Applied Energy 114 (2014) 385–399

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Fulfillment of net-zero energy building (NZEB) with four metrics in a single family house with different heating alternatives

Ayman Mohamed [a,*], Ala Hasan [b], Kai Sirén [a]

[a] Aalto University School of Engineering, Department of Energy Technology, P.O. Box 14400, FI-00076 Aalto, Finland
[b] VTT Technical Research Centre of Finland, Tekniikantie 4A, Espoo, P.O. Box 1000, FI-02044 VTT, Finland

HIGHLIGHTS

- With four metrics, the NZEB definition is investigated using Finnish and international data.
- Regarding the Finnish data, fulfilling the NZEB-emission is the easiest, then the NZEB-PE, the NZEB-cost, NZEB-site.
- Making the house high in thermal energy efficiency is not a step towards achieving NZEB-emission by shared biomass CHPs.
- The NZEB-PE is easier to fulfill by the international weighting factors than the Finnish ones.
- Generally, the NZEB balance is more attainable by the shared biomass than the standalone CHPs.

ARTICLE INFO

Article history:
Received 6 April 2013
Received in revised form 17 September 2013
Accepted 30 September 2013

Keywords:
Net Zero Energy Buildings (NZEB)
Primary energy
CO_2-eq emissions
Micro and small-scale combined heat and power (micro and small CHP)
Biomass

ABSTRACT

This study aims to investigate the fulfillment of four Net Zero Energy Building (NZEB) balances, NZEB-PE, NZEB-site, NZEB-emission and NZEB-cost, considering the four metrics of primary energy (PE), site energy, CO_2-eqemissions and energy cost, respectively, using weighting factors based on Finnish and international reference data. The study analyzes five conventional energy systems and seven biomass-based standalone and shared combined heat and power (CHP) systems. These systems are connected to a single family house located in Helsinki, Finland, with two energy efficiency levels: a standard house and a passive house, simulated by Trnsys software. The annual balance of the import and export of the operational thermal and electrical energies is applied. The simulated results indicate that the NZEB-emission, NZEB-PE, NZEB-cost, and NZEB-site are arranged in that order according to the ease of fulfilling the annual balance. Making the house high in thermal energy efficiency (or adding solar thermal collectors) for all the studied systems is a step towards achieving NZEB-PE, NZEB-cost, and NZEB-site. On the contrary, achieving the NZEB-emission by the shared CHPs connected to the standard house is easier than the passive house. The NZEB balance is more attainable by the shared CHPs than the standalone CHPs. The NZEB-PE is easier to achieve using the international factors than using the Finnish PE factors.

Contents

Abbreviations: CCS, carbon dioxide capture and storage; CHP, combined heat and power; CO_2-eq, equivalent CO_2 emissions; DC-SE, Direct Combustion Stirling Engine; DH, district heating; DHW, domestic hot water; GSHP, ground source heat pump; HWT, hot water tank; ICE, Internal Combustion Engine; IFGT, Direct Combustion Indirect Fired Gas Turbine; NZEB, Net Zero Energy Building; ORC, Organic Rankine Cycle; PE, primary energy; PEMFC, polymer electrolyte membrane fuel cell; PH, passive house; P/H, power to heat ratio; PV, photovoltaic panels; RES, renewable energy source; SE, Stirling engine; SPF, seasonal performance factor of the GSHP; STC, solar thermal collectors; SH, standard House; UG-SE, Updraft Gasifier Stirling Engine; WP-SE, wood pellet Stirling engine.

* Corresponding author. Tel.: +358 50 431 5774; fax: +358 9470 23418.
E-mail address: ayman.mohamed@aalto.fi (A. Mohamed).

0306-2619/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apenergy.2013.09.065

1. Introduction

The building energy needs in the European Union represent 40% of the final energy consumption [1]. This indicates the potential to make buildings highly energy efficient. The recast of the EU Directive on Energy Performance of Building (EPBD) specified that by the end of 2020, all new buildings shall be "nearly zero energy building" [2]. Additionally, the International Energy Agency (IEA) joint Solar Heating and Cooling (SHC) Task 40 and Energy Conservation in Buildings and Community systems (ECBCS) Annex 52 titled "Towards Net Zero Energy Solar Buildings" is making an international effort on the standardization of the Net Zero Energy Building (NZEB) definition [3]. The NZEB definitions and the compatibility of proposed definitions with current national building codes and international standards are reviewed in [4]. Mainly four balance metrics are used to define NZEB by different twelve methodologies.

In the northern countries of Europe, dependency only on the onsite solar energy as a renewable energy source to achieve the annual balance of the NZEB faces many obstacles, such as the mismatching between the energy production and consumption [5] and the limited area of roof and/or façade, primarily in the dense city areas [6]. In Finland, the abundance of biomass (wood) as the highest renewable energy source share (22% in 2011 [7]) encourages the investigation of using micro and small-scale biomass-based combined heat and power (CHP) systems as energy systems to achieve the NZEB balance or even reduce dependency on onsite solar energy.

Some aspects that must be described to put the NZEB definition in a consistent framework are highlighted in [5]. The balance metric is a key of NZEB definition. It can be primary energy (PE), site energy, CO_2-eq emissions or energy cost [8]. Moreover, the exergy and emergy are proposed as metrics by [9,10], respectively. However, these exergy and emergy metrics are not common popular indicators. The primary energy, site energy, and CO_2-eq emissions are widespread metrics used in many research studies. For instance, using primary energy as a metric presenting standard, low, passive, nearly and net zero energy buildings in relation to economic perspectives is studied by [11–15]. A new and renovated net zero energy buildings are assessed using primary energy and life cycle assessment in [16]. Both primary energy and CO_2-eq emissions of passive and low energy buildings are presented in relation to electric heating, wood boilers and stoves, and heat pumps as variant heating systems [17]. However, a zero site energy home in UK is studied in [18]. In Serbia, a negative, zero, and positive-net residential building energized by electricity from the grid and from the photovoltaic panels (PVs) are studied using site energy metric balance [19]. In Australia, fulfilling the definitions of zero site energy and emission is presented using monitoring results of energy self-sufficient houses in [20]. CO_2-eq emissions as an optimal objective besides the economic objective for low energy building is used in [21,22]. Additionally, the economic perspectives of zero carbon homes in UK are studied in [23].

The debate about which is the appropriate metric, PE or CO_2-eq emissions, is pointed out by [17,24]. Obviously, the national decision about the metric to be used varies from country to country. For example, the code for sustainable homes in the UK sets a target for all new homes to be zero carbon by 2016 [25]. Currently in Finland, the Finnish building regulation codes D3-2012 [26] and D5-2012 [27] indicate national primary energy factors that have to be used for any new building.

This study investigates fulfilling four NZEB definitions according to four different weighting factors based on Finnish reference data by comparing the NZEB balance achievement by five conventional

Table 1
The Finnish and international weighting factors for different energy carriers.

NZEB definition	Unit	Weighting factors					Ref.
		Electricity	District heating	Wood pellet/wood chips	Light oil	Local renewable sources (solar)	
Finnish weighting factors							
NZEB-Finnish PE	$kW\,h_{pe}/kW\,h_{end}$	1.7	0.7	0.5	1.0	0	[26]
NZEB-site	$kW\,h/kW\,h_{end}$	1	1	1	1	0	[8]
NZEB-Finnish emission	$g_{co2}/kW\,h_{end}$	456	226	18	267	0	[28]
NZEB-cost	$c/kW\,h_{end}$	13.24	6.29	5.47	10.66	0	[30]
International weighting factors							
NZEB–IEA–PE	$kW\,h_{pe}/kW\,h_{end}$	2.35	0.77	0.14/0.06	1.3	0	[29]
NZEB–IEA-emission	$g_{co2}/kW\,h_{end}$	430	241	43/35	311	0	[29]

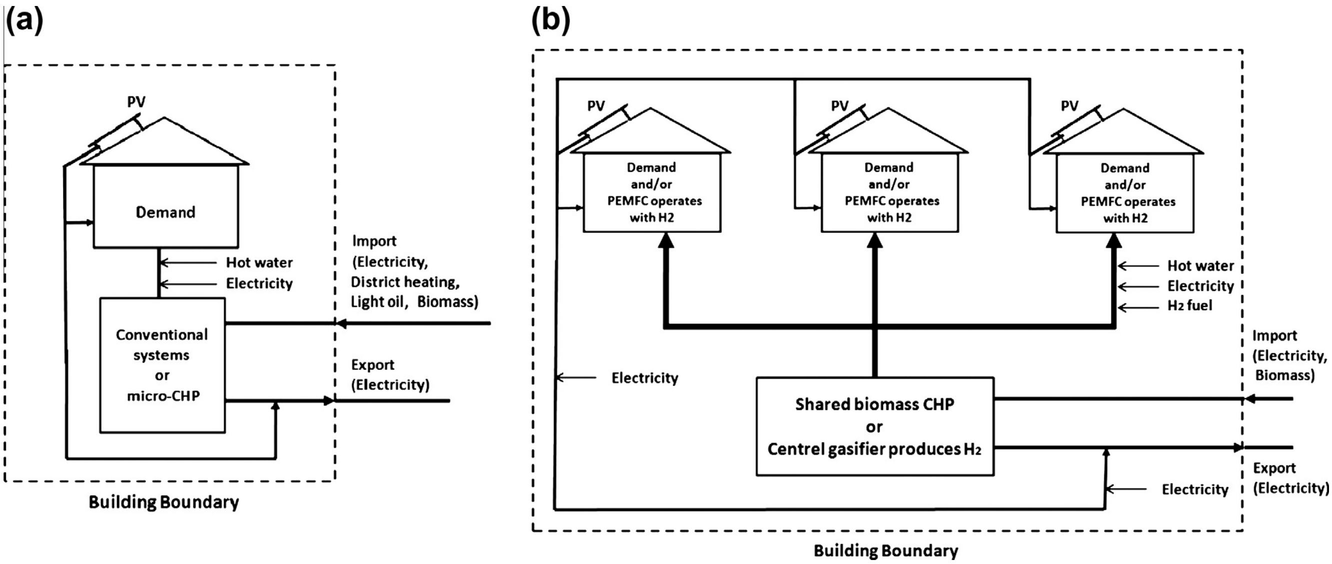


Fig. 1. Building boundary and imported/exported energy carriers of: (a) a single house and (b) a community of houses.

energy systems and seven biomass micro and small-scale CHPs systems. The energy systems provide two single family houses which have two different energy efficiency levels (standard house (SH) and passive house (PH)) located in Helsinki, Finland. Moreover, the comparisons are also carried out using weighting factors of international reference data.

1.1. NZEB crediting metrics

The four most common metrics used are: primary energy (PE), site energy, CO_2-eq emissions, and energy costs [8]. The four NZEB definitions used in this study are Net zero primary energy building based on Finnish weighting factors defined by [26] (NZEB-Finnish PE), Net zero site energy building (NZEB-site), Net zero emission building based on Finnish weighting factors defined by [28] (NZEB-Finnish emission), and Net zero energy (cost) building (NZEB-cost). Additional NZEB definitions using international weighting factors based on IEA SHC 37 Subtask B [29] are investigated: NZEB-IEA-PE and NZEB-IEA-emission. For each definition, the weighting factors of energy carriers used are shown in Table 1. The NZEB-site definition does not differentiate between the energy carriers, crossing the building boundary. That is clearly shown in Table 1 where the weighting factors of all energy carriers are unity. It should be noted that the weighting factors of NZEB-cost for electricity, district heating, light oil, wood pellet and woodchips are the annual average prices in 2011 [30]. In the current study, symmetrical static weighting factors are considered, i.e., for a two-way energy carrier (e.g., electricity), the weighting factors are equal for both imported and exported energies. According to the IPCC report [31] and EU's RED [32], the wood pellet and wood chips as renewable energy sources have neutral greenhouse gas (GHG) emissions. Due to land use, transportation and processing, the primary energy factors and CO_2-eq emissions factors are not neutral at all for biomass fuels [33], as shown in Table 1. It should be emphasized that the weighting factors are used only for the operational energy, whereas the embodied energies are not taken into account in this study. According to the Finnish building regulation code D5-2012 [27], the typical operating energies are heating, ventilation, domestic hot water and lighting, HVAC equipment, and appliances.

1.2. NZEB balance

The balance boundary defines which energies are counted in the balance, and the NZEB balance defines the type of balance used either between the imported and exported energies or energy demands and generation [5]. In this study, the building boundary is the single family house defined by its foot-print area, plus a small lot used to install any energy system, e.g., the solar system. If a shared biomass-based micro and small-scale CHPs are used, the building boundary extends to include the community of houses and the shared systems as well. Thus, the building boundary always includes the generation system. The balance between the exported and imported energies [8] passing across the building boundary is considered as shown in Fig. 1. The net balance period is one year. Generally, the results are normalized per floor area. The weighted imported energy is the sum of all delivered energy, summing all energy carriers each multiplied by its respective weighting factor. The imported energy carriers used in this study are electricity from the grid, district heating, light oil, and biomass (wood pellet and wood chips) fuels. Conceptually, the NZEB balance needs at least one two-way energy flow system, where a grid can deliver energy to the building and receive back from the building. The electric grid is a common two-way energy grid, where the weighted exported energy can be calculated by multiplying the exported electricity by its weighting factor. Thus, it is assumed that the feed-in into the electric grid is possible. However, the Fortum company [34] offers to buy the surplus electricity produced by the PV panels installed in single-family houses located only in the southern cities in Finland. It should be noted that no heat is exported to the thermal distribution network. The annual import/export balance is achieved by using the net weighted energy depending on each NZEB definition. In order to achieve the NZEB balance, the annual net weighted energy should be equal to zero, according to the following equation;

$$\text{Weighted imported energy} = \sum\nolimits_{k=1}^{u} (E_{imp,k} \cdot f_k) \tag{1}$$

$$\text{Weighted imported energy} = \sum\nolimits_{k=1}^{u} (E_{exp,k} \cdot f_k) \tag{2}$$

$$\begin{aligned}\text{Net weighted energy} &= \text{Weighted imported energy} \\ &\quad - \text{Weighted exported energy} \\ &= 0\end{aligned} \tag{3}$$

where f is the weighting factor for each energy carrier, k refers to one energy carrier, and E_{imp} and E_{exp} are imported and exported energy carriers, respectively, summed from the hourly simulated value. The annual weighted imported energy accounts for all energy

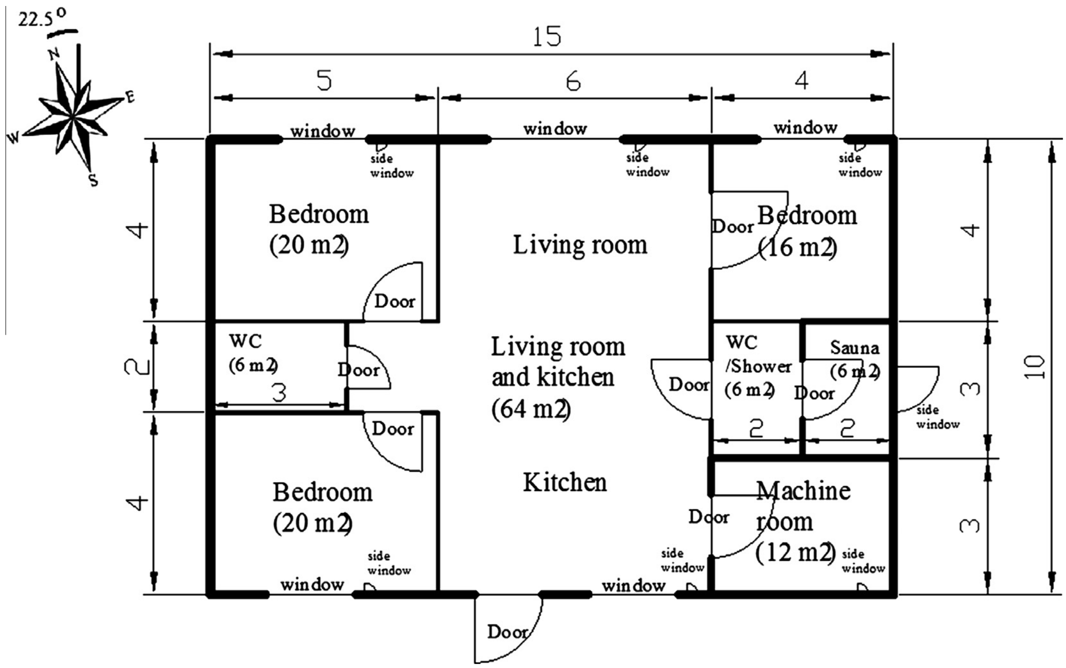


Fig. 2. Plan view of the single family house (all dimensions in meters).

Table 2
Characteristics of the single family house envelope.

House description	Standard house	Passive house
Thermal transmittance U-value (W/m^2 K) of the thermal envelope		
External wall	0.169	0.074
External roof	0.09	0.065
Ground floor layer with soil layer below	0.16	0.07
Windows, doors and exit doors	0.98	0.68
Air tightness n50 (1/h)	2.0	0.6

Table 4
The simulated thermal and electric demands of the standard and passive houses.

House description	Standard house	Passive house
Thermal demands in (kW h/m^2 a)		
Radiator heating	51.06	18.54
Heating demand of mechanical ventilation	13.33	2.43
Space heating demand	64.39	20.97
DHW demand	38.03	22.13
Total thermal demand	102.42	43.10
Electric demands in (kW h/m^2 a)		
Electric consumption of the HVAC systems	7.07	5.50
Electric consumption of the lighting	7.01	7.01
Electric consumption of the appliances	15.77	15.77
Total electric demand	29.85	28.28

carriers imported to the building passing through the building boundary. The generated electricity by any on-site renewable energy systems first covers the building electrical demand, and then the surplus electricity is merely accounted for as the annual weighted exported energy passing through the building boundary.

2. Methodology

Aiming to investigate the achievement of the four suggested NZEB definitions, initially, the simulated results of the hourly energy demand for a standard house (SH) and a passive house (PH) are obtained. The conventional thermal energy systems and shared biomass micro and small CHP systems are illustrated as well as the on-site supplementary systems. Finally, the balance of the four NZEB definitions regarding all energy systems is checked without any on-site supplementary systems. If the NZEB balance is not achieved, the required on-site supplementary system size is determined.

2.1. Building description

As mentioned before, the two energy performance levels of a single family house in Finland are considered. Based on the statistics Finland for building sock of 2012 [35], residential buildings accounted for 63% of the total gross floor area and 85% of the building stock (75% detached houses and 10% blocks of flat). 68% of the Finnish population lives in single family houses. The standard

Table 3
Features of the mechanical ventilation system and DHW needs.

House description	Standard house	Passive house
Air flow rate		
ACH for the occupied zones (Whole year)	0.7 all rooms, 0.98 living room	0.7 all rooms, 0.98 living room
Heat recovery efficiency	60%	85%
Specific fan power of the mechanical ventilation (SFP) kW/(m^3/s)	2	1.5
DHW daily flow (l/person per day)	62	37.6

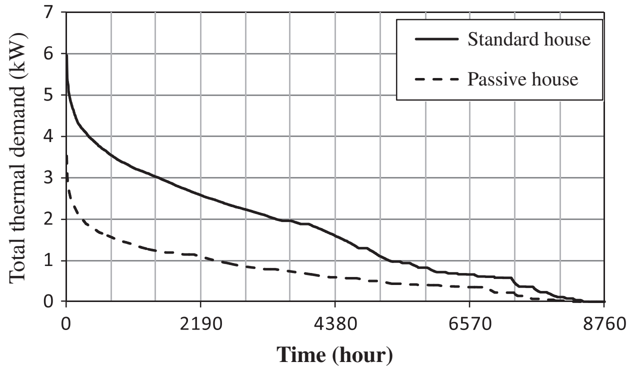


Fig. 3. Duration curves of the simulated total thermal demand for the standard and passive houses.

house (SH) is defined in accordance with the energy level by the Finnish building regulation codes D3-2012 [26] and D5-2012 [27]. The passive house (PH) is defined in accordance with the Finnish Association of Civil Engineers [RIL 249-2009] [36], which defines the requirements of a passive house in Finland.

Because 75% of building stock is situated in south of Finland [37], the house is located in Helsinki, Finland (60.2°N, 24.9°E). It is one-story house with floor area of 150 m^2. Fig. 2 presents the plan drawing of the house. The height of the first floor is 2.5 m, covered by a ventilated attic space that is not considered a heating space. The total glazing area is 21 m^2, which corresponds to 16% of the heated floor area. External solar shading is considered as solar protection for all windows. Additionally, a window opening strategy is used by considering 0.375 m^2 (1.5 m height and 0.25 m width) of each window is airing and has a possibility to open to avoid overheating during summer. Therefore, there is no need for cooling systems.

The characteristics of the SH and PH, such as thermal transmittance, air tightness and windows, are summarized in Table 2. Four people live in the house. The indoor air temperature is set at 21 °C [26]. All rooms in the house are heated by radiators. These radiators can be electric or hot water types according to the thermal energy systems. An air handling unit (AHU) is used as a mechanical ventilation system which consists of supply and extraction fans, a heating coil, and a heat recovery system. The supply air temperature to the rooms is set at 18 °C. If the outdoor temperature is higher than 18 °C, the supply air passes directly to the building through a bypass duct. The domestic hot water DHW demand is calculated based on 55 °C supply temperature to the taps and 5 °C incoming cold water [26]. The detailed values of the mechanical ventilation system and DHW for the SH and PH are shown in Table 3. The profiles of occupancy, DHW, lighting, and household appliances are compiled based on a detailed measured hourly profile of the RET project conducted by VTT in 2005 [38].

The SH and PH are simulated by Trnsys 17 software [39]. The simulated thermal and electric demands of the SH and PH are shown in Table 4. The simulation results indicate that, the space heating demand and DWH demand are reduced by 67.4% and 41.8% between SH to PH, respectively. The total thermal demand is reduced by 57%. The reduction of the electric demand is only 5% taken place in the PH related to use a highly efficient energy ventilation system. Moreover, the duration curves of the total thermal demands are shown in Fig. 3. These results indicate that the peak thermal demands of the SH and PH are 5.9 kW and 3.5 kW, respectively.

2.2. Energy systems

In 2011, the energy consumption of the energy sources in single family houses in Finland was 29% electricity, 42% biomass, 13% light oil, 10% ambient energy, and 6% DH [40]. Use of DH and GSHP for heating in single family houses was grown through the last decade. For new single family houses constructed between 2006 and 2011, the percentages of the heating sources are 25% direct electric heating, 38% ground source heat pump (GSHP), 14% district heating, 8% biomass (pellet, wood and woodchips), 2% oil, 13% others [41]. Therefore, five conventional thermal systems are applied in this study, covering the most implemented heating sources in the single family houses. Besides, seven biomass-based micro and small-scale CHP systems are investigated. For all systems, the house is assumed to be connected to the electric grid. Therefore, the electric grid compensates the shortage of the house electricity supply as well as receives the surplus electricity.

2.2.1. Conventional thermal systems

Five energy systems are chosen based on thermal supply by conventional systems. To calculate the imported energy that crosses the building boundary, the thermal energy demands are divided by the relevant system efficiency. These efficiencies are defined according to the Finnish building code D5-2012 [27]. The first system is the electric heating system. The electric radiator efficiency is 94%. The second system is the district heating (DH) system. The monthly efficiency of DH varies between 96% and 91%. The third system is a ground source heat pump (GSHP). The annual mean seasonal performance factor (SPF) of the GSHP is taken as 3.0 for space heating and 2.3 for DHW. Light oil and wood pellet boilers are the fourth and the fifth systems, respectively. The light oil and wood pellet boiler capacities are 10 kW each according to the minimum available capacities in the market. The monthly efficiencies of the light oil and wood pellet boilers vary from 92–73% and 76–56%, respectively. It should be emphasized that systems efficiencies are fed as hourly values through the simulation process. It should be noted that the thermal distribution losses and the electric consumption by the pumps are taken into consideration according to the Finnish building code D5-2012 [27]. According to the wood pellet boiler recommendation, 50 L water storage has to be considered for each 1 kW thermal capacity of the boiler [42]. Therefore, a 500-L hot water tank (HWT) is coupled by all energy systems to be utilized for space heating and DHW needs.

2.2.2. Biomass-based micro and small-scale CHP systems

Seven biomass-based micro and small-scale CHP systems are investigated as renewable energy systems to achieve the NZEB balances. A 1.4 kWe wood pellet Stirling engine (WP-SE) is the standalone biomass-based micro CHP. The performance of this unit is available in [43]. According to the literature review, this (WP-SE) is the only standalone biomass-based micro CHP available in the market that is appropriate for the demands of a single family house. Five shared biomass-based micro and small-scale CHP systems are: a 35 kWe Direct Combustion Stirling Engine (35 kWe DC-SE) [44], a 35 kWe Updraft Gasifier Stirling Engine (35 kWe UG-SE) [44], a 100 kWe Indirect Fired Gas Turbine (100 kWe IFGT) [45], a 30 kWe with Internal Combustion Engine coupled with gasifier (30 kWe ICE) (the woodchip is converted to combustible gases by heating in a reduced oxygen environment in a downdraft gasifier after which the gas is cleaned and combusted in a modified compression ignition engine) [46], and a 0.86 kWe direct combustion Organic Rankine Cycle (0.86 kWe ORC) [47]. Table 5 provides the performance of the previous biomass-based shared and micro CHP systems. The last selected energy system considered is a domestic scale polymer electrolyte membrane fuel cell (PEMFC) that operates with hydrogen produced via an on-site central biomass gasification plant. According to Toonssen et al. [48], the biomass is converted to a produced gas in an atmospheric fluidized bed gasification process using steam as the gasifying agent. The producer gas is cleaned and processed to produce 99.99% pure

Table 5
Performance of standalone and shared biomass CHP and fuel cell systems.

Description	Number of houses		Electric power P_e (kW)	Thermal output H_{th} (kW)	Electrical efficiency η_e%	Thermal efficiency η_{th}%	Overall efficiency η_{tot}%	Power/ Heat P/H	Ref.
	Standard	Passive							
1.4 kWe wood pellet SE	1	1	1.38	5.4	14.3	57.8	72.1	0.256	[43]
35 kWe direct combustion SE	44	67	35	215	12.0	74.0	86.0	0.16	[44]
35 kWe updraft gasifier SE	30	45	35	145	18.0	72.0	90.0	0.24	[44]
100 kWe direct combustion IFGT	41	62	100	200	28.0	56.0	84.0	0.5	[45]
30 kWe gasifier, ICE	16	25	30	80	23.0	61.0	84.0	0.377	[46]
0.86 kWe biomass fired ORC	9	14	0.86	47.26	1.41	78.69	80.1	0.0184	[47]
The hydrogen based PEMFC	1	1	2.70/1.8	4.80/3.2	15.32	27.28	42.60	0.56	[48,52]

hydrogen in order to meet the requirements for a PEMFC. The compressed hydrogen is supplied to a hydrogen grid that can be connected to a domestic scale PEMFC (henceforth referred to only as PEMFC), as shown in Fig. 1b. From an economical point of view, according to [49], producing hydrogen from biomass is already economically competitive related to other hydrogen production methods from renewable energies, for example, onshore wind, offshore wind, solar thermal electric, solar PV, and nuclear energy. It should be noted that the overall efficiency of a fuel cell operating with hydrogen produced via centralized gasifier-fed biomass or coal is until now less than 50% [48,50,51], mainly due to losses in the conversion process.

The biomass fuel fed to the shared CHP systems of these cases is woodchips. A 500-L HWT is installed as a terminal storage tank for space and domestic hot water demands at each house, as mentioned earlier. Therefore, no central storage tank is considered. Fig. 4 shows the standalone CHP electric and thermal connections. The PV panels and the solar thermal collectors (STC) connections shown in Fig. 4 are applied in further stages in this study as will be illustrated in Section 2.3. The same thermal and electric connections are applied for the shared CHP, but indirectly through the electric grid and the thermal distribution network. The different biomass shared systems are selected according to the electric and thermal outputs and their efficiencies to investigate the effect of their thermal and electric characteristics in achieving the NZEB balances.

Regarding the number of houses served by any shared biomass CHP showed in Table 5, the thermal tracking operation is the common control strategy for CHP units. Therefore, the numbers of the SH and PH are calculated by dividing the thermal output including the distribution losses of the thermal network by the peak thermal demand of the house. From the simulated results, it is found that even if one hour is used as the simulation time-step, it is necessary to install a 1 kWe electric heater as an auxiliary system to avoid any fluctuations in the water supply temperature. In order to increase the operating hours of the shared CHPs to increase the produced electricity, the peaks of thermal demands of SH and PH are optimized to be 4.8 kW and 3.2 kW rather than the peaks of 5.9 kW and 3.5 kW, respectively, using the same auxiliary electric heater capacity. For the shared CHP, the community of the houses includes similar houses with its own tank and pumps. Also, the thermal outputs of PEMFC are scaled to be matched with the peak thermal demand of the SH and PH. The performance and the control strategy of PEMFC are based on [52]. Table 5 shows the performance of the installed PEMFC for the SH and PH, based on either biomass or hydrogen fuel.

It must be emphasized that the associated emissions of startup burning biomass which always contain NO_x and CO with high CO_2-

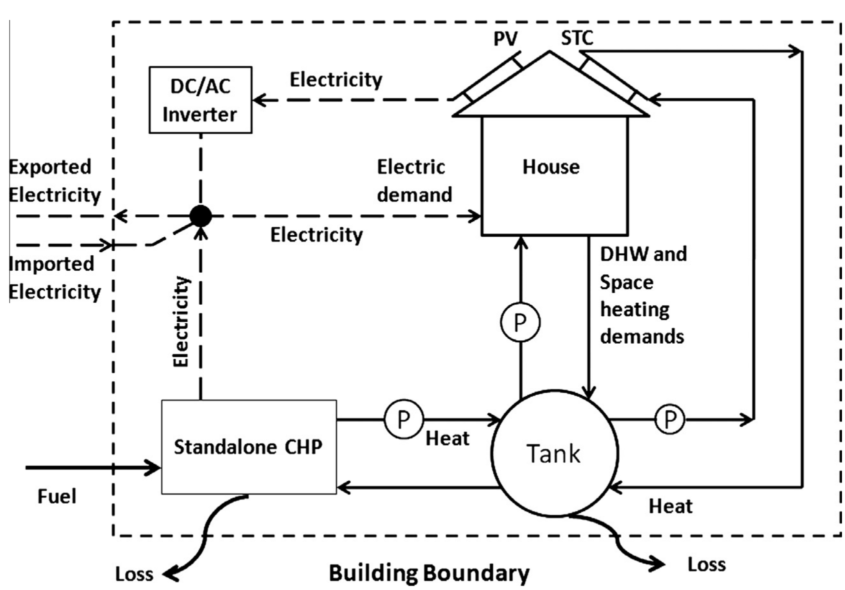


Fig. 4. Standalone CHP thermal and electric connections.

eq emissions are not taken into account, as well as any particular pollutions associated with biomass burning.

2.3. On-site supplementary systems

The NZEB balance for each definition is investigated for all energy systems mentioned separately in Section 2.2. An on-site supplementary system has to be installed whenever the NZEB balance is not achieved by producing electricity or heat from the solar energy. As shown in Table 1, the weighting factor of any heat and power produced on-site from solar energy is zero for all NZEB definitions. Two ways are applied to fulfill the NZEB balance: (1) Installing photovoltaic (PV) modules to offset the difference between the imported and exported crediting by producing electricity on-site. (2) In order to study the effect of reducing the thermal demand on the NZEB balance for all energy systems, flat plate solar thermal collectors (STCs) are installed as an additional heating system, and the NZEB balance is not achieved; the required PV area can be determined as well. The following subsections illustrate the performance of the on-site supplementary systems used in this study.

2.3.1. Photovoltaic (PV) modules

The orientation of the PV modules is selected to face south with a tilt angle of 45°. The electricity production after the inverter of a one square meter of PV is 93.0 kW h/a, which is equivalent to 0.62 kW h/a per floor area of the house. It should be noted that in all cases, the calculated PV area is rounded up to get an integer number of modules.

2.3.2. Flat plate solar thermal collectors (STC)

The flat plate solar thermal collector (STC) module has a gross area of 2.874 m^2 where it is used and simulated by [53]. To collect maximum solar radiation by the STC in Finland, the STC is oriented facing south with a 45° tilt based on [12]. This is in accordance with Finnish building code D5 [27], which indicates that the best orientation is south, southeast or southwest, and the optimal tilt angle is between 30° and 70°. The STC area is determined by parametric analysis for different areas of the STC with two different systems the DH and the WP-SE. Fig. 4 shows the STC connection with the standalone CHP (the WP-SE). The same connection is applied for all alternative heating systems. The thermal load (space heating and DHW) is extracted from the hot water storage tank. The DH and STC supply the heat to the storage. The STC has the priority over any alternative system when the enough solar energy is available. The STC is controlled according to the temperature difference cross the STC (ΔT_{sc}). The solar pump turns ON under condition of 2 °C $\leqslant \Delta T_{sc} \leqslant$ 10 °C. Additionally, the solar pump turns OFF whenever the top tank temperature is 95 °C. The DH and WP-SE system is controlled to achieve the top storage tank temperature to be between 65 °C and 55 °C. Fig. 5 shows the annual useful solar energy of DH and WP-SE cases, which goes through the 500-L storage tank for the SH and PH. According to Fig. 5, the gradient of the solar thermal energy gained decreased rapidly after four modules of the STC. Therefore, four modules of the STC with a gross area of 11.5 m^2 are selected to be installed for all systems and houses. However, the annual useful energy gain is slightly changed from case to another due to the thermal performance of each system and the thermal demand of the SH and PH, but the same trend is observed due to using similar control strategy and coupling connections between all systems and the STC. In the case of DH, the useful solar energy gain of coupling an 11.5 m^2 STC are 13.42 and 10.44 kW h/m^2 a for the SH and PH, respectively, which cover approximately 35.3% and 47.2% of DHW demands for the SH and PH, respectively.

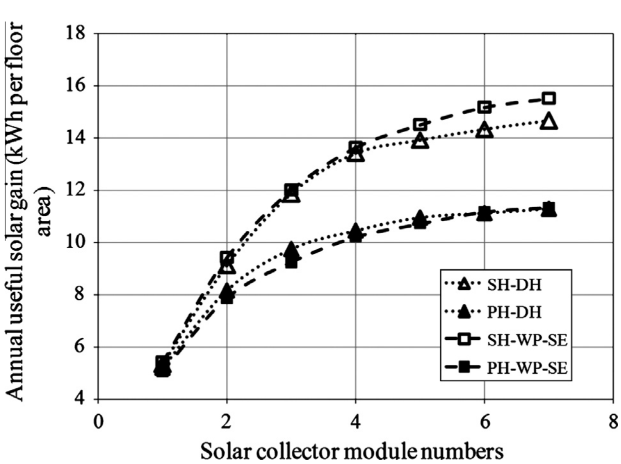


Fig. 5. Annual useful energy by solar thermal collector versus its module numbers for DH and WP-SE cases.

3. Results and discussion

As mentioned above, the twelve energy systems for both SH and PH are simulated using the Finnish weighting factors regarding each NZEB definitions separately. The balance is then checked and achieved by post-processing and calculating how much PV area is required to achieve the annual balance. After that the effect of coupling the STC is analyzed. The comparison of using Finnish and international weighting factors is carried out.

3.1. Net zero primary energy building (NZEB-Finnish PE)

The weighting factors of the energy carriers of (NZEB-Finnish PE) definition are defined by the Finnish building code D3-2012 [26], shown in Table 1. Fig. 6 shows the imported and exported primary energy (PE) for all energy systems. The sum of imported primary energies is illustrated on the *X*-axis. The *Y*-axis shows the exported PE which is related only to the surplus electricity of the CHP systems production. The vertical distance from the presented point of any case to the zero balance line must be supplied by the on-site electricity production from PV to achieve the NZEB balance.

Table 6 shows the PV area required to achieve the balance of all the NZEB definitions for the SH and PH. It should be noted that after installing the required PV area, some of the produced electricity will move all the points to the left on the *X*-axis, due to the self-matching of the production and consumption and will then move them upward to the zero balance line as exported electricity. The example in Fig. 6 shows the case of the shared 100 kWe IFGT with the community of SHs, indicated by point A. The imported and exported PEs are 130 and 71 kW h/m^2 a, respectively. By installing a PV area of 56 m^2 to achieve the NZEB-Finnish PE balance according to Table 6, point A moves to the left to point B′ (where the imported PE is reduced to 120 kW h/m^2 a due to the self-matching of the electricity consumption of the PV electricity production) and then moves upward to point B due to export of the same amount of PE which fulfills the balance between imported and exported PE. The sum of the distances from point A to B′ and from B′ to B is equal to the vertical distance from point A to A′.

In accordance with the Finnish PE limit defined in the building codes D3 [26], the corresponding imported Finnish PE must be lower than 159.5 kW h/m^2 a for a 150 m^2 floor area. This limit is shown in Fig. 6. Without installing any PV area, the SH with electrical heating, light oil boiler and PEMFC cases are not appropriate as energy systems since their corresponding imported Finnish PEs

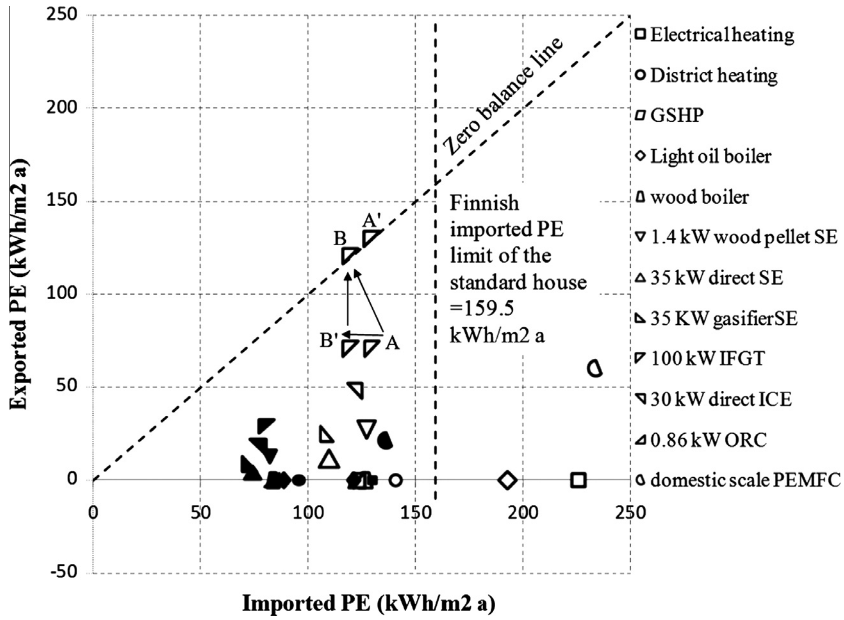


Fig. 6. Imported/exported primary energy according to the Finnish reference data for all cases (unfilled and filled marks are the SH and PH cases, respectively).

are higher than the defined limit. The reason is the high weighting factors of electricity (1.7), light oil (1.0), and very low overall efficiency of 42.6% of the PEMFC based on biomass fuel. When the house becomes PH, all the energy systems are within the code PE limits.

From Fig. 6, it can be noticed that the net Finnish PE of all PH cases is less than the corresponding SH cases according to the vertical distance between any point and the zero balance line. Generally, the higher reductions are by the conventional systems that depend on an electric grid or fossil fuel to produce thermal energy (highest net Finnish PE reduction is 93 kW h/m^2 a for the electrical heating case), while the lower reductions are by the shared biomass CHPs. The reason is that whenever the thermal demand is low, the associated electricity production, utilized by the house and/or exported is low. The lowest reduction of Finnish PE is only 8 kW h/m^2 a for the 100 kWe IFGT, which has a high electric efficiency of 28% and a P/H ratio of 0.5. The same results mentioned above are presented in Table 6 but in the form of the PV area required for the SH and PH cases. The smallest PV areas required are 49 m^2 and 56 m^2, underlined and indicated in Table 6, corresponding to the 100 kWe IFGT with the PH and SH, respectively.

3.2. Net zero site energy building (NZEB-site)

In the NZEB-site balance, the quantity of the physical delivered energies crossing the building boundary are only accounted for without taking any consideration for other features of the energy such as its source, pollution, cost and availability [8]. Therefore, the weighting factors for all energy carriers equal unity as shown in Table 1. Obviously the system, which provides high energy efficient building (i.e., PH) and has high efficiency, is the best solution from the NZEB-site point of view, where low imported energies will be needed. Therefore, as shown in Fig. 7, the shorter vertical distance is from the GSHP case of PH to the zero balance line, and this means that the GSHP as a thermal energy system which has a high SPF connected to a PH, has the lowest net site energy of 51 kW h/m^2 a, which must be generated on-site by installing an 85 m^2 PV area to achieve the balance, according to Table 6. The PEMFC providing the SH is the worst case. It has 438 and 83 kW h/m^2 a as imported and exported site energies, respectively, and it is out of the presented scale of Fig. 7. Therefore, the NZEB-site definition is hard to apply due to the high investment cost needed for the on-site supplementary system, for example the PV area to achieve its balance as shown by the high values indicated in Table 6.

From Table 6, it can be noticed that the required PV for electrical heating is equal for SH and PH; same for the GSHP system. The reason is that the electricity is the only energy carrier imported from the grid and exported by the PV crossing the building boundary and symmetrical weighting factor is used. Therefore, the resulting PV area required will always be the same for all the NZEB definitions.

3.3. Net zero emission building (NZEB-Finnish emission)

Fig. 8 shows the imported and exported CO_2-eq emissions in kg_{CO2}/m^2 a for all energy systems. The imported CO_2-eq emissions mean the released CO_2-eq emissions associated with the imported energies, whereas the exported CO_2-eq emissions mean the displaced CO_2-eq emissions in the grid associated with the exported energies from renewable energy sources, using the symmetric CO_2-eq emissions factors in Table 1. It can be seen that the points indicated in Fig. 8 can be categorized into two groups. Group 1 includes the conventional systems plus the 0.86 kWe ORC. Group 2 includes the rest of all systems. As shown in Fig. 8, the imported CO_2-eq emissions decrease when the house is more thermally efficient (i.e., PH) for Group 1 because the thermal demand is covered by the conventional systems while the electricity needs are imported from the grid separately. The exception is in case 0.86 kWe ORC where, the very small amount of electricity produced on-site is associated with heat production, but it is utilized entirely by the house. All these cases are on the *X*-axis, i.e., there is no electricity exported. The best cases among this group are the wood pellet boiler and 0.86 kWe ORC fed by biomass, which have a low CO_2-eq emissions factor, unlike other conventional systems fed by electricity, fossil fuel, or district heating which have already relativity high CO_2-eq emission factors. See Table 1.

Table 6
PV area required to achieve the balance for the four NZEB definitions for the SH and PH.

Energy systems	PV area required of standard house (m^2)				PV area required of passive house (m^2)			
	NZEB-Finnish PE	NZEB-site	NZEB-Finnish emission	NZEB-cost	NZEB-Finnish PE	NZEB-site	NZEB-Finnish emission	NZEB-cost
Electrical Heating	215	215	215	215	124	124	124	124
District heating	134	247	150	146	91	149	99	97
Ground source heat pump	117	**117**	117	117	85	**85**	85	85
Light oil boiler	183	275	182	232	115	162	115	140
Wood boiler	121	297	57	151	80	167	49	95
1.4 kWe wood pellet Stirling engine	95	308	18	131	67	167	30	84
35 kWe direct combustion, Stirling engine	94	270	31	124	68	155	36	82
35 kWe updraft gasifier, Stirling engine	80	261	14	110	61	152	28	76
100 kWe Direct Combustion Indirect Fired Gas Turbine	**56**	287	**0**	**95**	**49**	165	**8**	**69**
30 kWe gasifier Internal Combustion Engine	70	282	0	106	56	162	18	74
0.86 kWe Organic Rankine Cycle	117	288	56	146	79	165	48	94
Domestic scale PEMFC connected to shared gasifier	165	655	0	247	109	358	19	151

Under-lined values indicate the minimum PV area required for each NZEB definition.

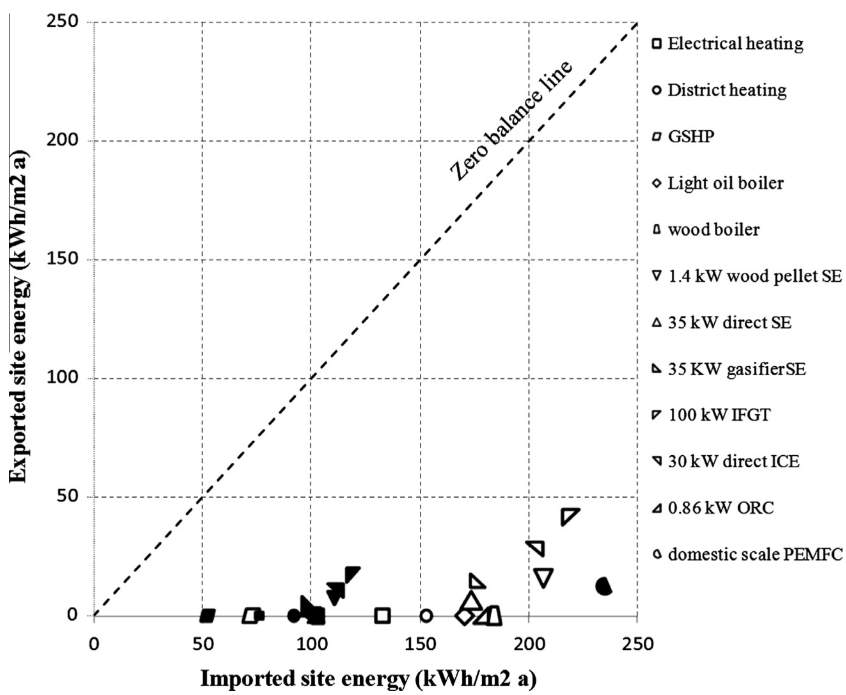


Fig. 7. Imported/exported site energy for all the cases (unfilled and filled marks are the SH and PH cases, respectively).

In contrast is Group 2, (which includes the standalone WP-SE and the shared CHP systems), as they are affected negatively by making the house more thermally efficient (i.e., PH). Therefore, the SH cases are closer to the zero balance line than the PH cases. The reason has two attributes. First, electrical demand of the PH does not have the same reduction relative to the SH as the thermal demand. As shown in Table 4, the electric reduction that takes place in the PH is only related to the use of a highly efficient energy ventilation system with only 5% reduction, while the thermal reduction is 57%. This means that while the operational strategy of the CHPs is thermal tracking, the possibility of the SH to produce electricity (whether utilized by the house demand and/or exported to the grid), is higher than for the PH. For example, the annual exported electricity of the 100 kWe IFGT system for the SH and PH is 41.47 and 17.10 kW h/m^2 a, respectively, and the annual imported electricity for the SH and PH is 17.5 and 16.6 kW h/m^2 a, respectively. The annual imported biomass energy is 203 kW h/m^2 a and 102 kW h/m^2 a for the SH and PH, respectively. The biomass weighting factors of 18 g_{co2}/kW h_{end} for wood pellets and wood chips are very low compared to the weighting factor of 456 g_{co2}/kW h_{end} of the grid electricity. As shown in Fig. 8, the total associated emissions of the imported energy for the PH of 9.8 kg_{CO2}/m^2 a, which is slightly lower than that for the SH of 11.3 kg_{CO2}/m^2 a, but the total associated emissions of the imported electricity for the PH of 7.9 kg_{CO2}/m^2 a is lower than that for the SH 19.2 kg_{CO2}/m^2. It can be concluded that, getting NZEB-Finnish emission balance is easier with SH than with PH, however, the total imported energy is higher. Therefore, a building with a very low thermal energy demand will certainly reduce the total imported energy but it will not be a

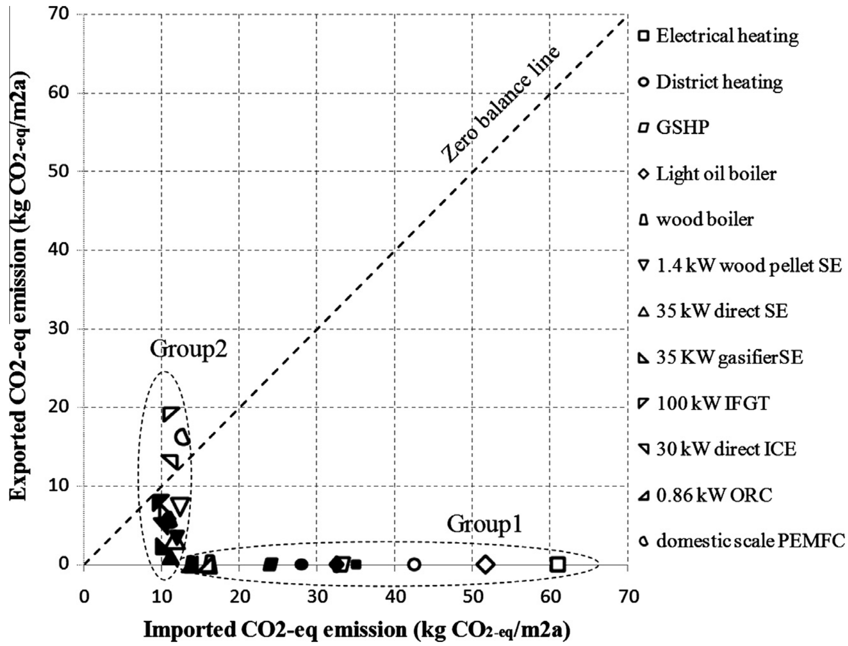


Fig. 8. Imported/exported CO_2-eq emissions according to the Finnish reference data for all cases (unfilled and filled marks are the SH and PH cases, respectively).

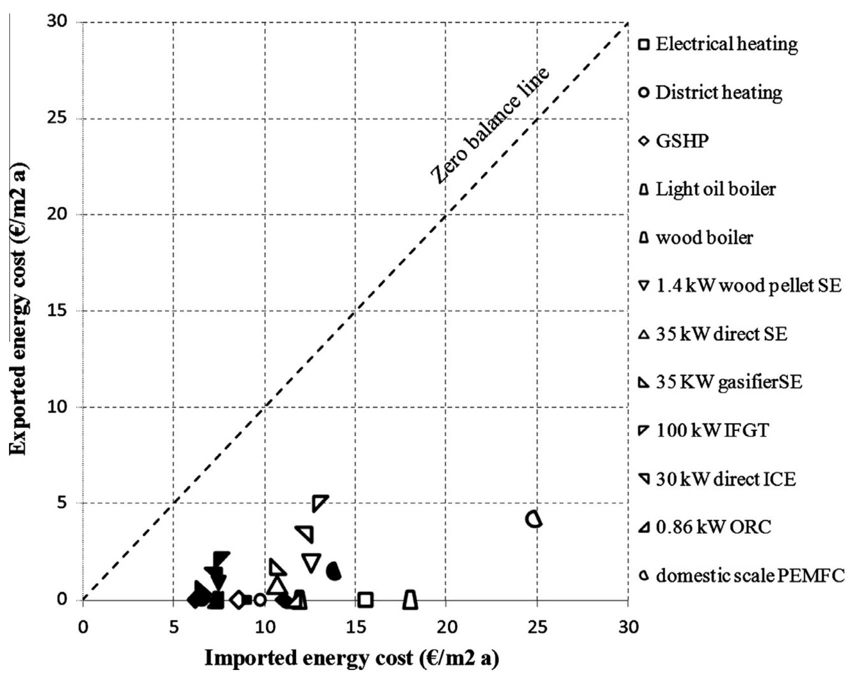


Fig. 9. Imported/exported energy cost for all the cases (unfilled and filled marks are the SH and PH cases, respectively).

step towards achieving NZEB with the biomass-based CHP systems that operate under thermal tracking strategy.

Fig. 8 also shows that there are three biomass CHP systems that are plus net emission cases: 100 kWe IFGT, 30 kWe gasifier ICE, and PEMFC with the community of the SHs. These biomass CHP systems have higher P/H ratios as well as higher electrical efficiencies. Table 6 shows the PV area required to achieve the balance of the NZEB-Finnish emission for all cases of the SH and PH, which shows that the NZEB-Finnish emission in the biomass systems needs the smallest sizes of the PV to obtain the balance compared to the other definitions.

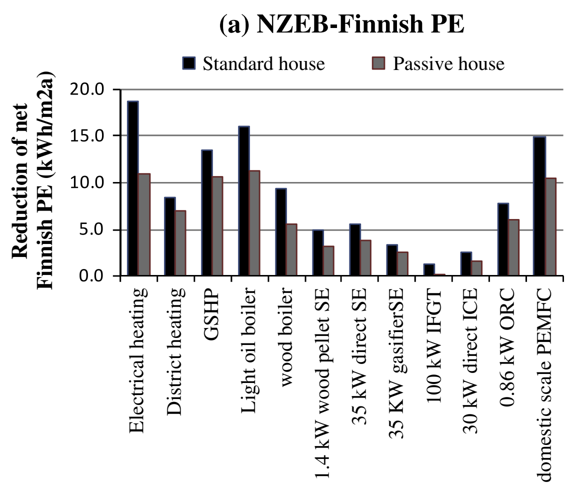
3.4. Net zero energy cost building (NZEB-cost)

Fig. 9 shows that increasing the building energy efficiency from the SH to PH decreases the net operational energy cost for all of the energy systems. As shown in Table 6, the PV area required to achieve the balance of the NZEB-cost is higher than both the NZEB-Finnish PE and NZEB-Finnish emission for all energy systems. The reason is that the ratio of the energy carrier cost to the electricity cost is always higher than the ratio of the weighting factor of the energy carrier of either PE or CO_2-eq emissions to the weighting factor of the electricity of both the NZEB-Finnish PE and NZEB-Finnish emission. For example, the wood to electricity weighting factor ratio of 3.4 and 25.3 of the NZEB-Finnish PE and the NZEB–Finnish emission, respectively are higher than that for of the NZEB-cost 2.4. Additionally, according to the associated reduction of the PV area required due to increasing the building energy efficiency from the SH to PH is higher than both of the NZEB-Finnish PE and NZEB-Finnish emission. It can be noticed from Fig. 9 that the shared 100 kWe IFGT with the PH is the best case, and the second is the 30 kWe direct ICE with the PH, where two cases have high electrical efficiencies of 28% and 23%, respectively. The PEMFC with the SH is the worst case due to low overall efficiency based on biomass. It can be concluded that applying the NZEB-cost where larger a PV area is required to achieve the balance needs a higher investment cost than both the NZEB-Finnish PE and NZEB-Finnish emission. Also, from the operational energy cost point of view, if the NZEB-cost definition has to be applied, it is necessarily to make the house highly energy efficient.

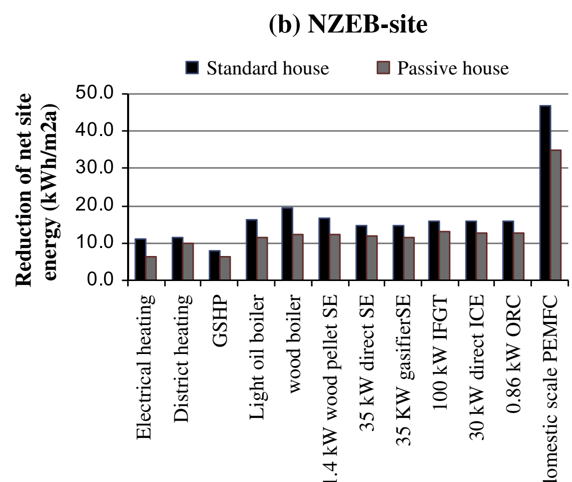
3.5. Influence of installing the solar thermal collector (STC) on the NZEB definitions

The aim of this section is to analyze the influence of a STC on the NZEB definitions. As mentioned in Section 2.3.2, the STC area of 11.5 m^2 is selected in the SH and PH. The control strategy of the STC is selected to give the priority of utilizing the useful solar energy produced by the STC over any energy system. The consumed electricity by the circulating pump of the STC is taken into account. The useful solar energy produced varies slightly according to energy system and the house thermal demand.

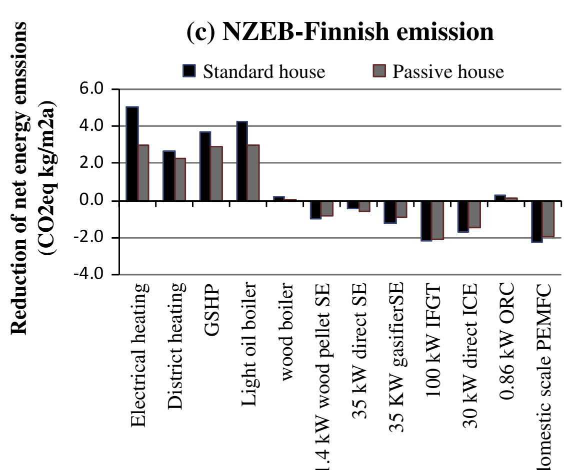
Fig. 10a shows the effect of installing the STC on the net Finnish PE and the PV area required before and after installing the STC for the NZEB-Finnish PE. The reductions are due to the compensating portion of the imported energy by thermal energy produced onsite from solar energy by the STC with zero PE factor. Thus, the



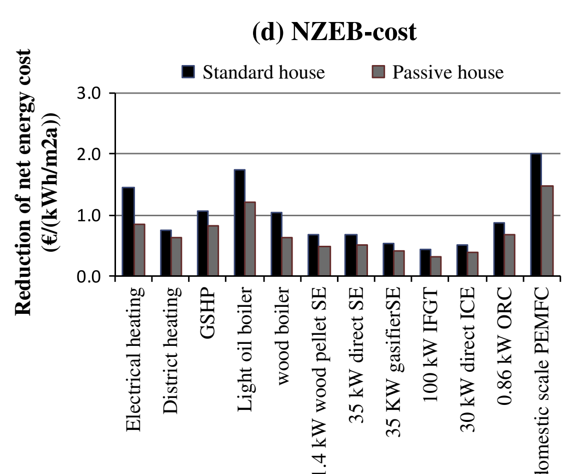
PV area w/o SCT	SH	215	134	117	183	121	95	94	80	56	70	117	165
PV area w/i SCT		197	126	104	168	112	91	89	77	55	68	110	151
PV area w/o SCT	PH	124	91	85	115	80	67	68	61	49	56	79	109
PV area w/i SCT		114	85	75	105	75	64	64	59	49	55	74	99



PV area w/o SCT	SH	215	247	117	275	297	308	270	261	287	282	288	655
PV area w/i SCT		197	228	104	249	266	282	246	238	262	257	262	580
PV area w/o SCT	PH	124	149	85	162	167	167	155	152	165	162	165	358
PV area w/i SCT		114	133	75	144	147	147	136	133	144	142	145	302



PV area w/o SCT	SH	215	150	117	182	57	18	31	14	0	0	56	0
PV area w/i SCT		197	140	104	167	57	22	32	18	0	0	55	0
PV area w/o SCT	PH	124	99	85	115	49	30	36	28	8	18	48	19
PV area w/i SCT		114	91	75	104	49	33	38	32	15	23	48	26



PV area w/o SCT	SH	215	146	117	232	151	131	124	110	95	106	146	247
PV area w/i SCT		197	137	104	211	138	123	115	104	90	100	136	223
PV area w/o SCT	PH	124	97	85	140	95	84	82	76	69	74	94	151
PV area w/i SCT		114	90	75	125	87	78	76	71	65	70	86	133

Fig. 10. Reduction of net energy crediting by installing an 11.5 m^2 STC for all of the NZEB definitions. The table under each sub-figure indicates the associated PV area before and after installing the STC in m^2.

systems that are fed by imported fuels which have a high PE factor as electricity and light oil and/or have low efficiency as biomass-based PEMFC have the highest reductions of 18.8, 16.1, and 14.9 kW h/m^2 a with the SH, respectively. On the other hand, the micro and small-scale CHP have low reduction of the net Finnish PE. The 100 kWe IFGT has a negligible affect for the SH and the PH because the 100 kWe IFGT has a high electrical efficiency and reducing the thermal demand will also reduce the associated produced electricity.

Fig. 10b shows the effect of installing the STC on the net site energy and the PV area required before and after installing the STC for the NZEB-site. Because the weighting factor for all energy carriers is unity, the reduction of the net site energies is mainly reflected by efficiencies in the systems. For example, the largest and lowest reductions of the net site energy of 46.8 and 6.3 kW h/m^2 a are the biomass-based PEMFC with SH and the GSHP with PH, respectively. It can be noticed that reducing the thermal demand by installing the STC is a step toward achieving the NZEB-site balance.

For the NZEB-Finnish emission, Fig. 10c shows the effect of installing the STC on the CO_2-eq emissions and the PV area required before and after installing the STC. For conventional thermal energy systems except the wood boiler, have a reduction of the CO_2-eq emissions within the range of 5.1 and 2.2 kg_{CO2}/m^2 a. For the biomass-based systems and due to a very small biomass weighting factor relative to other used fuels, additional PV area is required to achieve the balance as shown in the table under Fig. 10c, especially when changing the house from SH to PH. The reason is similar to that illustrated in Section 3.2.

Regarding the NZEB-cost, Fig. 10c shows the effect of installing the STC on the operational energy cost and the PV area required before and after installing the STC. The reduction of the operational energy cost of all systems has the same behavior as the reduction of the PE. Generally, the potential reduction in operational energy cost is higher than that of the PE, because the ratios of all energy carriers' weighting factors to the grid electricity weighting factor of the NZEB-cost definition are higher than that of the NZEB-Finnish PE definition.

It can be concluded that for the conventional thermal energy systems, the reduction of the net credits and associated reduction of the PV area required are affected inversely by the system thermal efficiency (where low thermal efficiency means high savings in imported energy) and proportionally with the weighting factors of the imported energies of each NZEB definition (high weighting factor means high savings in imported energy). For biomass-based micro and small-scale CHP systems, the reduction of the net credits and associated with the reduction of the PV area required are affected inversely with both overall and electrical efficiencies of the CHP and proportionally with the ratio of the weighting factor of biomass to grid electricity for each NZEB definition, where the produced electricity by the CHP reduces and/or offsets the imported electricity. The order of the NZEB definitions according to their net credits and PV required reductions are NZEB-site, NZEB-cost, NZEB-Finnish PE and NZEB-Finnish emission, followed by the ratios of the biomass to electricity weighting factors (1:1 = 1), (5.47:13.24 = 0.41), (0.5:0.7 = 0.29), and (18:456 = 0.04),as shown in Fig. 10b, d, a and c, respectively.

It can be concluded that for all of the NZEB definitions (except NZEB-site) and without any exporting heat to the thermal distribution network, installing the STC has lower benefits over installing the PV system, especially for the biomass CHP systems due to the following reasons: (1) While the electricity has higher weighting factor for all NZEB definitions, the electricity produced by the PV can cover a part of the electric demand and thermal demand as well by converting it to heat through the auxiliary heater for example. (2) Depending on the solar energy availability, the electricity produced by the PV can be utilized and/or exported, while the heat gained by the STC is controlled to be based on the thermal demand. (3) Installing the STC reduces the availability to operate the biomass CHP for longer periods and produce electricity which can offset the imported grid electricity; (4) For the NZEB-Finnish emission definition which has a very low biomass weighting factor compared with the grid electricity factor, dependence on providing the thermal demands of a biomass CHP creates an opportunity to produce electricity even though this biomass CHP has low electrical efficiency.

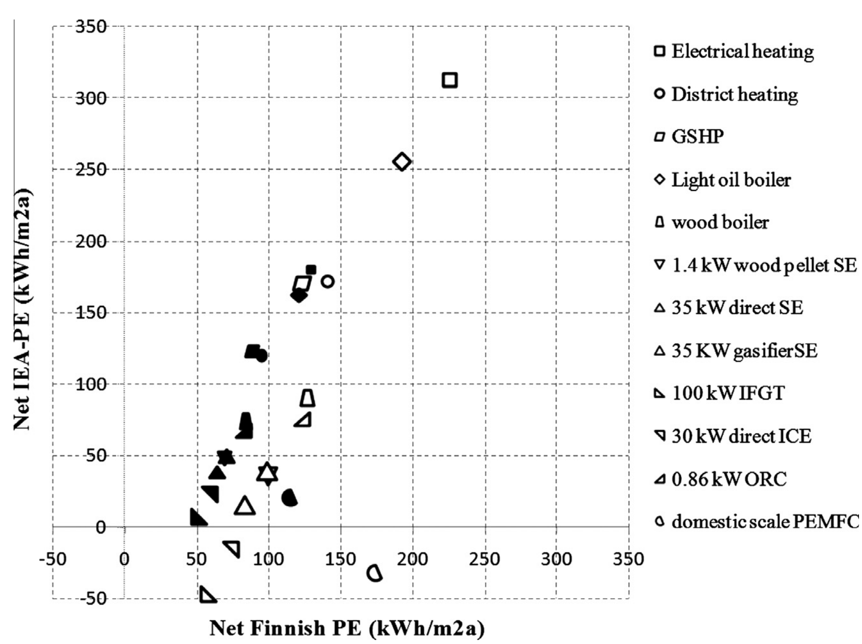


Fig. 11. Net Finnish PE vs. net IEA primary energy of the twelve cases providing standard and passive houses (unfilled and filled marks are SH and PH cases, respectively).

Table 7
Comparison PV area required to achieve the balance for the NZEB primary energy and $CO_{2\text{-eq}}$ emission definitions based on Finnish and international reference data for the SH and PH.

Energy Systems	PV area required of standard house (m^2)				PV area required of passive house (m^2)			
	NZEB-Finnish PE	NZEB–IEA–PE	NZEB-Finnish emission	NZEB–IEA-emission	NZEB-Finnish PE	NZEB–IEA–PE	NZEB-Finnish emission	NZEB-IEA-emission
Electrical heating	215	215	215	215	124	124	124	124
District heating	134	118	150	163	91	83	99	106
Ground source heat pump	117	117	117	117	85	85	85	85
Light oil boiler	183	176	182	214	115	111	115	131
Wood boiler	121	62	57	73	80	51	49	56
1.4 kWe wood pellet Stirling engine	95	25	18	37	67	33	30	39
35 kWe direct combustion, Stirling engine	94	27	31	41	68	34	36	41
35 kWe updraft gasifier, Stirling engine	80	11	14	25	61	27	28	34
100 kWe Direct Combustion Indirect Fired Gas Turbine	56	0	0	0	49	5	8	15
30 kWe Gasifier Internal Combustion Engine	70	0	0	6	56	16	18	25
0.86 kWe Organic Rankine Cycle	117	52	56	66	79	47	48	53
Domestic scale PEMFC connected to shared gasifier	165	0	0	17	109	14	19	34

3.6. Comparison between the influence of different weighting factors on the same NZEB definition

This section aims to compare the influences of using the weighting factors based on Finnish and international references data as shown in Table 1.

3.6.1. Influence of Finnish and IEA primary energy factor on the NZEB-PE

The difference between the primary energy factors of Finland and IEA is related to the relative portion of the electricity production by RESs in the national or international grid. Fig. 11 shows the relation between net IEA–PE and net Finnish PE for all of the studied cases. Regarding the NZEB-Finnish PE, the PE values of all the cases decrease with change in the house from the SH to the PH as shown in Section 3.1. For the NZEB–IEA–PE, the PE values of the conventional thermal energy systems decrease with change in the house from the SH to the PH, while the PE values of the biomass CHP systems increase. From both Fig. 11 and Table 7, it can be noticed that the biomass CHP systems, the 100 kWe IFGT, the 30 kWe gasifier ICE and the domestic scale PEMFC, providing the SH are all plus NZEB–IEA–PE, while in Fig. 11 it can be seen that the NZEB-Finnish PE balance is not achieved solely by any system. It can be concluded that achievement of the NZEB–IEA–PE always needs a PV area less than the NZEB-Finnish PE with both the SH and PH, especially for the biomass CHP systems with the SH (except the 0.86 kWe ORC system) as shown in Table 7.

3.6.2. Influence of Finnish and IEA CO_2-eq emissions factors on the NZEB-emission

Based on the CO_2-eq emissions factors shown in Table 1, it can be noticed that, except the electricity, the IEA CO_2-eq emissions factors of the other energy carriers are higher than the Finnish ones. Therefore, the required PV areas to achieve the NZEB-Finnish emission balance are smaller than that for the NZEB–IEA emission regarding the same energy system and the house energy demand level, as indicated in Table 7. For example, for the conventional systems, the light oil boiler and wood pellet boiler, connected to the SH, need 182 and 57 m^2 of PV area, respectively to achieve the balance of NZEB-Finnish emission, while 214 m^2 and 73 m^2 of PV area are needed for the NZEB–IEA emission, respectively. For the biomass CHP systems, 100 kWe IFGT, 30 kWe gasifier ICE and the domestic scale PEMFC are all plus NZEB-Finnish emission, whereas only the 100 kWe IFGT connected to the SH is plus NZEB–IEA emission. It is also noticed that both of the NZEB-Finnish emission and NZEB–IEA emission have negative effects when increasing the building thermal efficiency with the biomass CHP systems. It can be concluded that achieving the NZEB-Finnish emission balance is easier than the NZEB–IEA emission balance for all the studied energy systems with both the SH and the PH.

4. Conclusions

This study aims to investigate the achievement of four Net Zero Energy Building (NZEB) balances, NZEB–PE, NZEB-site, NZEB-emission and NZEB-cost, considering the four metrics of, primary energy (PE), site energy, CO_2-eq emissions and energy cost, respectively, using weighting factors based on Finnish reference data. Five conventional thermal energy systems and seven micro and small-scale biomass-based CHPs are investigated when connected with two different energy levels of a single family house, a standard house (SH), and a passive house (PH) in Finland. The annual balance of import/export concerning the operational thermal and electrical energies was investigated. Additionally, a comparison between using national Finnish and international weighting factors of both primary energy and equivalent CO_2-eq emission is analyzed.

The following findings are obtained from this comparative study:

- Electrical heating, light oil boiler and domestic scale H_2 PEMFC with the SH have imported PE higher than the PE limit value defined by the current Finnish building regulation code.
- The NZEB definitions can be arranged in the following order according to the ease of achieving of the annual balance: (1) NZEB-Finnish emission (2) NZEB-Finnish PE (3) NZEB-cost and (4) NZEB-site. This order is due to the ratio of the weighting factors of any energy carrier to that for the grid electricity (Here, the electrical grid is the only two ways energy flow considered).
- For the conventional thermal energy systems, however, increasing the thermal energy efficiency by using efficient thermal insulation or by installing solar thermal collectors (STC) is a step towards fulfilling all of the NZEB balances.

- Making the thermal energy demand of a building very low (PH instead of SH) has a reverse effect on the balance achievement of NZEB-Finnish emission for the biomass-based micro and shared CHPs. This is because of the thermal tracking control strategy used, no possibility of heat export to the thermal distribution network and the ratio of the weighting factors of the electricity to the biomass, which is very high in this definition. A similar conclusion is found for the NZEB–PE and NZEB-emission based on the international reference data.
- For the biomass CHP systems, installing solar thermal collectors reduces the availability to operate the CHP for longer periods and consequently to produce electricity from biomass that has a low weighting factor compared with the grid electricity.
- Fulfilling the NZEB–PE using the weighting factors based on the international reference data is easier than using the weighting factors based on the Finnish reference data. Achieving the NZEB-emission is easier using the Finnish reference data than the international reference data.
- This study shows that, up to date, a domestic scale biomass CHP is not the best solution for the NZEB to replace a centralized power supply. A local shared biomass CHP is better due to its characteristics (high overall efficiency and power to heat ratio).

Acknowledgements

The authors would like to acknowledge the academy of Finland for funding this work. The authors would like also to acknowledge the IEA task 40/Annex 52 regarding the effort made to develop the NZEB concept.

References

[1] Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on the energy efficiency. Official Journal of the European Union; 2012. 14/11/2012.
[2] EPBD recast, Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). Official Journal of the European Union; 2010. 18/06/2010.
[3] IEA. SHC Task 40/ECBCS Annex 52, Towards Net Zero Energy Solar Buildings, IEA SHC Task 40 and ECBCS Annex 52, <http://task40.iea-shc.org/>, 2008 (accessed 30.07.2013).
[4] Marszal AJ, Heiselberg P, Bourrelle JS, Musall E, Voss K, Sartori I, et al. Zero energy building - a review of definitions and calculation methodologies. Energy Build 2011;43(4):971–9.
[5] Sartori I, Napolitano A, Voss K. Net zero energy buildings: a consistent definition framework. Energy Build 2012;48:220–32.
[6] Fong KF, Lee CK. Towards net zero energy design for low-rise residential buildings in subtropical Hong Kong. Appl Energy 2012;93:686–94.
[7] Statistics Finland, Energy Consumption. <http://www.stat.fi/til/ehk/2011/>. (accessed 30.07.2013).
[8] Torcellini P, Pless S, Deru M. Zero energy buildings: a critical look at the definition. USA: National Renewable Energy Laboratory (NREL); June 2006.
[9] Kılkış Ş. A net-zero building application and its role in exergy-aware local energy strategies for sustainability. Energy Convers Manage 2012;63:208–17.
[10] Srinivasan RS, Braham WW, Campbell DE, Curcija CD. Re(De)fining net zero energy: renewable emergy balance in environmental building design. Build Environ 2012;47:300–15.
[11] Saari A, Kalamees T, Jokisalo J, Michelsson R, Alanne K, Kurnitski J. Financial viability of energy-efficiency measures in a new detached house designin Finland. Appl Energy 2012;92:76–83.
[12] Hamdy M, Hasan A, Siren K. A multi-stage optimization method for cost-optimal and nearly-zero-energy building solutions in line with the EPBD-recast 2010. Energy Build 2013;56:189–203.
[13] Leckner M, Zmeureanu R. Life cycle cost and energy analysis of a Net Zero Energy House with solar combisystem. Appl Energy 2011;88:232–41.
[14] Marszal AJ, Heiselberg P. Life cycle cost analysis of a multi-storey residential net zero energy building in Denmark. Energy 2011;36:5600–9.
[15] Marszal AJ, Heiselberg P, Jensen RL, Nørgaard J. On-site or off-site renewable energy supply systems Life cycle cost analysis of a net zero energy building in Denmark. Renew Energy 2012;44:154–65.
[16] Thiers S, Peuportier B. Energy and environmental assessment of two high energy performance residential buildings. Build Environ 2012;51:276–84.
[17] Georges L, Massart C, Van Moeseke G, De Herde A. Environmental and economic performance of heating systems for energy-efficient dwellings: Case of passive and low-energy single-family houses. Energy Policy 2012;40:452–64.
[18] Wang L, Gwilliam J, Jones P. Case study of zero energy house design in UK. Energy Build 2009;41:1215–22.
[19] Bojic M, Nikolic N, Nikolic D, Skerlic J, Miletic I. Toward a positive-net-energy residential building in Serbian conditions. Appl Energy 2011;88:2407–19.
[20] Saman WY. Towards zero energy homes down under. Renew Energy 2013;49:211–5.
[21] Hamdy M, Hasan A, Sirén K. Applying a multi-objective optimization approach for design of low-emission cost-effective dwellings. Build Environ 2011;46:109–23.
[22] Hamdy M, Hasan A, Sirén K. Optimum design of a house and its HVAC systems using simulation-based optimization. Int J Low-Carbon Technol 2010;5(3):120–4. <http://ijlct.oxfordjournals.org/content/5/3/120.short>.
[23] Osmani M, O'Reilly A. Feasibility of zero carbon homes in England by 2016: A house builder's perspective. Build Environ 2009;44:1917–24.
[24] Hernandez P, Kenny P. From net energy to zero energy buildings: defining life cycle zero energy buildings (LC-ZEB). Energy Build 2010;42:815–21.
[25] Department of Communities and Local Government (DCLG). Code for Sustainable Homes: a step change in sustainable home building practice. London: HMSO; 2006.
[26] D3 Finland Code of building Regulation. Energy management in buildings, regulations and guidelines. Helsinki: Ministry of Environment; 2012.
[27] D5 Finland Code of building Regulation. Calculation of power and energy needs for the heating of buildings, guidelines. Helsinki: Ministry of Environment; 2012.
[28] Heljo J, Laine H. Report 2005:2. Sähkölämmitys ja lämpöpumput sähkönkäyttäjinä ja päästöjen aiheuttajina. Suomessa. Näkökulma ja malli sähkönkäytön aiheuttamien CO_2-ekv päästöjen arviointiavarten.Tampere University of Technology. Institute of, Construction Economics [in Finnish].
[29] Hastings R. IEA SHC 37 Subtask B: Exemplary Renovation Projects; 2010.
[30] Statistics Finland. Energy Prices. <http://www.stat.fi/til/ene_en.html>. (accessed 30.07.2013).
[31] IPCC. 2011: IPCC Special report on renewable energy sources and climate change mitigation. Prepared by working group III of the intergovernmental panel on climate change. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Seyboth K, Matschoss P, Kadner S, Zwickel T, Eickemeier P, Hansen G, Schlömer S, von Stechow C, editors. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 1075p.
[32] European Commission. Commission staff working document. Impact assessment. accompanying document to the report from the commission to the council and the European Parliament on sustainability requirements for the use of solid and gaseous biomass sources in electricity, heating and cooling. COM(2010) 11 final SEC(2010) 66.; 2010. 54p + annexes.
[33] Sjølie HK, Solberg B. Greenhouse gas emission impacts of use of Norwegian wood pellets: a sensitivity analysis. Environ Sci Policy 2011;14:1028–40.
[34] Fortum company in Finland <http://www.fortum.com/countries/fi/yksityisasiakkaat/energiansaasto/aurinkopaneeli/pages/default.aspx>. (accessed 30.07.2013).
[35] Statistics Finland. Building stock 2012. <http://www.stat.fi/til/rakke/2012/rakke_2012_2013-05-24_kat_002_en.html> (accessed 30.07.2013).
[36] RIL 249-2009. Matalaenergiarakentaminen, asuinrakennukset. Suomen Rakennusinsinööri liitto RIL ry [in Finnish].
[37] Kalamees T, Jylhä K, Tietäväinen H, Jokisalo J, Ilomets S, Hyvönen R, et al. Development of weighting factors for climate variables for selecting the energy reference year according to the EN ISO 15927-4 standard. Energy Build 2012;47:53–60.
[38] Laitinen A, Shemeikka J. RET-pientalonmäärittely.VTT Building and Transport. Espoo; 2005 [in Finnish].
[39] Solar Energy Laboratory. Univ. of Wisconsin-Madison. TRNSYS 17 – a TRaNsientSYstem. Simulation program; 2010.
[40] Statistics Finland. Energy consumption in households. <http://tilastokeskus.fi/til/asen/2011/asen_2011_2012-11-16_tau_002_en.html> (accessed 30.07.2013).
[41] Motiva, Specialist in Energy and Material efficiency. <http://motiva.fi/rakentaminen/lammitysjarjestelman_valinta>. (accessed 30.07.2013).
[42] Palmer D et al. Biomass heating: a guide to small log and wood pellet systems. The department of energy and climate change and forestry commission Scotland for the regional biomass advice network (RBAN); 2011. <http://www.biomassenergycentre.org.uk/pls/portal/docs/PAGE/BEC_TECHNICAL/BEST%20PRACTICE/36491_FOR_BIOMASS_1.PDF> (accessed 30.07.2013).
[43] Thiers S, Aoun B, Peuportier B. Experimental characterization, modeling and simulation of a wood pellet micro-combined heat and power unit used as a heat source for a residential building. Energy Build 2010;42:896–903.
[44] Wood SR, Rowley PN. A techno-economic analysis of small-scale, biomass-fuelled combined heat and power for community housing. Biomass Bioenergy 2011;35:3849–58.
[45] Kautz M, Hansen U. The externally-fired gas-turbine (EFGT-Cycle) for decentralized use of biomass. Appl Energy 2007;84:795–805.
[46] Volter Company. <http://www.volter.fi>. (accessed 30.07.2013).
[47] Qiu G, Shao Y, Li J, Liu H, Riffat S. Experimental investigation of a biomass-fired ORC-based micro-CHP for domestic applications. Fuel 2012;96:374–82.
[48] Toonssen R, Woudstra N, Verkooijen A. Decentralized generation of electricity from biomass with proton exchange membrane fuel cell. J Power Sources 2009;194:456–66.

[49] Balat H, Kırtay E. "Review" Hydrogen from biomass – present scenario and future prospects. Int J Hydrogen Energy 2010;35:7416–26.
[50] Toonssen R, Woudstra N, Verkooijen A. Decentralized generation of electricity with solid oxide fuel cells from centrally converted biomass. Int J Hydrogen Energy 2010;35:7594–607.
[51] Page S, Krumdieck S. System-level energy efficiency is the greatest barrier to development of the hydrogen economy. Energy Policy 2009;37:3325–35.
[52] Dorer V, Weber A. Performance assessment of residential cogeneration systems in Switzerland. A report of subtask C of FC+COGEN-SIM, The simulation of building-integrated fuel cell and other cogeneration systems. Annex 42 of the international energy agency energy conservation in buildings and community systems programme first published; January 2008.
[53] Ribberink H, Lombardi K, Yang L, Entchev E. Hybrid renewable – microgeneration energy system for power and thermal generation with reduced emissions. In: 2nd international conference on microgeneration and related technologies. Glasgow; April 2011.