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Author(s)	Jung, Nusrat; Paiho, Satu; Shemeikka, Jari; Lahdelma, Risto; Airaksinen, Miimu
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Energy Performance Analysis of An Office Building in Three Climate Zones

Nusrat Jung[1,2]*, Satu Paiho[2], Jari Shemeikka[2], Risto Lahdelma[1], Miimu Airaksinen[2]

[1]Department of Mechanical Engineering, School of Engineering, Aalto University, Espoo, Finland
[2]VTT Technical Research Centre of Finland, Espoo, Finland
* Corresponding author, e-mail address: Nusrat.jung@aalto.fi;nusrat.jung@vtt.fi

Abstract

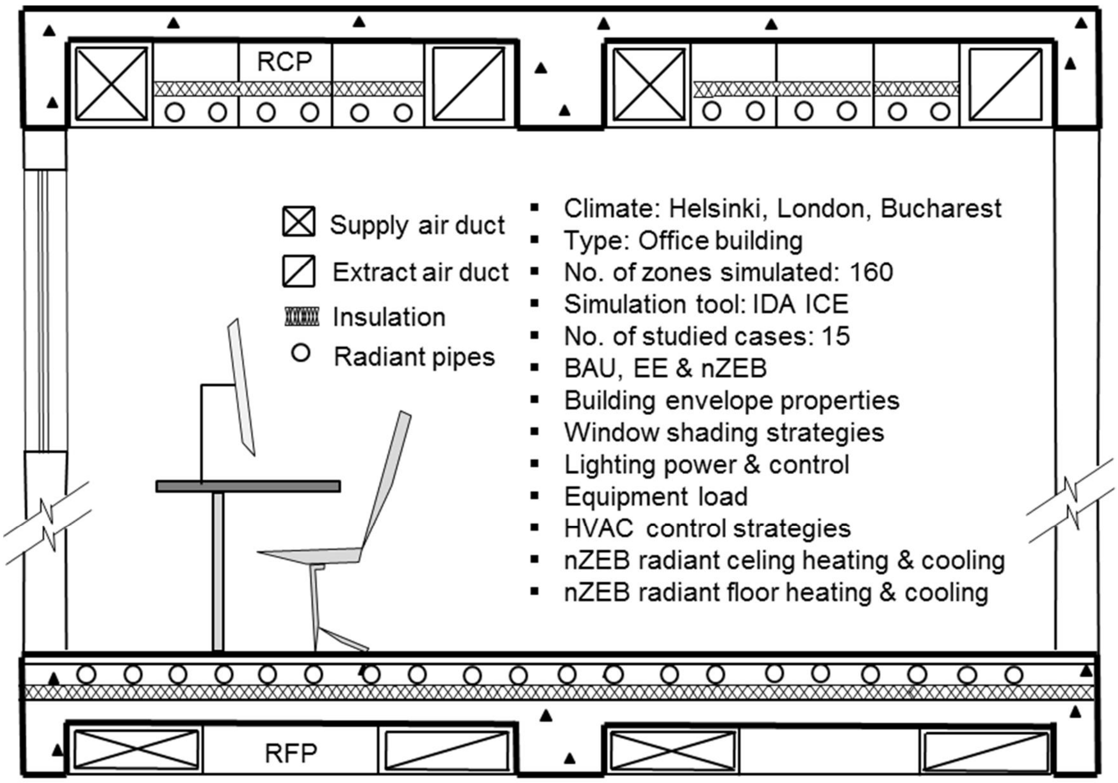
Most of the studies encompassing dynamic simulations of multi-storey buildings account only for a few selected zones, to simplify, decrease simulation run-time and to reduce the complexity of the 'to be simulated' model. This conventional method neglects the opportunity to see the interaction between different zones as it relates to whole building performance. This paper presents fifteen individual cases of dynamic simulations of a six-storey office building with 160 zones. The energy performance analysis was conducted for three climate zones including Helsinki in Finland, London in the United Kingdom and Bucharest in Romania. For each location, the following three cases were simulated: (i) building as usual simulated according to valid national building codes; (ii) Energy-efficient (EE) case with selected necessary parameters enhanced to reduce total delivered energy demand; and (iii) nZEB case representing partial enhancement of the EE case based on the parametric analysis. The results of nZEB indicate that for Helsinki, it is possible to reduce the space-heating load by 86%, electricity consumed by lighting, appliance, and HVAC by 32%. For London, the heating load is reduced by 95%, cooling load is slightly increased, and electricity demand is decreased by 33%. For Bucharest, 92% of energy in heating can be saved, cooling energy demand was reduced by 60% and electricity consumption by 34%. Based on the nZEB cases for each location, alternative heating and cooling choices of a radiant floor panel system and radiant ceiling panel system were explored. There are small differences in absolute consumption demand for heating, cooling, and electricity for three cases in each location. The specific energy/m^2 for heating remained nearly the same in all systems for all three cases in each location. Marginal difference in heating energy required for space heating can be seen for London nZEB IHC and London nZEB RCP of 0.8 kWh/m^2/year and for Bucharest nZEB IHC and Bucharest nZEB RCP case of 1.3 kWh/m^2/year. RFP has the availability of large surface area for heat exchange and can provide heating at a low temperature and cooling at high temperature, but requires supporting air based cooling during the humid season. For RCP, the limited temperature exchange surface may increase the airflow rate, but supplies it at a lower temperature for the same load.

Keywords

Energy performance, Energy efficiency, nZEB, multi zone, office buildings, dynamic simulations, Helsinki, London, Bucharest, radiant ceiling panels, radiant floor panels, IDA ICE

Nomenclature			
nZEB	nearly Zero Energy Building	ASHRAE	American Society for Heating, Refrigerating and Air-Conditioning Engineers
NZEB	Net Zero Energy Building	FMI	Finnish Metrological Institute
BAU	Building as Usual	IDA ICE	IDA Indoor Climate and Energy
EE	Energy Efficient	HVAC	Heating Ventilation and Air Conditioning
DHW	Domestic Hot Water	*U-value*	heat transfer coefficient (W/m^2 K)
VAV	Variable Air Volume	g value	solar energy transmittance of the glass
CAV	Constant Air Volume	n50 1/h^1	Air changes at a differential pressure of 50 Pa
SFP	Specific Fan Power	ppm	Part per million
AHU	Air Handling Unit	COP	Coefficient of Performance
CO_2	Carbon dioxide	Q_{solar}	Transmitted direct and diffused solar radiation
ΔT	Temperature difference	DH	District heating
RFP	Radiant floor panel	RCP	Radiant ceiling panel
SE	Specific energy	DCV	Demand controlled ventilation

Graphical Abstract



1 Introduction

As we proceed towards 2020, the EU directives [1] and country specific guidelines (e.g., [2–4]) are becoming more stringent to reduce energy consumed by buildings. European building policies such as that of Energy Performance of Building Directive (EPBD, Directive 2002/91/EC) and EPBD recast stated the implementation of nearly zero energy from 2018 onwards [5,6]. An nearly zero energy building (nZEB) can be described as a high-performance building [7] that may use the on-site produced renewable energy, or supply energy to energy grids, but zero balance is not required. In the same frame of reference lies the net zero energy building (NZEB), which is defined as a building that produces as much energy as it consumes and has zero kWh/m^2 annual balance of net delivered energy. However, there is no established definition of a zero energy building such as described in [8–12], nor the terms used, such as nZEB and NZEBs [13,14]. In addition to the terminology used, the energy balance and calculation methods also differ for NZEBs [15]. The Federation of European Heating, Ventilation, and Air-Conditioning Associations has suggested an approach for nZEB [16]. Both definitions require very high energy-efficiency, although nZEB approach allows for more flexibility in design and solutions based on economic optimization. Even though much research has been conducted in past years on nZEBs and NZEBs, only a few have been built, [10,13,17] indicating that major barriers to realization still exist. Besides, many of the studies suggested system solutions that are complicated requiring different kinds of skills in implementation and building operation phases [18].

In Europe, office buildings are the second largest category of the non-residential building stock with a floor space corresponding to one-quarter of the total non-residential area. During the last 20 years, the electricity consumed by the non-residential buildings has increased by 74% [19].The annual energy consumption in the non-residential sector in the EU is 280 kWh/m^2 covering all end-uses, which is at least 40% greater than the equivalent value for the residential sector.

In Finland, there were approximately 10,900 office buildings with the total gross floor area of 19.3 million m^2 at the end of 2013. About 43% of the Finnish office buildings are connected to district heating (DH), 24% are heated with oil, and 25% by electrical heating [20]. In the UK, there are 350,000 offices [21–23]. According to Enerdata's data, the total floor area of office spaces in the UK was approximately 135.7 million m^2 in 2008, representing 18% of the total non-residential building stock [24]. Gas provides the majority of space heating and hot water [25]. In Romania, 19,100 office buildings form 13% of the non-residential building stock with total floor area of 7.8 million m^2. A large number of Romanian buildings are connected to the DH network that is in need of major repairs [2]. Large scale commercial buildings such as offices, have greater fluctuations in internal gains due to multiple spaces requiring heating and cooling [26]. This study follows the hierarchical approach proposed by EPBD [1] which priorities the energy efficiency measures first to ensure the use of efficient techniques to reduce the total delivered energy demand in three climate zones.

The dataset on typical energy consumption of office building stock is far less covered as compared to residential buildings [19]. Main reason being that the office buildings are often categorized as a subset of non-residential building stock, commercial building stock, service sector or tertiary sector making it difficult to track [27]. nZEB energy requirements as defined by the EU Member States for non-residential buildings for Finland and UK are under development for new or existing buildings [4]. For Romania, it is set as maximum primary energy of 50-192 kWh/m^2/y for *new non-residential* buildings and is not yet defined for the *existing non-residential* buildings [28]. Based on the data provided by Building Performance Institute Europe, the specific energy use in Finnish offices is approximately 260 kWh/m^2 and in the UK offices it is about 320 kWh/m^2 [19]. In the UK, the mean electrical energy use is 115 kWh/m^2, and the mean fossil-thermal energy consumption is 137 kWh/m^2 in general for office buildings [23]. The average energy use of all Romanian buildings is 275 kWh/m^2 [29], which is quite high when compared to all Finnish buildings with average energy consumption of 125 kWh/m^2. Based on the reference cases of simulation studies by Ahmed et al. and Mohamed et al. [30,31], for the year 2012, the specific heating energy required by Finnish offices is ~22-60 kWh/m^2/year, and cooling energy is ~8-17 kWh/m^2/year. For London, specific heating energy is ~15-17 kWh/m^2/year, and cooling energy is ~9-10 kWh/m^2/year with weather data for year 2010 based on Boyano et al. [32]. For Bucharest, specific heating energy is between ~56-117 kWh/m^2/year, and cooling energy is ~ 22-37 kWh/m^2/year based on [2,33]. The extrapolated data from the mentioned studies is available in Table S1. However, the specific heating and cooling energy demand are only examples, and may vary greatly among themselves due to differences in calculation methodologies, accounted energy flows, variation in case building properties, country legislation, building code, primary energy factor, construction year, indoor thermal condition, etc. Within the same country these values may vary depending on the year of construction, applied weather data, building type, occupancy level, installed heating and cooling systems, etc.

Another persistent discussion is the accuracy of the simulation studies based on the number of zones simulated. Most of the conventional simulation based studies encompassing energy performance analysis of multi-storey buildings account for few selected zones. This approach is often adopted to simplify, decrease simulation run-time and to reduce the complexity of the 'to be simulated' model. Studying a few selected zones of a building has its limitations, especially in the Nordic climate zone because of uneven temperature distribution related to air heating in residential buildings with an uneven usage of space [34]. This conventional method neglects the opportunity to see the interaction between different zones to the whole building performance. As demonstrated by Simson et al. (2017) average error increases with the decrease in modeling detail [35]. Besides, the simplified methods are not able to distinguish the differences in power needs accurately. This is an apparent gap since progressively more and more intermittent renewable energies are being supplied to the energy networks, requiring quick and more accurate response from the demand side. Therefore, creating the need for more accurate simulations on the demand side.

Despite the complications of dealing with larger data sets and arduous processes, a full scale building simulation model with 160 zones was created to more accurately assess multiple performance level parameters of a real building in three different climate zones. This study aims to obtain robust and diversified solutions for large office buildings that can be: (a) applied to reduce the amount of delivered energy or net energy supplied to the office building (b) that can be conveniently set and perform in three different climate zones. In addition to that, it will provide new data on energy demand profile of office building in three climate zones making it comparable to each other. The climate zones studied in this study include Helsinki, representing northern Europe as heating dominated climate; London, representing moderate climate; and Bucharest, representing southeastern Europe with a balanced demand for heating and cooling annually. This will aid extrapolation of variables (to some extent) and suitability of certain techniques to demonstrate how a building performed in one climate zone in comparison with other climate zone [36].

2 Methodology

2.1 Organisation of this study

This study is organized in sections, where Section 2.2 presents a step-wise methodology that was followed to conduct the dynamic simulations. Section 3 describes the building model, building envelope properties and operational parameters applied to all three climate zones. Section 4 presents the results and further discusses the parameters on the reduction of delivered energy demand by application of the selected cumulative strategies. Section 4.2 presents the comparison between two alternative heating and cooling systems of radiant floor panel system (RFP) and radiant ceiling panel (RCP) system. Section 4.3 presents the optimum building parameters to consider based on the results of this study to achieve nZEB office buildings. Section 4.4 describes the limitations of this study followed by conclusions in Section 5.

2.2 Simulation cases

Annual dynamic simulations (8760 hours) were conducted in three different energy performance cases to determine the near optimal solution for each climate zone. The near optimal solutions are implemented by changing the value of one parameter at a time until sufficient reduction in delivered energy is achieved, or the effect of parameter change becomes insignificant. The energy performance cases include for each location, three cases of: (i) building as usual simulated according to valid national building codes; (ii) Energy-efficient (EE) case with selected necessary parameters enhanced to reduce total delivered energy demand; and (iii) nZEB case representing partial enhancement of the EE case based on the parametric analysis were simulated. In the nZEB case, the input variables were optimized and guided by expert knowledge and experience. The variables presented in the study were tested by conducting several rounds of simulations to obtain an optimum building envelope with improved system properties that are viable in practice. The simulation plan carried out in the following two phases is presented in **Figure 1** and

.

Phase I - The simulation model was created using the industry foundation classes file format from an architect's building information model. It is based on the realistic measurements of the building, system types, and its various components.The building model was created in IDA ICE software and three climate zones were applied. The heating dominated climate zone of Northern Europe is represented by Helsinki-Finland, London-United Kingdom represents the moderate climate, and southeastern Europe is represented by Bucharest-Romania. Associated building envelope and ventilation properties were determined based on the climate zone and its corresponding building code regulations. Section 3.1 comprehensively describes the used input variables for the simulations. Parametric analysis was conducted only for the northern climate zone. A different set of input variables for the set of combination parameters was carried out specifically for the type of solar shading, type of window glazing, the thermal mass of building slabs (thickness), temperature set point during night-time was varied, and ventilation system and control type (variable air volume sizing for each of 160 zones). The most efficient design parameters obtained from the parametric analysis were applied in EE and nZEB cases to achieve the maximum benefits in reducing delivered energy demand. The results of parametric study were presented in [38] and are not discussed in this study.

Phase II **-**For the nZEB case, the heating was simulated with the radiator, which is categorized as ideal heaters in IDA ICE, and cooling was achieved by using room-conditioning units. These units were removed and replaced with (i) a radiant floor panel (RFP) system and (ii) a radiant ceiling panel (RCP) system for all three climate zones. RCP had to be sized manually based on the availability of the ceiling area due to the tapered beam structure. Selection was based on the market availability, applicability and control accuracy; more details are presented in Section 3.1. Benefits and challenges of both systems were studied and are presented in section 4.2. As the final step, Table 7 presents the cumulative results of the simulations as a set of near optimal solutions for heating and cooling systems suggesting the specific system level parameters, definitions, and considerations required or needed to achieve an nZEB office building.

Table 1 Organization of the simulation plan

Climate data files	Helsinki, Finland, FMI 2012	London, United Kingdom, ASHRAE 2013	Romania, Bucharest ASHRAE 2013
Phase I	(1) Helsinki BAU	(2) London BAU	(3) Bucharest BAU
	(4) Helsinki EE	(5) London EE	(6) Bucharest EE
	(7) Helsinki nZEB	(8) London nZEB	(9) Bucharest nZEB
	For nZEB Helsinki, London, Bucharest		
Phase II	(10) Helsinki nZEB radiant floor panel (RFP) system	(11) London nZEB radiant floor panel (RFP) system	(12) Bucharest nZEB radiant floor panel (RFP) system
	(13) Helsinki nZEB radiant ceiling panel (RCP) system	(14) London nZEB radiant ceiling panel (RCP) system	(15) Bucharest nZEB radiant ceiling panel (RCP) system

3 Building model description

The multi-story office-building model used for the dynamic simulation is located near Helsinki, Finland, and it is newly built. The office building, as modeled based on the real building, consists of six floors with a ground floor area of 1600 m^2, a net floor area of 9400 m^2, a total floor area of 9775 m^2, and flat rooftop area of 1400 m^2. The total external wall area is 3400 m^2 with doors covering a total of 42 m^2 and windows covering 22.2% of the vertical walls. The building has the main entrance in the central C-shape area as shown in Figure 2. It has a typical cell office layout where the C shape of the building enables windows on both the inside and external walls, the office cells are running separated by a shape corridor and a central foyer with lift access on each floor. The office building has elevators, individual office rooms, multipurpose rooms, storage rooms, mechanical room, multiple lobbys, technical spaces and other facilities (see Table S2 in supporting information). The ground floor mainly consists of meeting and has of 4.2 m floor-to-floor height. The floor-to-floor height of the second floor, third floor, fourth floor and the fifth floor are 3.6 m each, and the sixth floor is 3.9 m high. The building performance simulation program IDA ICE version 4.2 is dynamic multi-zone simulation software used to conduct the energy simulations for this study. The simulation tool is widely used and has been validated by ASHRAE 140-2004 CEN 13791, CEN 15255, CEN 15256 (2007), Technical Memorandum 33 (TM33), and International Energy Agency SHC Task 34 [39].

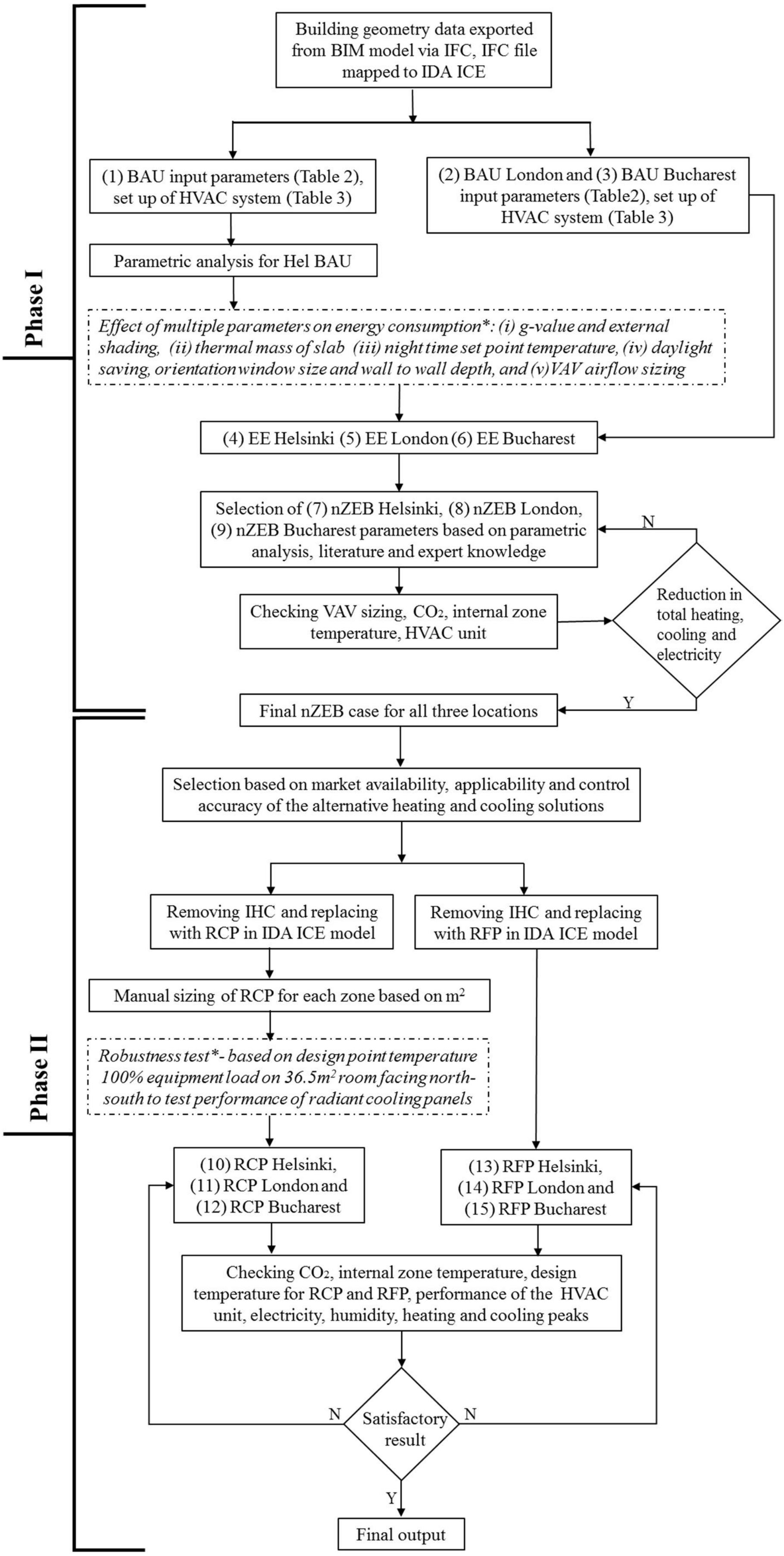

Phase I
Building geometry data exported from BIM model via IFC, IFC file mapped to IDA ICE
(1) BAU input parameters (Table 2), set up of HVAC system (Table 3)
(2) BAU London and (3) BAU Bucharest input parameters (Table2), set up of HVAC system (Table 3)
Parametric analysis for Hel BAU
Effect of multiple parameters on energy consumption*: (i) g-value and external shading, (ii) thermal mass of slab (iii) night time set point temperature, (iv) daylight saving, orientation window size and wall to wall depth, and (v) VAV airflow sizing
(4) EE Helsinki (5) EE London (6) EE Bucharest
Selection of (7) nZEB Helsinki, (8) nZEB London, (9) nZEB Bucharest parameters based on parametric analysis, literature and expert knowledge
N
Checking VAV sizing, CO2, internal zone temperature, HVAC unit
Reduction in total heating, cooling and electricity
Y
Final nZEB case for all three locations
Phase II
Selection based on market availability, applicability and control accuracy of the alternative heating and cooling solutions
Removing IHC and replacing with RCP in IDA ICE model
Removing IHC and replacing with RFP in IDA ICE model
Manual sizing of RCP for each zone based on m2
Robustness test*- based on design point temperature 100% equipment load on 36.5m2 room facing north-south to test performance of radiant cooling panels
(10) RCP Helsinki, (11) RCP London and (12) RCP Bucharest
(13) RFP Helsinki, (14) RFP London and (15) RFP Bucharest
Checking CO2, internal zone temperature, design temperature for RCP and RFP, performance of the HVAC unit, electricity, humidity, heating and cooling peaks
N
Satisfactory result
N
Y
Final output

Figure 1 Flowchart describing the simulation plan (**data not presented in this study*)

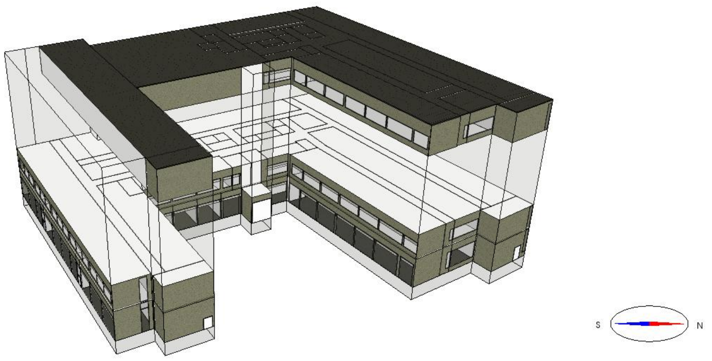


Figure 2 Three dimensions' representation of ground floor, first floor and sixth floor as modeled in IDA-ICE simulation tool

The model used in this study for energy performance analysis is based on realistic measurements, components, and system types of the building. Figure 3 presents the zones in the simulation model showing the typical ground floor plan, first-floor plan at level 4.2m and sixth-floor plan at level 18.6m with thermal zones as described in **Figure 3**. The floor plan of the second, third, fourth and fifth-floor area are duplicates, thus to simplify the model, the IDA ICE zone multiplier function was used. The simulation model has 160 zones as presented in Table S2 (in supplementary information) and the model floor area is 9365.1 m^2.

For the nZEB case, approximately 217 optimized rounds of dynamic simulations were carried out for all climate zones. Twelve days of dynamic start-up were used, which means twelve days were simulated before the proper simulation at the beginning of the year based on the corresponding weather file. A dynamic time step of 1.5 hours with the tolerance of 0.02 was used; tolerance defines the degree of accuracy to be reached in the calculated variables. Typically, a simulation run for one location and one case lasted 1-2 hours (housing an Intel® Xeon ® CPU E5-2650v2 with 32 logical processors). For the radiant heating and cooling systems, simulations lasted from 2.5-6 hours. During the parametric analysis, the time was extended to 3-15 hours at each attempt due to the increased number of cases.

Figure 3 Typical ground floor plan, first-floor plan at level 4.2m, and sixth-floor plan at level 18.6m with thermal zones as described in Table S2, modeled in IDA ICE.

3.1 Building envelope properties and operational parameters for Helsinki, London, and Bucharest

Reference weather data files available from the Finnish Metrological Institute (FMI) for Helsinki 2012 were used for the simulation model. Bucharest and London weather data files were used in IDA ICE based on data from ASHRAE Fundamentals as available in the simulation program. The following describes the parameters that were changed during the simulations:

Helsinki parameters: originate from the Finnish Building Code D2-Indoor Climate and Ventilation of Buildings [40]; Building Code D3 - Energy Management in Buildings [41]. Some values for the EE case were used from Building Code D5 - Calculation of Power and Energy Needs for Heating of Buildings [42]. Zero Energy case values are based on expert knowledge and experiences. For heating demand, DH was used, and 0.94 efficiency ratio was assumed for DH supply system. Domestic hot water consumption was at 103 l/(m^2, year) for all cases. For cooling, chillers were used with 2.5 COP (metered energy to water). The zone supply temperature setpoint was 20°C and AHU supply temperature setpoint was 9°C.

London parameters: were used as given in the National Calculation Methodology modeling guide for buildings other than dwellings in England and Wales [43]. EE case values were formulated upon the Target Zero 70% improvement in Part L emissions for an office building [44]. Commercial development of large-scale decentralized district heating plants is underway in London, [45] considering that, DH was used at an efficiency ratio of 0.94. Electric chillers for cooling energy production were similar to that of the Helsinki case.

Bucharest parameters: values are based on the Romanian norm C107-2005 modified in the year 2010 [46]. In Romania, minimum requirements for office U-values do not exist, but typical values for new construction are 0.60 W/m^2K for walls, 0.25 W/m^2K for roofs, 0.35 W/m^2K for floors and 1.30 W/m^2K for windows [2]. The EE and nZEB case values are based on expert knowledge and practical experiences. Bucharest has some examples of successful DH supply systems; thus, DH was used in the simulation model with 0.94 efficiency ratio, although the typical efficiency is much lower.

Set point for temperatures for standard air handling units: during winter the set point was 21˚C, and during summer it was less than 25˚C based on prEN15251:2015; these set points define the lower and upper limit for all office indoor environments. In this study class II, categorized as the reasonable level of expectation was used where the temperature range for heating during winter should be between 20-24˚C and the temperature range for cooling during summer should be between 23-26°C [47]. The heating was simulated with the radiators (categorized as ideal heaters in IDA ICE), and cooling was achieved by using room conditioning units (categorized as ideal coolers in IDA ICE) with the mechanical supply of air with heat recovery [48]. For the VAV, CO_2 and temperature control used in the nZEB cases, the indoor temperature was reduced to 24˚C due to intermittent control and, 1˚C was gained by heating caused by the operation of the fan in HVAC unit.

Ventilation strategies: the CO_2 concentration in a zone is frequently used as a measure of the ventilation rate per occupant [49,50], being an indicator for the emission of human bio-effluents [51]. The CO_2 concentrations were kept at all times below 900 ppm to meet the criteria for classification level II of 800 ppm and III of 1350 ppm respectively [52]. The mechanical airflow with constant air volume (CAV) and variable air volume (VAV) rate were between 1.5-5 $dm^3/(s\ m^2)$, i.e., depending on the size of the room. Two standard air handling units (AHUs) were modeled. The first AHU was applied to cater individual office rooms and other conference and meeting rooms etc. with running times from 7:00-17:00. For all the nZEB cases, the first AHU was modeled to take advantage of VAV, CO_2 control and temperature control; it was kept off at other occasions when the rooms are not occupied. The second AHU serviced the common areas such as storage rooms, corridors, staircases, water closets, etc. with running times from 7:00-18:00 and 25% at other times. The second air AHU was modeled with CAV for all cases. For BAU, EE and nZEB cases, for AHU 2 mechanical ventilation with CAV were applied in all cases.

Table 2 Building envelope properties and building operational parameters used as input values for simulations

Parameter/Units	**Northern Europe, Helsinki, Finland**			**Central Europe, London, United Kingdom**			**South-Eastern Europe, Bucharest, Romania**		
	BAU	EE	nZEB	BAU	EE	nZEB	BAU	EE	nZEB
External wall U-value, W/m²K	.17	.16	.12	.26	.25	.1	.80	.45	.15
Roof U-value, W/m²K	.09	.09	.09	.18	.18	.1	.40	.30	.1
External floor U-value, W/m²K	.16	.14	0.1	.22	.22	.15	1.50	1	.25
Internal floor U-value, W/m²K	2.3	2	1. 7	1	1	.15	1.50	1	.80
Air tightness, n50 1/h [1]	2	2	.5	10 m³/(hm²)	3 m³/(hm²)	2 m³/(hm²)	5	3	.6
Window glazing U-value, W/m²K	1	.9	.45	1.80	1.60	.5	3	2	.45
Window g value	.35	.35	.24	.40	.40	.2	0.85	.65	.24
Window shading	Blinds between window panes			Blinds between window panes			Blinds between window panes		
Shading strategy	Blinds on, if Q-sol > 150W/m²			Blinds on, if Q-sol > 150W/m²			Blinds on, if Q-sol > 150W/m²		
Ext. Door U-value, W/m²K	1	1	.7	2.20	2.20	.7	4	2.50	1
Approx. Lighting control	No lighting control		Presence & daylight control	No lighting control		Presence & daylight control	No lighting control		Presence & daylight control
Lighting power	9 W/m²			7.5W/m²			9 W/m²		
Equipment load	100% 12W/m²		30% reduced 8.4 W/ m²	100% 12W/m²		30% reduced 8.4 W/ m²	100% 12W/m²		30% reduced 8.4 W/ m²

[1] Virtual pressure test

The operational time for the fans in the first AHU were based on the presence of occupants as defined by the schedule. The schedule in BAU case was based on Finnish building code D3; for the EE case, the schedule was set at 25% [7-8, 17-18], 75% [8-9, 16-17], 100% [9-16] during the week except for Saturday and Sunday. For the nZEB case, it was set at 25% [7-8, 17-18], 75% [8-9, 11-13, 15-16], 100% [9-11, 13-15], and 50% [16-17], considering that office workers arrive and leave the work place gradually during morning hours and evening hours. A similar approach was taken by varying the schedule during lunchtime. The HVAC system parameters are presented in Table 3.

Lighting and appliances: lighting levels at work desks were considered 500 lux 9W/m² in office rooms based on EN1246-1:2011 and ISO 8995-1, and vary between 0-15 W/m² based on the size and usage of the room as presented in Table S2 [53,54]. The appliances for nZEB simulation cases in all three climate zones were 30% more efficient as compared to cases BAU and EE. For lighting, three parameters were varied, including rated input per unit, luminous efficacy, and the convective fraction. The T-5 regular fluorescent tube was used, which has a higher luminous efficacy than T8 or T12 lamps, which are commonly used in office buildings. In this study, 50 lm/W was used as the input value for luminous efficacy, which is the value at the desk, due to typical optical properties of luminaires. Corridor lighting was modified which was kept at 100% during office hours and 50% during non-office hours: 100% [7:30-18], 20% otherwise. Occupancy was set at 15 m²/occupant. The lights for storage rooms and technical rooms were always kept off on the schedule. For the zero energy cases, intelligent lighting with presence and daylight controls was considered 95% during office hours to 5% during non-office hours. The equipment load was reduced to 70% for all nZEB cases; this load reduction can be realistically achieved by using power management system.

Table 3 HVAC system parameters

Location	**Case**	**Unit**	**Type**	**Pressure head supply/exhaust** [Pa/Pa]	**Fan efficiency Supply/Exhaust**	**System SFP** [kW/(m³/s)]	**Heat exchanger temp. Ratio/min exhaust temp.**
Helsinki	BAU	AHU 1	CAV	780/770	0.78/0.77	1/1	0.5/0
		AHU2	CAV	780/770	0.78/0.77	1/1	0.5/5
	EE	AHU 1	CAV	780/770	0.78/0.77	1/1	0.79/-5
		AHU2	CAV	780/770	0.78/0.77	1/1	0.59/0
	nZEB	AHU 1	VAV+CO_2+ temp	1200/1200	0.6/0.6	2/2	0.85/-10
		AHU2	CAV	450/450	0.6/0.6	0.75/0.75	0.75/0
London	BAU	AHU 1	CAV	780/770	0.78/0.77	1/1	None
		AHU2	CAV	780/770	0.78/0.77	1/1	0/5
	EE	AHU 1	CAV	780/770	0.78/0.77	1/1	0.79/-5
		AHU2	CAV	780/770	0.78/0.77	1/1	0.59/0
	nZEB	AHU 1	VAV+CO_2+ temp	1200/1200	0.6/0.6	2/2	0.85/-10
		AHU2	CAV	450/450	0.6/0.6	0.75/0.75	0.75/0
Bucharest	BAU	AHU 1	CAV	780/770	0.78/0.77	1/1	None
		AHU2	CAV	780/770	0.78/0.77	1/1	0/5
	EE	AHU 1	CAV	780/770	0.78/0.77	1/1	0.73/5
		AHU2	CAV	780/770	0.78/0.77	1/1	0.59/0
	nZEB	AHU 1	VAV+CO_2+ temp	1200/1200	0.6/0.6	2/2	0.80/-10
		AHU2	CAV	450/450	0.6/0.6	0.75/0.75	0.75/0

Alternative heating, cooling and ventilation concepts for nZEBs: The nZEB cases of all three locations were used as a base to apply alternative heating and cooling solutions. From heating and cooling emission point of view, radiant floor panel (RFP) and radiant ceiling panel (RFP) were also shown as variant systems by [36]. The choice of alternative heating and cooling system were made based on the market availability, applicability and control accuracy. The cost-efficiency, while not evaluated in this study, was considered indirectly by restricting the choice of parameters to available solutions on the market. Other than that, three hypothetical scenarios to enable future coupling of diverse renewable energy technologies with the building for it to become nZEB were also considered.

For the nZEB case, the heating was simulated with the radiator, which is categorized as ideal heaters in IDA ICE, and cooling was achieved by using room conditioning units. These units were removed and replaced with RFP and RCP systems. The design power for RFP was 40 W/m^2 with ΔT (water) at design power of 5°C with a sensor based on air temperature. In IDA ICE, the temperature differences and the design power is used to calculate supply mass flow. Additionally, , when VAV is used together with alternative cooling systems in IDA ICE, VAV was used first by the control algorithm, and set points of other room units are offset 2°C. The design power for RCP was sized manually for each and every 160 zones depending on the availability of ceiling area of the case building for radiant ceiling panel. The sizing was done to operate the RCP system effectively as presented in section 4.2. The design conditions ΔT (water-zone air) at design power were between 6.5-16.5°C, and ΔT (water) at design power were set at 3-5 °C. The modelling approach in the steady state used in IDA ICE is based upon the resistance method described in the standard EN 15377-1 [48].

4 Results and discussion

4.1 BAU, EE, and nZEB

The overall results demonstrate a significant improvement in building energy performance and reduction in total energy supplied to the building for both EE and nZEB cases as compared to BAU. The delivered energy demand in kWh/m^2/year for heating, cooling and electricity usage for three performance levels in Helsinki, London, and Bucharest climate zones is presented in **Figure 4** and Table 4. These results account for the combination of the parameters, which were improved incrementally through the BAU, EE case and nZEB case, as described as input variables in Table 2.

For Helsinki, it is possible to reduce the space heating load by 86% and electricity consumed by lighting, appliance, and HVAC by 32% when compared to the BAU case. There was not much reduction in the cooling load since the demand for seasonal cooling is rather small. Similarly, for London, the heating load is reduced by 95%, cooling load is slightly increased, and electricity demand is decreased by 33% in the nZEB case. For Bucharest, most energy savings can be seen in heating by 92%, cooling energy demand reduced by 60% and electricity consumption by 34% as compared to the BAU. The BAU values for Bucharest were rather poor and were chosen based on existing office buildings. They may not represent the new construction scenario. Section 4.1.1 further elaborates on the effect of changing building envelope, windows and lighting strategies on the energy consumption, and Section 4.1.2 describes the effects of parameters chosen on reducing the delivered energy demand for HVAC control strategies in the building.

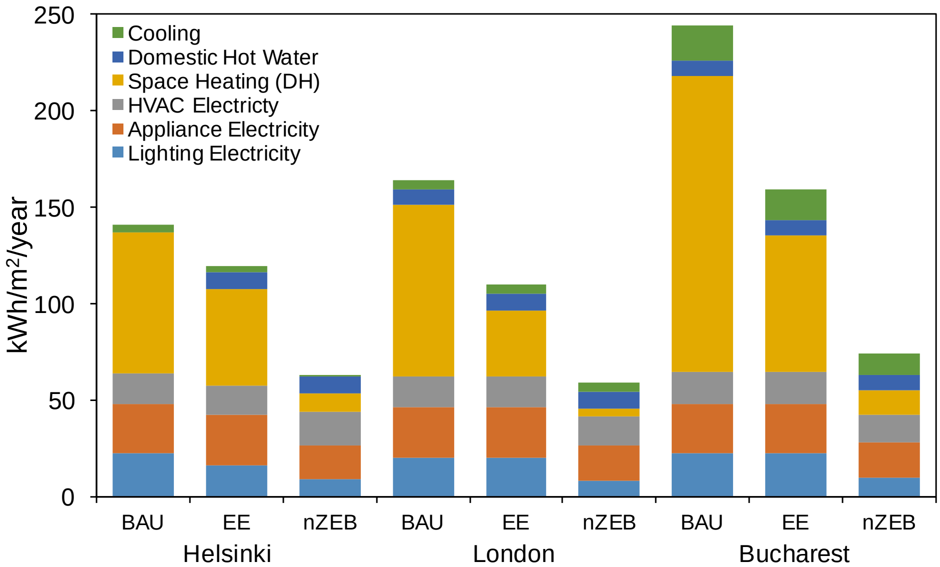
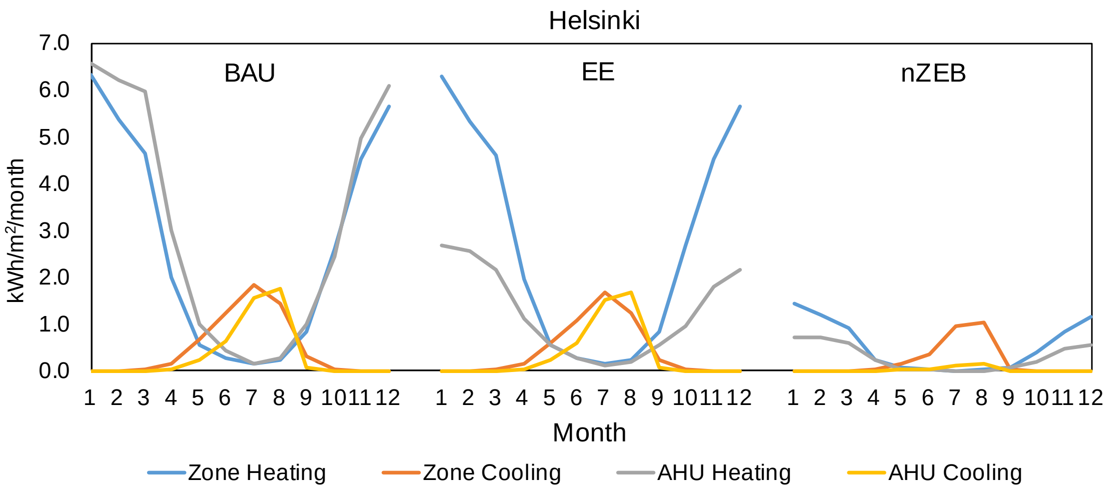


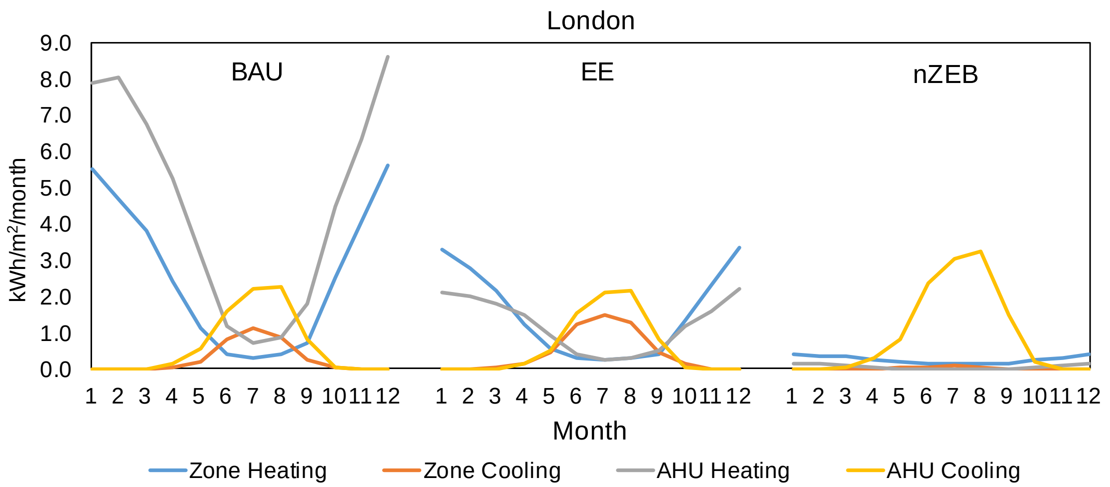
Figure 4 Specific energy demand for BAU, EE, and nZEB in three climate zones

Month-by-month variations in heating and cooling demand for BAU, EE, and nZEB cases for all three climate zones are presented in **Figure 5**. The y-axis is scaled differently for each city to improve visualization of the results. The annual pattern in heating and cooling demand remains similar across all three cases for each city, however, the magnitude is systematically reduced between BAU and nZEB cases due to energy performance improvements in HVAC and building envelope parameters. For all climate zones, monthly zone heating and cooling and AHU heating energy demand are reduced between BAU and nZEB. However, the reduction in AHU cooling between BAU and nZEB is less noticeable, and for London, actually increases from 7.61 to 11.62 kWh/m^2/year. This is because the temperature setpoint for the nZEB VAV, CO_2 and temperature control is reduced from 25 to 24°C. Thus, additional energy input into the cooling coils of the AHU is required to maintain the lower temperature.

Table 4 Delivered energy (kWh/m^2/year) comparisons for BAU, EE case and nZEB case of all three climate zones

	Hel BAU	**Hel EE**	**Hel nZEB**	**Lon BAU**	**Lon EE**	**Lon nZEB**	**Buc BAU**	**Buc EE**	**Buc nZEB**
Lighting electricity	22.7	16.6	8.9	20.5	20.5	8.3	22.7	22.7	9.8
Appliances electricity	25.7	25.7	18	25.7	25.7	18	25.7	25.7	18
HVAC electricity	15.8	15.6	16.8	16.3	16.2	15.5	16.4	16.2	14.7
Total electricity	64.2	57.9	43.7	62.5	62.4	41.8	64.8	64.6	42.5
Space heating (DH)	73.2	50.1	10.2	88.7	34.4	4.1	153	70.7	12.5
Hot water (DH)	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3
Total heating	81.5	58.4	18.5	97	42.7	12.4	161.3	79	20.8
Total Cooling	3.9	3.6	1.1	4.4	5	4.8	18.2	16	11
Total	149.6	119.9	63.3	163.9	110.1	59	244.3	159.6	74.3





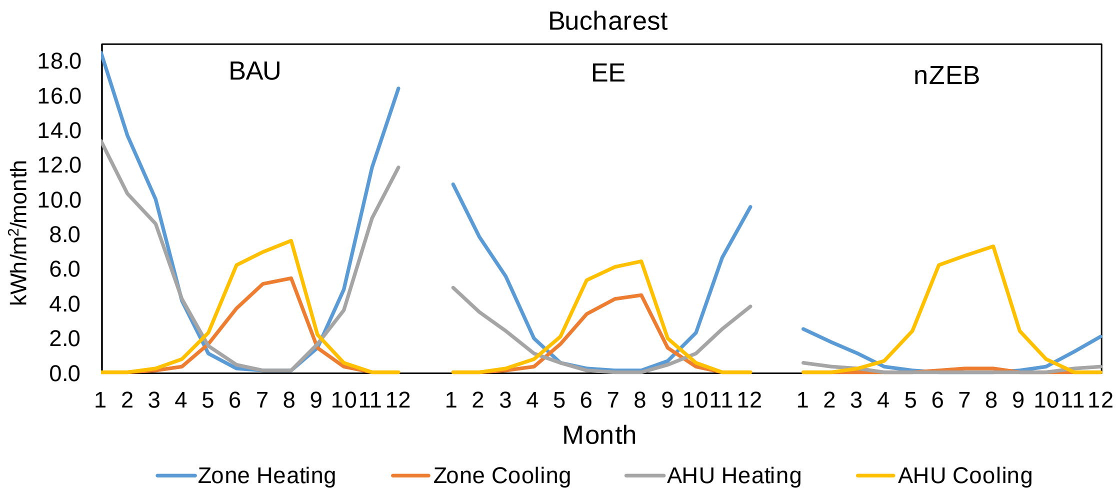


Figure 5 Monthly zone and AHU heating and cooling demand for BAU, EE, and nZEB in three climate zones. Note: the y-axis upper-limit is different for each location.

4.1.1 Building envelope and lighting

The building envelope and its structural properties have a significant role in building energy performance. The properties of the external and internal walls, roof, intermediate floors, outside windows, and doors and their frames were enhanced for all three climate zones across all cases. The volume of the model was 34801.4 m^3. Average U-value for the model varied for all cases. For example, for Helsinki BAU to Helsinki nZEB, the average U-value varied from 0.3523 W/(m^2K) to 0.1931 W/(m^2K). Figure 6 shows the amount of total (net) thermal energy supply and losses during the year. Evidently, the building insulation properties of Helsinki (Table 2) are relatively better in comparison to those of London and Bucharest. This is mainly due to the colder climate requiring better building envelope properties to reduce heat losses. During the parametric analysis, it was found that for a typical commercial multi-story building, the lower roof and floor U-value (W/m^2K) is less important. For example, the roof U-value for the nZEB Helsinki case was preferred to be 0.9 W/m^2K instead of 0.5 W/m^2K because the influence on heating energy was marginal as compared to the investment cost.

Among other parameters, reducing window U-values from 1 W/m^2K from the BAU to 0.45 W/m^2K and g value from 0.35 to 0.24 for the Helsinki nZEB case reduced the solar losses by 96% yearly. For London, the average U-value for BAU case was 0.5722 W/(m^2K) and the nZEB case was 0.1998 W/(m^2K). The window and solar losses for London were reduced by 100% from BAU to the nZEB case. Solar gains of 3.71 kWh/m^2/year were observed in London nZEB. As can be seen from Figure 6, mechanical supply air forms a large need for thermal energy losses in all cases in all locations, but in comparison to BAU cases it was reduced by 35% in Helsinki nZEB case, 15% in London nZEB and 24% in Bucharest nZEB. For Bucharest, the average U-value for BAU was 1.085 W/(m^2K), and for nZEB, the average U-value was 0.3411 W/(m^2K). The Bucharest BAU insulations were comparatively weaker than those of Helsinki and London, leading to greater reduction in thermal losses of 17 kWh/m^2 by varying the wall U-value from 0.80 W/m^2K to 0.30 W/m^2K. Solar gains of 4.13 kWh/m^2/year were observed in Bucharest EE case and & 6.25 kWh/m^2/year were observed in Bucharest nZEB case.

Minimizing solar gain is vital and can be better controlled by influencing the g value depending on the energy demand. As an example, the window and solar gains and losses are shown for each month of the year in Figure 7 for BAU, EE, and nZEB cases, along with the corresponding annual net gain or loss.

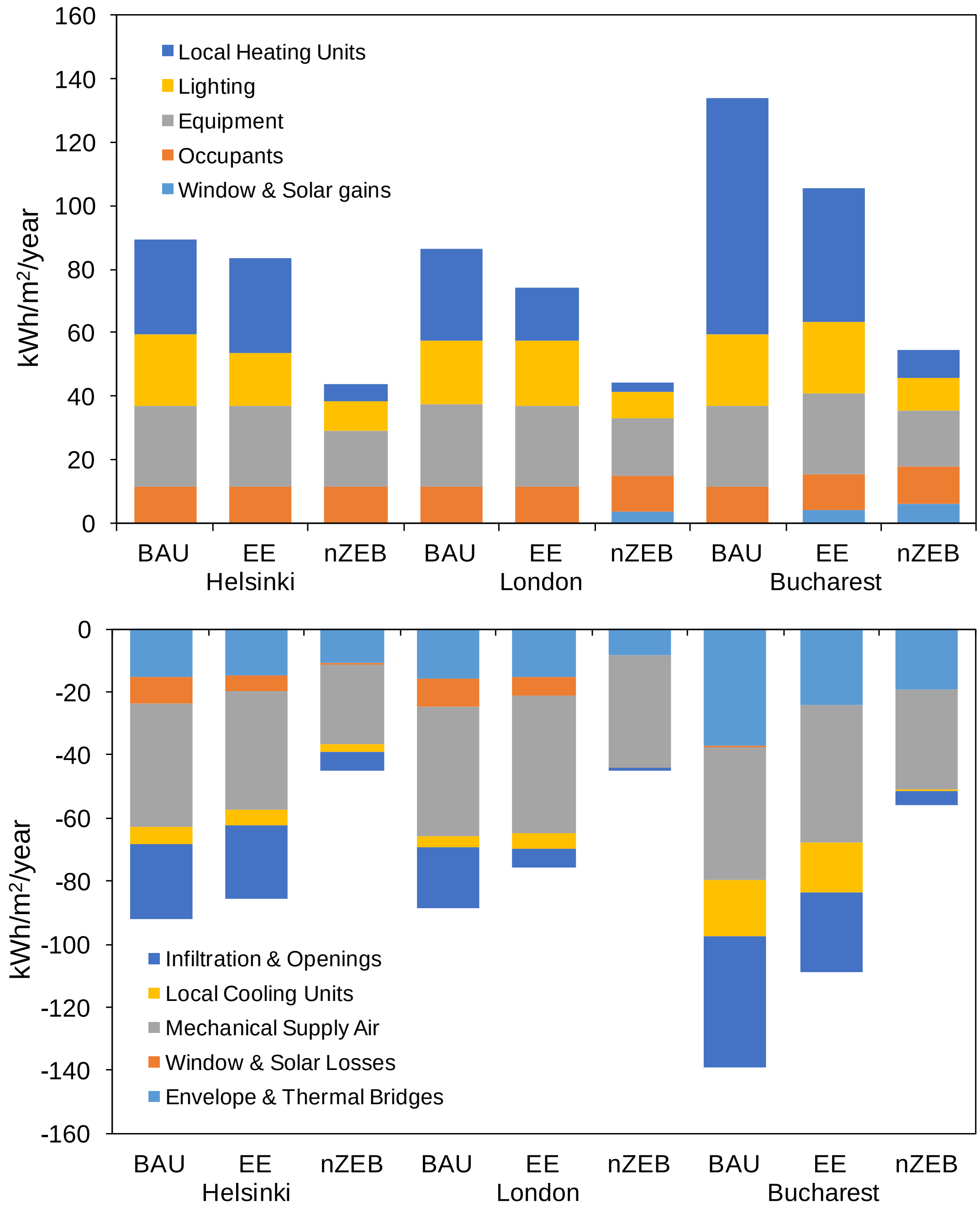


Figure 6 Total thermal energy supply and losses for each case.

Also, window daylight transparency for nZEB cases was adjusted to be less than 0.45 to enable daylight savings working in tandem with the electrical lighting systems. This lighting control strategy reduced electricity use by using artificial light and provided indirect benefit by reducing internal heat gains by 30% in nZEB cases and the respective cooling load. Presence lighting control was also applied by altering the use of artificial light in various spaces depending on the presence of occupants in the areas in all nZEB cases. This parameter reduced the heating gains as a result of lighting by 60% from BAU to nZEB cases for Helsinki and London; for Bucharest nZEB case, these gains were reduced by 57%.

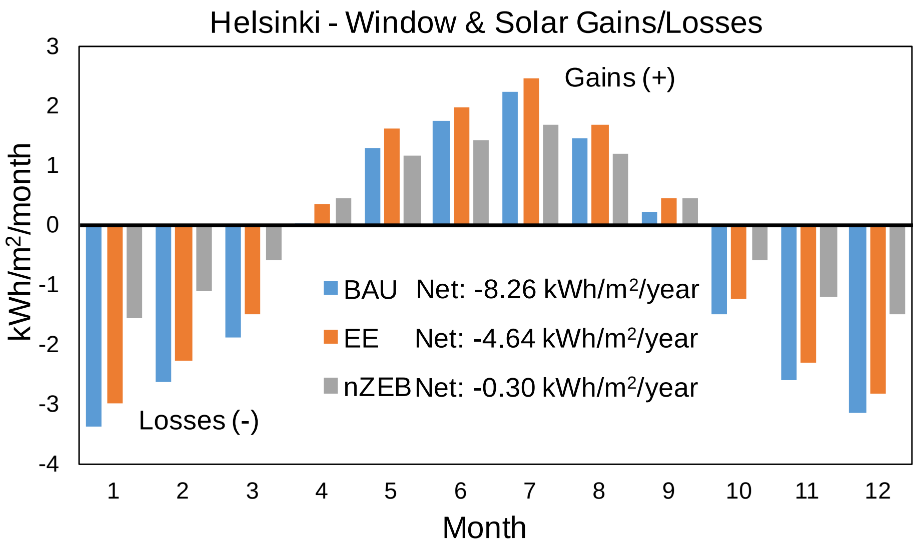


Figure 7 Monthly variation in window and solar energy gains and losses for Helsinki BAU, EE, and nZEB cases.

4.1.2 HVAC and infiltration

Mechanical ventilation and infiltration of the outdoor air have significant impacts on the annual energy demand of a building. Along with the tightened building envelope, heat recovery methods along with VAV, CO_2 and temperature control in the spaces were incorporated in all nZEB cases. For all three climate zones, BAU and EE case included a CAV ventilation system with heat recovery. Across all climate zones, improved heat recovery was applied to support the transfer of heat from the effluent airstream to the influent air stream, therefore, retaining part of the thermal energy. The effectiveness of the heat exchanger in the heat recovery system for Helsinki increased from 0.5 to 0.79 for AHU 1 between BAU and EE cases, resulting in increased heat recovery from 49.41 to 70.56 kWh/m^2/year. Due to the enhanced heat recovery, the amount of energy needed to heat the supply air (AHU heating) decreased from 27.05 to 5.81 kWh kWh/m^2/year in AHU 1. A similar trend was observed in the London and Bucharest cases. The VAV, CO_2 and temperature control in IDA ICE can both heat and cool with the supply air and can force air depending upon the maximum limit set. Therefore, the airflow rate varied based on occupancy aiding in minimizing the additional ventilation at the same time while maintaining the zone temperature. Table 5 presents the load distribution with zone heating/cooling, which is delivered from the ideal heaters and coolers (IHC), AHU heating is the heat supplied to all heating coils of the AHU, and AHU cooling is the energy removed by all cooling coils of the AHU. DHW remained constant and represented the energy delivered to the hot water circuit. The cumulative results in Table 5 demonstrate that by using the combination strategies, it is possible to reduce the AHU heating and zone heating demand significantly.

As shown in Table 3, the input variables for demonstrating lower supply and exhaust fan efficiency (0.6) in all nZEB cases is due to the VAV which is increasing or decreasing the pressure drop in the air according to the requirement in the zones, resulting in lower operating efficiency value for the fan. For example, in each city, the supply/exhaust pressure head increased from 780/770 Pa for BAU and EE to 1200/1200 Pa for nZEB as CAV was replaced by VAV. However, the power loss of mechanical supply air additionally is dependent on the reduced airflow due to the adjustment of the operation of the fan for the VAV system.

Table 5 Load distribution between zone heating/cooling and AHU heating/cooling in kWh/m^2/year

Case	Zone Heating	AHU Heating	Zone Cooling	AHU Cooling	Domestic Hot Water
Helsinki BAU	33.09	37.96	5.63	4.21	7.76
Helsinki EE	32.94	15.10	4.96	4.10	7.76
Helsinki nZEB	6.26	3.57	2.50	0.30	7.76
London BAU	31.69	55.00	3.40	7.61	7.76
London EE	18.37	14.86	5.30	7.31	7.76
London nZEB	3.16	0.75	0.29	11.62	7.76
Bucharest BAU	82.57	65.18	18.57	27.00	7.76
Bucharest EE	46.80	20.90	16.26	23.74	7.76
Bucharest nZEB	9.93	1.95	0.64	26.93	7.76

4.2 Radiant floor panel and Radiant ceiling panel systems

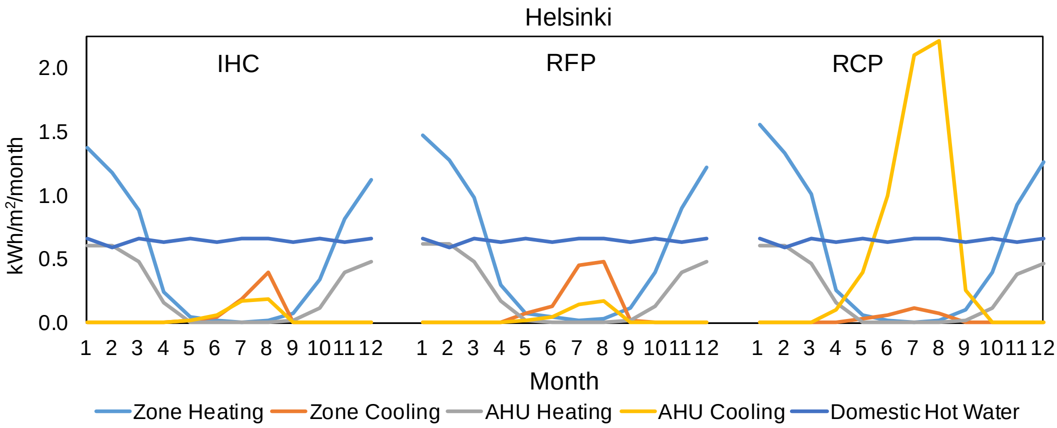
The nZEB cases of all three locations were used as a base to apply alternative heating and cooling solutions. For the nZEB case, the heating was simulated with the radiator, which is categorized as ideal heaters in IDA ICE, and cooling was achieved by using room-conditioning units. These units were removed and replaced with radiant floor panel (RFP) and radiant ceiling panel (RCP) systems. Figure 8 presents the results of the comparative analysis as delivered energy (kWh/m^2/year) of the radiant floor panel (RFP) and radiant ceiling panel (RCP) systems for Helsinki, London, and Bucharest. As evident from the results, there are small differences in absolute consumption demand for heating, cooling, and electricity for three cases in each location. The specific energy/m^2 for heating remained nearly the same in all systems for all three cases in each location. Marginal difference in heating energy required for space heating can be seen for London nZEB IHC and London nZEB RCP of 0.8 kWh/m^2/year and for Bucharest nZEB IHC and Bucharest nZEB RCP case of 1.3 kWh/m^2/year.

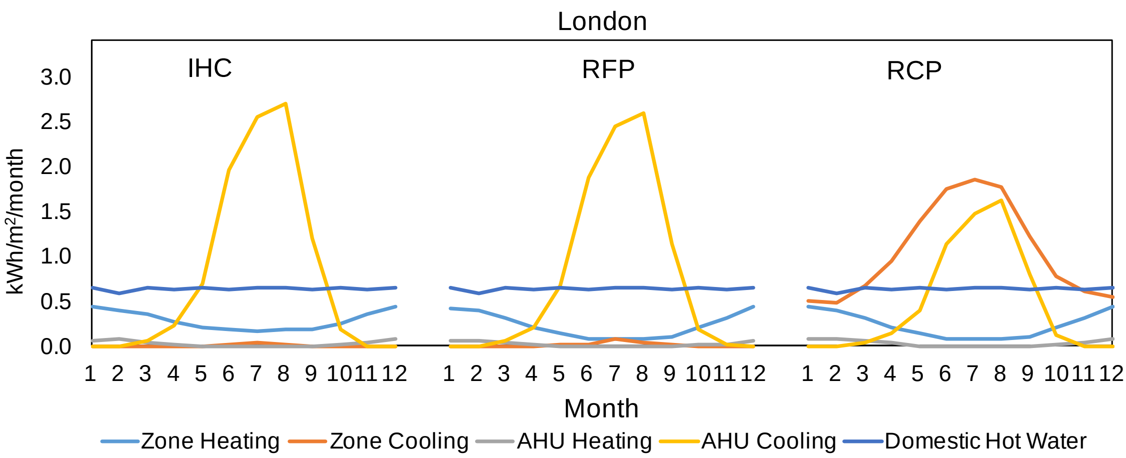
Table 6 Delivered energy (kWh/m^2/year) comparisons for nZEB case with ideal heater and coolers (IHC), radiant floor panels (RFP) and radiant ceiling panels (RCP) of all three climate zones

	Hel nZEB (kWh/m^2/year)			Lon nZEB (kWh/m^2/year)			Buc nZEB (kWh/m^2/year)		
	IHC	RFP	RCP	IHC	RFP	RCP	IHC	RFP	RCP
Lighting electricity	8.9	8.9	8.9	8.3	8.3	8.3	9.8	9.8	9.8
Appliances electricity	18	18	18	18	18	18	18	18	18
HVAC electricity	14.3	14.4	10.9	15.4	9.4	10.7	14.7	10.4	12.3
Total electricity	41.2	41.3	37.8	41.7	35.7	37	42.5	38.2	40.1
Space heating (DH)	9.4	9.7	9.7	4.0	3.1	3.2	12.8	11.8	11.5
Hot water (DH)	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3
Total heating	17.6	18	18	12.3	11.3	11.5	21.1	20.1	19.7
Total Cooling	0.4	0.6	2.5	3.9	3.7	7.3	11.2	8.8	8.9
Total	59.2	59.9	58.3	57.9	50.7	55.8	74.8	67.1	68.7

Figure 8 shows the annual distribution of zone heating, zone cooling, AHU heating and AHU cooling. The heating and cooling in building zones was supplied via IHC, RCP and RFP. For the IHC, the cooling energy is limited to the air flow rate supplied by the duct. For radiant floor panel systems, the design points for heating at 35/30°C and cooling at 17/20°C were found to be favorable; additionally, the air system requires 3l/sqm^2 for dehumidification and control accuracy. RFP has the availability of large surface area for heat exchange offering greater flexibility to varying design load. It can handle heating at a low temperature and cooling at high temperature, but requires supporting air based cooling during the humid season. Whenever the cooling load is large due to internal gains, the VAV-ventilation with cooled air will handle the extra cooling demand. However, the challenge in the case building remains that extra 100mm thick concrete slab is required and should be part of the building structure if RCP system was to be implemented.

For radiant ceiling panel, the design points for heating at 40/35°C and cooling at 17/20°C were found to be optimum. The benefit was mainly seen because it can be effortlessly controlled. However, it had limited capacity and was found to be sensitive to the high internal load levels because of restricted heat exchange space which was 50% due to the building slab shape in the case building. During the robustness test (not presented in this paper), it was noted that the increases in equipment load elevate the heat dissipation from the equipment, thereby necessitating greater cooling through the ceiling panel cooling system. As shown in Figure 8, limited temperature exchange surface may increase the air flow rate but supplies it at lower temperature for the same load. However, radiant ceiling panel seems to accommodate different internal loads reasonably. It also requires higher temperature level for heating and supporting VAV based cooling during peaks when compared to the radiant floor panel system.





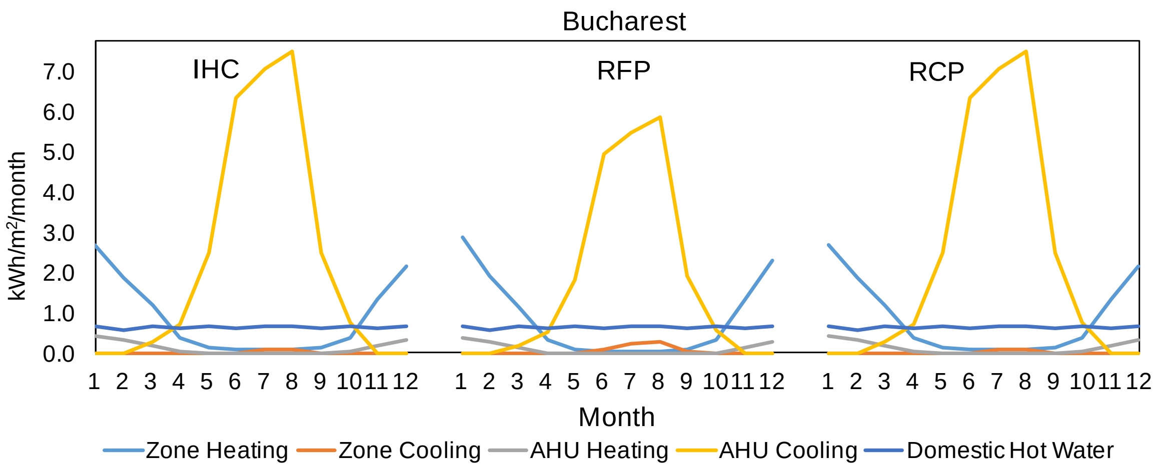


Figure 8 Annual distributions between zone heating/cooling versus AHU heating and cooling for ideal heaters and coolers (IHC), Radiant floor panel (RFP) and Radiant ceiling panel (RCP). Note: the y-axis upper-limit is different for each location.

4.3 Near optimal solutions for nZEB

The energy savings for space heating can be achieved by reducing envelope transmission and infiltration losses, using high-efficiency heat recovery system, utilizing solar gains and by choosing a heating system which can distribute heat efficiently in spaces. To avoid a high cooling load, the solar gains during summer can be reduced by integrating blind within windows, using ventilation cooling during night time. Delivered electricity can be reduced by using high-efficiency electric appliances, intelligent lighting with presence and daylight controls, reducing fan and pump energy in HVAC unit. Table 7 presents the typical parameters, which can be deduced from this study. These parameters (i) can be applied to reduce the amount of delivered energy or net energy supplied the office building and (ii) can be conveniently set and perform in three different climate zones, which are heating dominated (similar to Helsinki), moderate climate zones (similar to that of London), and climate zones, which have balanced demand of heating and cooling annually (similar to that of Bucharest).

Table 7 Typical parameters to achieve an nZEB office building in three types of climate zones

Parameter or measures required to achieve nZEB	Discussion for heating-dominated, moderate and cooling dominated climate zones
Building envelope U value, W/(m^{2}K)	Average U value for Helsinki is 0.1931 W/(m^{2}K); for London is 0.1998 W/(m^{2}K) and for Bucharest is 0.3411 W/(m^{2}K)
Window glazing U-value and g value	Please refer to Table 2 Building envelope properties and building operational parameters used as input values for simulations
Lighting control and power	
Ventilation min. air flow	Based on national regulations, for example, 0.15 l/s,m^2 during office hours
Ventilation max. air flow (l/s,m^2)	Typical average value during occupancy was 1 l/s,m^2, about 3 l/s,m^2 extra should be reserved in case of cooling peaks
Ventilation heat recovery (%)	For heating dominated and moderate climate zones >80% is recommended, for cooling dominated zones >75% was found to be sufficient
Demand controlled ventilation or Variable Air Volume with CO_2 control and temperature control	It is recommended for all nZEB buildings as it minimizes the unnecessary ventilation based on occupancy while maintaining thermal comfort of the occupants
Low-temperature heating	Recommended for all climate zones, as it was found to enable higher efficiency in the heat pump

High-temperature cooling	Having high-temperature cooling allows a substantial share of cooling which can be harvested from the geothermal energy piles if they are used for energy generation
Heating emission in space	Radiant heating panel with supply temperature 35-40 °C in the design point is recommended. Based on this study, RFP for heating are not recommend, as it results in control challenges due to intermitted operation of heating and long-time constants of a zero energy building
Cooling emission in space	Radiant cooling panels together with CAV can be used. Supply temperature should be at least min 17 °C in the design point. Cooling peaks should be supported by the ventilation. Based on this study, RFP for cooling is not suggested, as it presents some control challenges due to intermitted operation of heating and long-time constants of a zero energy building
Cooling in the ventilation unit	Supports the space cooling during cooling demand peaks. Sizing between 7/12 °C is recommended to enable the dehumidification during hot and humid seasons.
Night cooling	Natural ventilation approach resulted as the best outcome among others. It needs a vast amount of air change rates. If it is arranged with mechanical fans, the energy efficiency benefit might be lost
Heating set point set-back during unoccupied hours	The possibility of high morning peaks for both heating and cooling set points. The intelligent control can avoid the use of chiller for cooling and heating in the first hours of the occupancy. If renewable energy systems such as geothermal energy piles coupled with heat pump are available, the intelligent control can use the pile-cooling and heating energy first to avoid morning peaks
Cooling set point set-up during unoccupied hours	
Room level local indoor environment control	For heating, cooling, lighting and CO_2
Humidity control in the ventilation unit	According to the local climate, it is usually not needed in the heating dominated climates

4.4 Limitations

Many European countries calculate and compare primary energy instead of end-use energy [55]. Primary energy is defined as the total amount of a natural resource needed to produce a certain amount of end-use energy, including extraction, processing, transportation, transformation and distribution losses down the stream [56,57]. End-use energy is the final delivered energy to the building, required for space heating, hot water, cooling, and electricity, often also referred to as final energy. BPIE argues that “that the current approach using the Primary Energy Factors (PEFs) is detrimental to understanding the real energy performance of a building”[58]. The primary energy factors are often based on politics after strong lobbying by different stakeholders including energy carriers and do not as such reflect the actual physics of the real energy chains. Drawing energy balance boundaries around a single service or goods, as in the case of ZEBs, may lead to shortfalls in energy and emission accounting [59]. So, it was selected to consider annual end-use energy demands on a building level rather than primary energy.The comparative analysis of heating and cooling demand is not affected by country or region specific primary energy factors. However, the approach selected enables to continue the analyses on a macro-level, e.g. country-level, by also using the primary energy approach.

At times, the simulation model was too complicated because of intermittent HVAC controls during radiant heating and cooling systems simulation, which had VAV, CO_2 and temperature control. The solver attempted to run the single case of radiant ceiling panels over 17 hours to 5 days. This issue was resolved by editing minimum supply air temperature set point by 1°C and gaining it by heating caused by the operation of the fan in HVAC unit. On the contrary, the control system could have been modeled better by the authors to avoid this problem.

DH was found to be prevalent in Romania, and thus typical DH losses of 6% were applied to the EE and nZEB cases in the model. However, based on [60] the system-wide energy losses in DH are rather high ranging from 35%-75% including generation, transport, distribution and final consumption. This may mean that the heating demand in Romania can be further decreased than as presented in **Figure 4** if the efficiency rate was chosen to be 0.65 in the simulations.

5 Conclusion

This study presented full-scale energy performance simulations of an office building with 160 zones. Three cases of building as usual based on country specific regulation, energy efficient case and nearly zero energy case were simulated for three climate zones of Helsinki, London and Bucharest. The objective was fulfilled by reducing the amount of delivered energy or net energy supplied to the office building and the results demonstrated that the chosen parameters can be conveniently set and perform in three different climate zones. Typical parameters to achieve a nearly zero energy building were recommended in Table 7 based on the finding of this study. For Helsinki, it is possible to reduce the space heating load by 86% and electricity consumed by lighting, appliance, and HVAC by 32%. For London, the heating load is reduced by 95%, cooling load is slightly increased, and electricity demand can be decreased by 33%. For Bucharest, 92% of energy in heating can be saved, and cooling energy demand was reduced by 60% and electricity consumption by 34%. The overall conclusion suggests that it is easier to minimize the heating and cooling demand by using energy efficient measures than having to reduce the electricity consumption in office buildings. On the other hand, if the energy generated by renewables is coupled with the building, the production can straightforwardly support the required delivered energy for the electricity.

The nearly zero energy cases were further studied in all climate zones with two alternative heating and cooling solutions using radiant floor panels (RFP) and radiant ceiling panels (RCP). Both radiant heating and cooling systems are feasible solutions that can be readily implemented into a building design. There are small differences in absolute consumption demand for heating, cooling, and electricity for three cases in each location. The specific energy/m^2 for heating remained nearly the same in all systems for all three cases in each location. Marginal difference in heating energy required for space heating can be seen for London nZEB IHC and London nZEB RCP of 0.8 kWh/m^2/year and for Bucharest nZEB IHC and Bucharest nZEB RCP case of 1.3 kWh/m^2/year. RFP has the availability of large surface area for heat exchange and can provide heating at a low temperature and cooling at high temperature, but requires supporting air based cooling during humid season. For RCP, limited temperature exchange surface may increase the air flow rate but supplies it at lower temperature for the same load.

To further develop this study for achieving a net zero energy building with annual balance of 0 kWh/m^2, ground source heat exchangers can be added to support the use of heat pump and chiller. Solar collectors can be installed to supply hot water demand and if required to re-inject heat into the ground source heat exchanger. Also, a heat pump can support the AHU and hot water needed for radiant panel heating, whereas, an AHU based chiller can be used for radiant panel cooling. In addition to that, an auxiliary electric heater can be added if the solar collectors and heat pump are unable to fulfill the demand. It would become essential to consider thermal storages for heating, hot water, and cooling.

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References

[1] European Union, Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast), 2010. doi:doi:10.3000/17252555.L_2010.153.eng.

[2] Buildings Performance Institue Europe (BPIE), IMPLEMENTING NEARLY ZERO-ENERGY BUILDINGS (nZEB) in Romania- Towards a defination and Roadmap, 2012.

[3] The National Building Code of Finland, (n.d.). http://www.ym.fi/en-us/Land_use_and_building/Legislation_and_instructions/The_National_Building_Code_of_Finland#D Hepac and energy management (accessed September 8, 2015).

[4] Buildings Performance Institute Europe (BPIE), Nearly Zero Energy Buildings Definitions across Europe (status as of April 2015). Factsheet, 2015.

[5] European Parliament, European Parliament and Council, 2010a. Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings, 2010.

[6] European Union, European Parliament and Council, 2010b. Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings, n.d.

[7] European Commission, Energy Performance of Building Directive, 2010.

[8] S. Deng, R.Z. Wang, Y.J. Dai, How to evaluate performance of net zero energy building - A literature research, Energy. 71 (2014) 1–16. doi:10.1016/j.energy.2014.05.007.

[9] A.J. Marszal, P. Heiselberg, J.S. Bourrelle, E. Musall, K. Voss, I. Sartori, A. Napolitano, Zero Energy Building – A review of definitions and calculation methodologies, Energy Build. 43 (2011) 971–979. doi:10.1016/j.enbuild.2010.12.022.

[10] W. Pan, System boundaries of zero carbon buildings, Renew. Sustain. Energy Rev. 37 (2014) 424–434. doi:10.1016/j.rser.2014.05.015.

[11] I. Sartori, A. Napolitano, K. Voss, Net zero energy buildings: A consistent definition framework, Energy Build. 48 (2012) 220–232. doi:10.1016/j.enbuild.2012.01.032.

[12] Z. Szalay, A. Zöld, Definition of nearly zero-energy building requirements based on a large building sample, Energy Policy. 74 (2014) 510–521. doi:10.1016/j.enpol.2014.07.001.

[13] M. Kapsalaki, V. Leal, Recent progress on net zero energy buildings, Adv. Build. Energy Res. 5 (2011) 129–162. doi:10.1080/17512549.2011.582352.

[14] C.J. Kibert, M.M. Fard, Differentiating among low-energy, low-carbon and net-zero-energy building strategies for policy formulation, Build. Res. Inf. 40 (2012) 625–637. doi:10.1080/09613218.2012.703489.

[15] J.S. Bourrelle, I. Andresen, A. Gustavsen, Energy payback: An attributional and environmentally focused approach to energy balance in net zero energy buildings, Energy Build. 65 (2013) 84–92. doi:10.1016/j.enbuild.2013.05.038.

[16] M.V. Jarek Kurnitski, Francis Allard, Derrik Braham, Guillaume Goeders, Per Heiselberg, Lennart Jagemar, Risto Kosonen, Jean Lebrun, Livio Mazzarella, Jorma Railio, Olli Seppanen, Michael Schmidt, How to define nearly net zero energy buildings nZEB, REHVA J. (2012) 6–12.

[17] F.M. Butera, Zero-energy buildings: the challenges, Adv. Build. Energy Res. 7 (2013) 51–65. doi:10.1080/17512549.2012.756430.

[18] E. Fabrizio, F. Seguro, M. Filippi, Integrated HVAC and DHW production systems for Zero Energy Buildings, Renew. Sustain. Energy Rev. 40 (2014) 515–541. doi:10.1016/j.rser.2014.07.193.

[19] M. Economidou, J. Laustsen, P. Ruyssevelt, D. Staniaszek, D. Strong, Europe's buildings under the microscope - A country-by-country review of the energy performance of buildings, Buildings Performance Institure Europe (BPIE), 2011. http://www.institutebe.com/InstituteBE/media/Library/Resources/Existing Building Retrofits/Europes-Buildings-Under-the-Microscope-BPIE.pdf.

[20] Statistics Finland, 2015. (n.d.).

[21] Valuation Office Agency, Commercial and Industrial Floorspace and Rateable Value Statistics (2005 Revaluation), 2008. http://neighbourhood.statistics.gov.uk/dissemination/MetadataDownloadPDF.do?downloadId=24729.

[22] Office of the Deputy Prime Minister, Commercial and Industrial Floorspace and Rateable Value Staistics 2005 (2005 Reevaluation), 2006. http://webarchive.nationalarchives.gov.uk/20120919132719/http://www.communities.gov.uk/documents/planningandbuilding/pdf/143684.pdf.

[23] P. Armitage, D. Godoy-Shimizu, K. Steemers, T. Chenvidyakarn, Using Display Energy Certificates to quantify schools' energy consumption, Build. Res. Inf. 39 (2011) 535–552. doi:10.1080/09613218.2011.628457.

[24] ENTRANZE Webpage, Share of public/private offices in total non-residential floor areas, (2015). http://www.entranze.enerdata.eu/#/share-of-offices-in-total-non-residential-areas.html (accessed January 12, 2016).

[25] B. Boardman, Achieving zero delivering future-friendly buildings, Oxford, 2012. www.eci.ox.ac.uk/research/energy/achievingzero/.

[26] M. Thalfeldt, J. Kurnitski, A. Mikola, Nearly zero energy office building without conventional heating, Est. J. Eng. 19 (2013) 309–328. doi:10.3176/eng.2013.4.06.

[27] D. D'Agostino, B. Cuniberti, P. Bertoldi, Energy consumption and efficiency technology measures in European non-residential buildings, Energy Build. 153 (2017) 72–86. doi:10.1016/j.enbuild.2017.07.062.

[28] Buildings Performance Institue Europe (BPIE), Nearly Zero Energy Buildings Definations Across Europe,

Brussels, 2015. http://bpie.eu/wp-content/uploads/2015/09/BPIE_factsheet_nZEB_definitions_across_Europe.pdf.

[29] Euroheat and Power (2013 data), District Heating and Cooling Statistics 2015, 2015. http://www.euroheat.org/wp-content/uploads/2016/03/2015-Country-by-country-Statistics-Overview.pdf.

[30] K. Ahmed, J. Kurnitski, P. Sormunen, Demand controlled ventilation indoor climate and energy performance in a high performance building with air flow rate controlled chilled beams, Energy Build. 109 (2015) 115–126. doi:10.1016/j.enbuild.2015.09.052.

[31] A. Mohamed, M. Hamdy, A. Hasan, K. Sirén, The performance of small scale multi-generation technologies in achieving cost-optimal and zero-energy office building solutions, Appl. Energy. 152 (2015) 94–108. doi:10.1016/j.apenergy.2015.04.096.

[32] A. Boyano, P. Hernandez, O. Wolf, Energy demands and potential savings in European office buildings: Case studies based on EnergyPlus simulations, Energy Build. 65 (2013) 19–28. doi:10.1016/j.enbuild.2013.05.039.

[33] P. Zangheri, R. Armani, M. Pietrobon, L. Pagliano, M. Fernandez Boneta, A. Müller, Heating and cooling energy demand and loads for building types in different countries of the EU, (2014) 86. http://www.entranze.eu/files/downloads/D2_3/Heating_and_cooling_energy_demand_and_loads_for_building_types_in_different_countries_of_the_EU.pdf.

[34] L. Georges, M. Berner, M. Berge, hans M. Mathisen, Proceedings of BS2013: 13th Conference of International Building Performance Simulation Association, Chambéry, France, August 26-28 - 1803 -, in: Proc. BS2013 13th Conf. Int. Build. Perform. Simul. Assoc. Chambéry, Fr. August 26-28, 2013: pp. 1803–1810.

[35] R. Simson, J. Kurnitski, K. Kuusk, Experimental validation of simulation and measurement-based overheating assessment approaches for residential buildings, Archit. Sci. Rev. 0 (2017). doi:10.1080/00038628.2017.1300130.

[36] A. Hermelink, S. Schimschar, T. Boermans, L. Pagliano, P. Zangheri, R. Armani, K. Voss, E. Musall, Towards nearly zero- energy buildings. Definition of common principles under the EPBD, 2013. https://ec.europa.eu/energy/sites/ener/files/documents/nzeb_full_report.pdf.

[37] N. Jung, J. Shemeikka, R. Lahdelma, J. Nieminen, Towards net zero energy builings: dynamic simulations of an office building in three climate zones of Europe, in: Proc. IASTED Int. Conf. Model. Identif. Control, Modelling Identification and Control (MIC 2013), 2013: pp. 460–467. doi:10.2316/P.2013.794-076.

[38] N. Jung, J. Shemeikka, R. Lahdelma, J. Nieminen, Towards net zero energy builings: dynamic simulations of an office building in three climate zones of Europe, in: Modelling Identification and Control (MIC 2013), 2013.

[39] Equa Simulation Finland Oy, Validation of IDA Indoor Climate and Energy 4.0 with respect to CEN Standards EN 15255-2007 and EN 15265-2007, 2010. http://www.equa.se/en/ida-ice/validation-certifications.

[40] Finnish Ministry of the Environment, D2 Indoor Climate and Ventilation Guidelines, National Building Code of Finland, 2012. http://www.ym.fi/en-US/Land_use_and_building/Legislation_and_instructions/The_National_Building_Code_of_Finland#D Hepac

and energy management.

[41] Finnish Ministry of the Environment, D3 Indoor Climate and Ventilation of Buildings, National Building Code of Finland, 2012. http://www.ym.fi/en-US/Land_use_and_building/Legislation_and_instructions/The_National_Building_Code_of_Finland#D Hepac and energy management.

[42] Finnish Ministry of the Environment, D5 Calculation of Power and Energy needs for Heating of Buildings, 2012. http://www.ym.fi/en-US/Land_use_and_building/Legislation_and_instructions/The_National_Building_Code_of_Finland#D Hepac and energy management.

[43] Communities & Local Government, National Calculation Methodology (NCM) modelling guide (for buildings other than dwellings in England and Wales), 2008.

[44] Tata Steel, British Constructional Steelwork Association, Aecom, Cyril Sweett, The Steel Construction Institute, Development Securities PLC, Guidance on the Design and Construction of Sustainable, Low Carbon Office Buildings, 2012. www.targetzero.info.

[45] Greater London Authority, London Heat Network Manual, 2014. https://www.london.gov.uk/sites/default/files/london_heat_map_manual_2014.pdf.

[46] M. of R. Development, A. Tourism, C107/2005 - Normativ privind calculul termotehnic al elementelor de construcţie ale clădirilor. (in Romanian)., 2010.

[47] British Standard Institution Technical Committee CEN/TC 156, prEN 15251- Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics, 2008.

[48] EQUA Simulation AB, User Manual IDA Indoor Climate and Energy, Verison 4. (2013) 160–165. http://www.equaonline.com/iceuser/pdf/ICE45eng.pdf (accessed January 20, 2016).

[49] C.W.F. Yu, Jeong Tai Kim, Building Environmental Assessment Schemes for Rating of IAQ in Sustainable Buildings, Indoor Built Environ. 20 (2011) 5–15. doi:10.1177/1420326X10397780.

[50] K. Al-Rashidi, D. Loveday, N. Al-Mutawa, Impact of ventilation modes on carbon dioxide concentration levels in Kuwait classrooms, Energy Build. 47 (2012) 540–549. doi:10.1016/j.enbuild.2011.12.030.

[51] British Standard Institution, EN 13779 - Ventilation for non-residential buildings. Performance requirements for ventilation and room-conditioning systems, 2007. http://shop.bsigroup.com/ProductDetail/?pid=000000000030300123 (accessed January 31, 2016).

[52] British Standard Institution, Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics (BS EN 16798- revision of EN 15251), 2015.

[53] British Standard Institution, EN 12464-1 Light and lighting of indoor work places, 2011.

http://shop.bsigroup.com/en/ProductDetail/?pid=000000000030206727.

[54] ISO 8995-1, Lighting of work places - Part 1: Indoor, (2002). http://www.iso.org/iso/catalogue_detail.htm?csnumber=28857 (accessed January 25, 2016).

[55] K. Flodberg, Å. Blomsterberg, M.-C. Dubois, Low-energy office buildings using existing technology: simulations with low internal heat gains, Int. J. Energy Environ. Eng. 3 (2012) 19. doi:10.1186/2251-6832-3-19.

[56] I. Sartori, a. G. Hestnes, Energy use in the life cycle of conventional and low-energy buildings: A review article, Energy Build. 39 (2007) 249–257. doi:10.1016/j.enbuild.2006.07.001.

[57] S. Schimschar, K. Blok, T. Boermans, A. Hermelink, Germany’s path towards nearly zero-energy buildings—Enabling the greenhouse gas mitigation potential in the building stock, Energy Policy. 39 (2011) 3346–3360. doi:10.1016/j.enpol.2011.03.029.

[58] Buildings Performance Institute Europe (BPIE), The role of the primary energy factor in determining the energy performance of buildings: Policy Briefing, Policy Brief. 2 (2017).

[59] J.S. Bourrelle, Zero energy buildings and the rebound effect: A solution to the paradox of energy efficiency?, Energy Build. 84 (2014) 633–640. doi:10.1016/j.enbuild.2014.09.012.

[60] Cogeneration Observatory and Dissemination Europe (CODE2), D5.1 Final Cogeneration Roadmap Member State: Finland, (2014). http://www.code2-project.eu/wp-content/uploads/Code-2-D5-1-Final-non-pilot-Roadmap-Finland_final1.pdf (accessed April 15, 2016).