costs for the building and service systems, including those related to maintenance and replacement, including taxes, over a specified calculation period. In this study, the total incremental life-cycle cost (dLCC) is calculated and presented as a difference cost between each EGS cases and a reference case as given by Eq. (1).

$$dLCC = LCC - LCC_{ref} \quad (1)$$

The reference case consists of the reference building and DH-VCR as a heating/cooling EGS. In the urban area of the Helsinki region, 85% of the building stoke is served by the DH system (City-of-Helsinki, 2008), while the VCR system is the only system investigated with office building in (Ministry-of-the-Environment, 2012).

The LCC calculation follows a financial cost calculation concerning an individual owner perspective as given in ANNEX 1 of (Supplementing-Directive, 2012). The life-span for an office building is 20 years as recommended. The basic calculations are carried out using the 3% real discount rate. All building EEMs have life-spans equal to the calculation period, therefore the residual value will equal zero for all EEMs and packages. No disposal cost for building elements and EEMs are taken into consideration. Fig. 2 shows the fuel and energy prices and their escalation rates. All energy prices include taxes and transportation costs. Under the current Finnish energy policy, the feed-in tariff of the exported electricity produced via new small scale biomass- and biogas-based CHP has a target price of €83.5 $(MWh)^{-1}$ (Energy-Authority, 2013).

Table 2 – Primary energy factors, fuel prices, and escalation rates

Energy carrier	**Primary energy factor** [a] **$kWh_{pe}(kWh)^{-1}$**	**Price** [b] **$€(MWh)^{-1}$**	**escalation rate** [c] **%**
Electricity	1.7	154.8	2.74%
DH	0.7	79.67	1.78%
DC	0.4	26.0	1.78%
Pellets	0.5	56.0	1.54%

[a] PE factors based on Finnish code (D3, 2012).

[b] All prices are annual average prices based on 2013 and obtained from (Statistics-Finland, 2013).

[c] The escalation rate is calculated based on the energy price evolution for the last 10 years.

2.2 Net zero energy building calculation

The NZEB is defined as a building with greatly reduced energy demands through efficiency gains so that the balance of energy needs can be supplied with onsite or neighbouring renewable technologies (Torcellini et al., 2006). In this study, the NZEB building boundary is defined to include all EGSs as onsite supply options and the necessary space required to install any additional onsite or neighbouring renewable energy technology (Mohamed et al., 2014b). However, the imported fuel has to be taken into account in the NZEB balance. The typical operating energy uses are considered for the balance, including heating, ventilation, domestic hot water, lighting, HVAC equipment, and appliances. The import/export is the balancing type. Symmetrical primary energy factors are used for imported and exported electricity. Typically, the balance period is a year. The net PE is the metric balance. The NZEB balance is fulfilled when the net PE is equal or less than zero as shown by Eq. (2).

$$\text{net PE} = \sum \text{PE}_{\text{imp}} - \text{PE}_{\text{exp}} \qquad (2)$$

where PE_{imp} is the sum of the annual imported primary energies, and PE_{exp} is the annual primary energy of the exported electricity.

According to the offer provided by a local energy distribution company (Fortum, 2013), the PV system is installed completely by this company and it purchases the surplus electricity. The installation price of the whole PV system is €427.60 m^{-2} (including VAT) with a 20-year guarantee. The annual service fee is €46.70. In this study, the hourly electricity produced by the PV system is calculated by TRNSYS 17.1 software using the same reference year weather data. The orientation of the PV modules is selected to face south with a tilt angle of 45°. The calculated electricity production after the inverter of a one square meter of PV is 149.3 kWh y^{-1}. The hourly matching between the electrical demand and electricity produced via PV system is carried out using Matlab software. The exported price of the electricity produced via the PV system varies hourly depending on the spot market price. It is equal to the spot market price minus €2.40 $(MWh)^{-1}$ (margin fee) and €0.70 $(MWh)^{-1}$ (online service fee) (Fortum, 2013). The hourly and annual average spot market price of 2013 is obtained from Nord pool spot webpage (http://www.nordpoolspot.com/). The average price of €41.16 $(MWh)^{-1}$ is used.

3. Results and discussion

3.1 Energy demands

The simulated heating, cooling, electrical annual demands of the reference building and implementing separate building structure measures and building BSSP are shown in Fig. 2. The most efficient measures/packages among the packages are BSSP2 and BSSP3, where the ventilation control changed from constant air volume (CAV) to variable air volume (VAV), with saving potential of 24% for the space heating (SPH), 80% for ventilation heating, and 55% for ventilation cooling, while the space cooling (SPC) demand increases by 85%. The reason is related to withdrawing the heat released by the internal heat and solar gains during the night in summer (unoccupied time) where the daytime is too long in the high latitude.

The total annual heating (including DHW, SPH and ventilation heating), cooling (including SPC and ventilation cooling), electrical (including lighting, appliances, and HVAC auxiliaries) demands of the 144 building combinations including the reference building are shown in Fig. 3. All building combinations are categorized into two group indicated by BSSP1 and both BSSP2 and BSSP3 with respect to the large saving potential in the SPH.

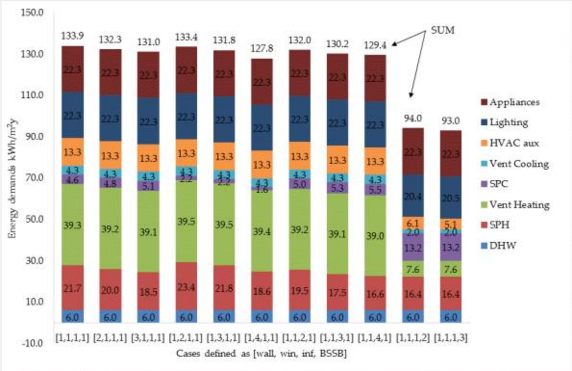

Fig. 2 – Annual energy demands of the reference building and those of implementing the EEM and the BSSP separately.

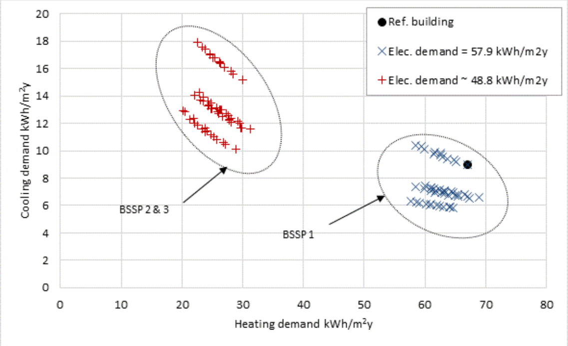

Fig. 3 – Heating, Cooling, and electrical demands of the 144 building combinations.

3.2 Cost optimality calculation

The reference case consisting of the reference building and DH-VCR has imported PE of 162.4 $kWhm^{-2}y^{-1}$ and dLCC of €0 m^{-2}.The solution space has imported PE in range of 107.6 $kWhm^{-2}y^{-1}$ and 177.0 $kWhm^{-2}y^{-1}$, and the dLCC range of €-82.40 m^{-2} and €306.00 m^{-2}. The cost optimal curves including all solutions that have either minimum dLCC or imported PE are shown in Fig. 4.

Table 3 – Local cost-optimal and minimum energy performance solutions and their building combinations for each EGS. The EGSs are in ascending order according to dLCC of the cost-optimal solutions.

	Local cost optimal solutions					**Min energy performance solutions**				
Energy Generation System EGS	**dLCC €m^{-2}**	**PE$_{imp}$ kWh m^{-2}y^{-1}**	**PE$_{exp}$ kWh m^{-2}y^{-1}**	**EEM [wall, win, inf, BSSP]**	**PV area to reach NZEB m^2**	**dLCC €m^{-2}**	**PE$_{imp}$ kWh m^{-2}y^{-1}**	**PE$_{exp}$ kWh m^{-2}y^{-1}**	**EEM [wall, win, inf, BSSP]**	**PV area to reach NZEB m^2**
PB-VCR	-82.4	117.1	0.0	[1,1,1,2]	2591	-61.5	107.6	0.0	[3,4,4,3]	2381
DH-VCR	-73.4	121.2	0.0	[1,1,1,2]	2683	-57.7	110.3	0.0	[3,4,4,3]	2442
ORC-VCR	-54.0	113.3	6.2	[2,2,4,2]	2369	-36.7	103.7	5.0	[3,4,4,3]	2295
SE-VCR	-53.8	112.2	7.5	[2,2,4,2]	2315	-36.5	107.7	6.0	[3,4,4,3]	2251
IFGT-VCR	-37.6	114.1	16.0	[2,2,4,2]	2173	-22.4	109.2	12.7	[3,4,4,3]	2418
DH-DC	-36.3	118.8	0.0	[2,2,1,2]	2629	-21.5	109.0	0.0	[3,4,4,3]	2133
ICE-VCR	-7.5	120.5	17.3	[2,2,4,2]	2285	1.4	113.4	12.8	[2,4,4,3]	2227

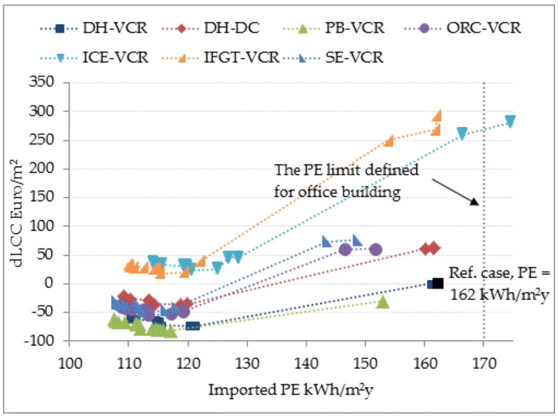

Fig. 4 – The cost optimal curve for all studied EGSs.

From Fig. 4, it can be concluded that biomass-based CHP technologies with a high power to heat ratio (P/H) (IFGT and ICE) have relatively high dLCC compared to those with low P/H. The reason for that is the high investment cost relating to higher associated electrical capacities as well as high operational energy costs due to lower thermal efficiency.

The PB-VCR has the global cost-optimal solution is with dLCC of €-82.40 m^{-2} and imported PE of 117 kWhm^{-2}y^{-1} as given in Table 3.

The PB technology, which is a mature product, has relatively low investment and annual costs. The pellet fuel prices and its escalation rate are the lowest among all energy carriers (Table 2). Moreover, the VCR system has an advantage over the DC system because it has lower annual fees.

Based on the aforementioned results of cost optimality when the CHPs are sized depending on the peak thermal demand, the CHP capacities are re-sized to be a ratio of the thermal peak demand while the remaining demand can be covered by an auxiliary pellet boiler. The CHPs are operated to be a main heating EGS and it has the priority to run over the auxiliary PB boiler. The CHP capacities are optimized where the dLCC is reduced without any significant increase in the imported PE. The optimized small scale CHP capacity is constrained to be not less than the minimum defined capacity of small scale CHP of 30 kWe (Beith, 2011). The CHP range for all CHP technologies is given in (Table A. 8, Appendix A).

With optimized CHP capacities, the solution space has imported PE in range of 107.6 kWhm^{-2}y^{-1} and 161.7 kWhm^{-2}y^{-1}, and the dLCC range of €-82.40 m^{-2} and €71.80 m^{-2}. The cost optimal curves including all solutions which have either minimum dLCC or imported PE are shown in Fig. 5.

Table 3 shows the local cost-optimal and minimum energy performance solutions for all EGSs (after optimizing the CHP capacities).

Regarding the biomass-based CHP, both ORC and SE with low P/H have lowest dLCC and imported PE as well. This is basically due to accounting the imported energies while the exported electricity is excluded. Moreover, the onsite generated electricity has a low utilization ratio by the electrical demand (≈ 34 % in case of cost-optimal solution of ORC-VCR). The low P/H yields to reduce the imported fuel under the operational strategy of thermal tracking. The ICE-VCR system records the highest imported PE and dLCC, while it has the highest exported PE. Generally, the cost-optimal solutions of the investigated small scale biomass-based CHPs with optimal capacities have LCC less than the LCC of the reference case.

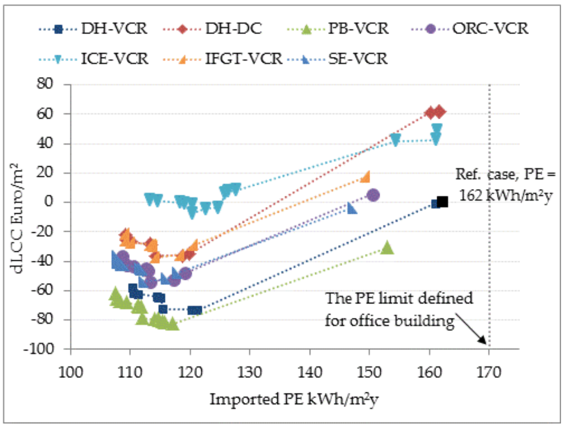

Fig. 5 – The cost optimal curve for all studied EGSs after optimizing the CHP capacities.

Regarding the building combinations of the cost-optimal solutions, the low investment and annual costs systems (PB-VCR and DH-VCR) have the most efficient package of BSSP2 with the same EEMs of the reference building without a need to invest more in other EEMs. Meanwhile, the biomass-based CHP with low thermal efficiency, need more investment in the building construction measures as wall 2, win 2, and inf 4 to reduce the thermal heating demand. The minimum energy performance solutions for all EGSs are the most efficient building EEMs and packages as shown in Table 3.

It must be emphasized that the results of this study do not take into account some issues relating to the EGS such as additional space required depending on the footprint, fuel procurement and storage, and the environmental impact of local emissions emitted from burning biomass onsite or in a dense area nearby.

3.3 Net zero energy building calculation

The NZEB calculations are carried out by extending the cost-optimal and minimum energy performance solutions by installing 200 m² as a module step as shown in Fig. 6. The PV area required to fulfill the NZEB balance between the imported and exported PE are given in Table 3.

It can be noticed that the PV area ≤ 1000 m² has a small increase in the dLCC. The reason is mainly related to the high match between the PV electricity production and the electrical demand. The percentage of the onsite utilized electricity varies between 65% and 72% depending on the EGSs.

It can be concluded that the dLCC of the extended local cost-optimal solutions by a PV system are less than those of the extended minimum energy performance solutions. Therefore, the NZEB is achievable with economic viability with a slight increase in the dLCC by less than €20 m^{-2} over the reference case when the cost-optimal solutions are extended by the PV system with PB-VCR, DH-VCR, ORC-VCR, SE-VCR as a EGSs. Of course, this conclusion helps the policy makers, building's investors, contractors, as well as researchers to identify other barriers facing the NZEB implementation. As concluded in (Mohamed et al., 2014a) the low imported PE does not necessary indicate the high energy matching situation especially when different imported energies (i.e. fuels) are imported beside the electricity and thermal heat.

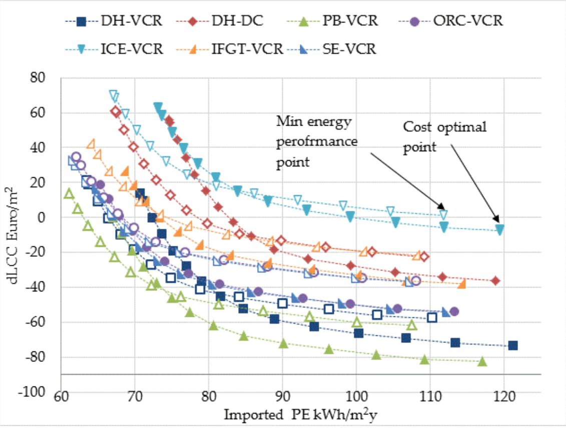

Fig. 6 – The dLCC of implementing PV system in 200 m^2 modules versus the imported PE for the local cost-optimal solutions (filled marker) and minimum energy performance solutions (unfilled marker) after optimizing the CHP capacities.

3.4 Sensitivity analysis

The sensitivity analysis is carried out with three other real discount rates for the cost-optimal solutions of optimized CHP capacities. Fig. 7

shows the imported PE and dLCC of the cost optimal solutions for the EGSs after optimizing the CHP with real discount rates of 1%, 6%, and 10% along with the based calculation of 3%. The EGSs are in ascending order according to the cost optimal solutions of the base calculation of 3%.

As shown in Fig. 7, the dLCC is calculated relatively to its reference case cost with the same real discount rate. The variation of the imported PE for each EGS with different real discount rates means a change in building combinations of the cost optimal solutions. The PB-VCR still has the minimum cost optimal solution among all EGSs, however, the difference between PB-VCR and DH-VCR reduces and becomes close to zero under the high real discount rate of 10%. The DH-VCR and DH-DC become more economical than the ORC-VCR and SE-VCR with a high real discount rate of 10%.

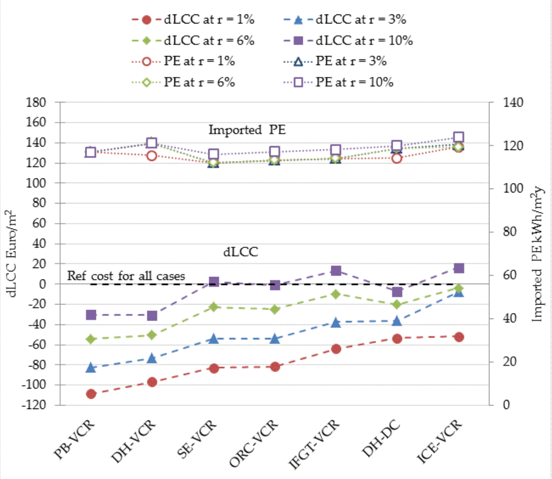

Fig. 7 – The local cost-optimal solutions versus imported PE consumption for each EGS at different real discount rates after optimizing the CHP capacities. The EGSs are in ascending order according to the local cost-optimal solutions of base calculation with 3 % real discount rate.

4. Conclusion

This study followed the EBPD comparative framework methodology to find the local cost-optimal solutions of four biomass-based CHP technologies compared with three conventional heating and cooling systems serving an office building in Helsinki, Finland as well as the global cost-optimal solution. The building energy efficiency measures (EEM) combinations consisting of building structure measures; external wall insulation, window type, and envelope air-tightness, and building service system packages (BSSP) of ventilation system, and daylight control are involved. The reference case defined by the reference building built in accordance with the building codes currently in force served by a district heating and vapor compression refrigeration cooling system (DH-VCR). The results show that the pellet boiler (PB-VCR) has the global cost optimal solution. With the CHPs capacities covering the peak thermal demand, the low power-to-heat (P/H) ratio CHP technologies have a life cycle cost (LCC) less than the reference case, while the CHP technologies with high P/H have higher LCC. The reason for that is the high investment cost relating to higher associated electrical capacities as well as high operational energy costs due to lower thermal efficiency. The CHPs with optimal capacities and with auxiliary pellet boilers have cost-optimal solutions less than that of the reference case. Furthermore, the NZEB solutions extended based on the cost-optimal solutions for all EGSs have lower dLCC than those extended based minimum energy performance solutions.

5. Acknowledgement

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6. Nomenclature

Symbols

BSSP	Building service system package
CAV	Constant air volume
CHP	Cogeneration heat and power
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
ICE	Internal combustion engine
IFGT	Indirect fire gas turbine
LCC	Life-cycle cost (€m^{-2})
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 ($kWh_{pe}m^{-2}y^{-1}$)
PV	Photovoltaic panels
Q	thermal capacity (kW)
SE	Stirling engine
SFP	Specific fan power ($kWm^{-3}s$)
SHGC	Solar heat gain coefficient
SPC	Space cooling demand ($kWhm^{-2}y^{-1}$)
SPH	Space heating demand ($kWhm^{-2}y^{-1}$)
VAV	Variable air volume
VCR	Vapor compression refrigeration cooling system

Subscripts/Superscripts

c	cooling
exp	exported
h	heating
imp	imported
pe	primary energy
ref	reference

Appendix A

Building structure measures', building service system packages', and energy generation systems' characteristics and costs.

Table A. 1 – External wall insulation levels and its cost.

Wall insul.	**Thickness m**	**U-values $Wm^{-2}K^{-1}$**	**Investment cost €m^{-3}**
Wall 1	0.24	0.17	64
Wall 2	0.35	0.12	
Wall 3	0.54	0.09	

Insulation material is mineral wool. (Isover, 2013)

Table A. 2 – Window types.

Window no	U-value $Wm^{-2}K^{-1}$	T-value	SHGC	Cost €m^{-2}
Win 1 [a]	1.0	0.56	0.68	250 [b]
Win 2 [a]	1.0	0.34	0.46	258 [b]
Win 3 [a,b]	0.85	0.29	0.42	290 [c]
Win 4 [a]	0.7	0.2	0.3	350 [b]

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

[b] The investment of win 1, 2, 4 are obtained from (Ministry-of-the-Environment, 2012) after subtracting the worker cost.

[c] The investment of win 3 is obtained from (Hamdy et al., 2013)

Table A. 3 – Air-tightness levels.

Infiltration level	Specification n50 (h^{-1})	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 (Hamdy et al., 2011) and updated to 2013 ones by using 3.2 % escalation rate (Statistics-Finland, 2013).

Table A. 4 – System packages of ventilation system, daylight control, and building automation.

BSSP #	1	2	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 $ls^{-1}m^{-2}$	1.85	min 0.07 max 1.85	min 0.07 max 1.85
Specific fan power (SFP) $kWm^{-3}s$	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), $ls^{-1}m^{-2}$	0.15	0.15	0.15
Ventilation control	CAV	CAV	CAV
Specific fan power (SFP) $kWm^{-3}s$	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 A. 5 – District heating and district cooling costs.

Sys.	Thermal capacity kW	Installation cost €	annual subscription costs €
DH [a]	61 > Q_h > 190	15500	22.7 Q_h + 2753.73
	191 > Q_h > 350	24800	22.7 Q_h + 2753.73
DC [a]	220 > Q_c > 315	372 Q_c	58.28 Q_c

[a] costs are from (Fortum, 2013)
Q_h: thermal heating capacity
Q_c: thermal cooling capacity.

Table A. 6 – Pellet boiler costs.

Thermal heating capacity kW	Installation cost €	Annual operation and maintenance (O&M) €
Q_h < 20 [a]	5328	300
20 < Q_h < 30 [a]	6138	300
30 < Q_h < 60 [a]	10676	500
60 < Q_h < 80 [a]	11319	700
80 < Q_h < 200 [b]	85000	2100
200 < Q_h < 350 [b]	100000	2100
350 < Q_h < 600 [b]	130000	2100

[a] costs of small pellet boiler capacities are from (Hemeltron, 2013)
[b] costs of larger pellet boiler capacities are from (Janfire, 2013)
annual average efficiency = 84 % based on Finnish code (D5, 2012)

Table A. 7 – Vapor refrigeration compression cooling system performance and cost.

System	Installation cost €	Annual O&M €
VCR	72020	620

annual average COP =3.0 based on (D5, 2012)

Table A. 8 – CHP technologies' characteristics and costs

Biomass-based CHP	η_e %	η_{th} %	η_{ov} %	P/H	Electric capacity range kWe
ORC	14	70	85	0.2	90–30 [a] 36–30 [b]
ICE	23	46	70	0.5	225–70 [a] 63–39 [b]
IFGT	28	56	84	0.5	225–70 [a] 45–38 [b]
SE	18	72	90	0.24	108–36 [a] 39–30 [b]

Biomass-based CHP	Inv. cost $€kW_e^{-1}$	Variable O&M $€(kWh_e)^{-1}$	Fixed O&M $€(kWh_e)^{-1}y^{-1}$
ORC	6696	0.0072	135
ICE	5987	0.03	147
IFGT	6800	0.024	131
SE	7652	0.032	33

[a] The CHP capacity range covering the peak thermal demand.
[b] The optimal sized CHP capacity range with auxiliary pellet boiler.
The biomass-based CHPs' references are (Wood and Rowley, 2011), (*Technology data for energy plants*, 2012), (Lukawski, 2010), and (Devlin, 2010).

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