Towards nZEB—Sustainable Solutions to Meet Thermal Energy Demand in Office Buildings

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Abstract The transition towards Nearly Zero Energy Buildings (nZEB) requires the implementation of clean, efficient and affordable energy mixes in buildings. While the first two pre-requisites are related to a technical breakthrough that is expected for increasing the efficiency and sustainability of the renewable-based energy mixes implemented in the built environment, the affordability is directly related to the costs of these mixes, particularly to the initial investment. The paper analyses the affordability of the renewable based energy mixes for thermal energy production and outlines that the initial investment is exponentially increasing with the specific energy demand of the building. The calculations are focused on office buildings, having specific features that impose a lower thermal energy demand as compared to residential or other buildings with special regime (hospitals, hotels, etc.). Even in these conditions, the analysis shows that installing a renewables-based energy mix that covers 50 % of the thermal energy demand represents an affordable action if the buildings have a specific thermal energy need less than 80 kWh/(m^2 year). A case study is discussed and support the general cost model, considering a thermal energy mix possible to be installed in the built environment and consisting of a solar-thermal system (with flat plate collectors) and a heat pump, along with a photovoltaic array able to deliver the energy required for powering the heat pump.

Keywords Energy efficiency · Low energy building · Nearly zero energy building · Renewable energy sources · Renewables energy mix

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I. Visa (ed.), *Sustainable Energy in the Built Environment - Steps Towards nZEB*, Springer Proceedings in Energy, DOI 10.1007/978-3-319-09707-7_10

1 Introduction

Nearly Zero Energy Building (nZEB) status will be mandatory for all new buildings starting with January 1st 2021 in European Member States [1]. Existent buildings undergoing major renovation shall also comply with these new regulations. This milestone is earlier set, on January 1st 2019, for public authorities' buildings. This is a necessary answer to the increase in the building stock and in the associated energy consumption expected due to the global population growth, estimated at 10 billion up to 2050 [2].

In a first step, to get the nZEB status, integrated design should consider cost-effective measures to reach high energy performance for buildings, considering the climatic conditions and the specific requirements of that buildings. The target is to lower the energy consumption used for heating, cooling, ventilation, hot water and lighting, while preserving the internal comfort. The second step focuses on the sustainable production of the needed energy, by on-site or nearby installed renewable energy systems.

The renewable energy systems (RES) implementation is related to the type of building, its location, the available space for RES installation, architectural design, but also initial and operating costs. There is a broad diversity of buildings types, out of which the residential sector has a major contribution (75 %) to the energy consumption, followed by the wholesale and retail (7 %), offices (5.75 %) and educational buildings (4.25 %) in EU [3].

This paper focuses on office buildings because large companies are likely to invest for reaching the nZEB status, as an open commitment towards sustainability. These buildings have some special features that influence the design criteria:

(a) shape, orientation and envelope;
(b) functional zones/rooms in which the office building is divided;
(c) use of space, the daily schedule, the occupancy;
(d) air pollution and odour control etc.

The consequences related to this specificity are further detailed.

(a) *Office buildings shape, orientation and envelope* influence the heating and cooling loads due to the exposure to sun and weather conditions, therefore passive design should be considered from the early design stages. There are many studies on the impact of the shape and orientation of the office buildings, from wide-spread, high-raised office buildings with vertical walls, optimized with simplified analysis methods [4, 5], parametric flexible system design [6, 7] or by multi objective genetic algorithm [8] up to studies on buildings with inclined walls having self-shading effect, cutting the cooling load in hot climatic zones [9, 10]. As compared to residential buildings, the office buildings envelope is often characterised by higher glazing-to-wall ratio reducing the insulation level and the thermal mass. The insulation quality determines the thermal resistance of the building envelope which is intensively investigated in literature and already regulated in national Building Codes, Standards and

Guides by mentioning the minimum permitted thermal resistance for the elements of the building envelope [11–13]. These thresholds are not differentiated by the type of buildings, but are low enough to be respected also by office buildings with high glazing-to-wall ratio. Recently, the effect on the heating and cooling demand of the office buildings was evaluated for different types of materials integrated in building walls for sensible heat storage, in solid and liquid state [14], for latent heat storage (organic and inorganic phase change materials [15, 16]) and for thermochemical heat storage based on adsorption and absorption phenomena [14]. Research on the thermal mass of exterior and interior construction elements show that, in certain conditions, the energy demand of the office building can be decreased [17, 18]. The glazing-to-wall ratio is important due to the compromise needed to be done between natural lighting, lighting savings and reducing heat losses [19]. Office buildings have large windows contributing to higher energy demand both for heating and cooling [20]. Besides better thermal resistance of both glazing and frames, smart windows with controlled optical properties [21, 22] and the integration of (semi)transparent photovoltaic modules [23, 24] are broadly investigated.

(b) *The functional zones in which the office buildings are divided* are located in peripheral and interior areas [25]. These zones may be or not extensively subdivided. In most cases, the peripheral zones are adjacent to large windows causing variable loads, due to the daily and seasonally changing of the weather conditions and of the apparent position of the sun on the sky. Compared to the interior zones, peripheral zones have higher heating demand in winter when the overall inside air temperature and relative humidity must be maintained, during the working schedule, between 21–23 °C, and 20–30 % respectively [26, 27], and have higher cooling demand in summer when the overall inside air temperature and relative humidity must be maintained, during the working schedule, between 23–26 °C, and 50–60 % respectively [26, 27]; in intermediate seasons, some peripheral zones may require heating while some other peripheral zones require cooling. Interior zones have an almost uniform cooling load during the year, depending mainly on interior sources as people, office equipment and lighting systems. While the heat load from people varies between 6 and 60 W/m^2 upon occupancy [26, 27], the usual electrical equipment and the lighting system add 10–50 W/m^2, and computers and office specific electronic equipment add another 50–110 W/m^2 [28].

(c) *The uses of an office building* is generally for office activities such as reading, writing and computer work, done during working days from 8 a.m. till 5 p.m.; some maintenance operations are done in a couple of hours before and/or after the main schedule, but usually during night these buildings can accept lower comfort parameters. These office buildings may contain also data centres, printing facilities, communications operations, and/or surveillance and security systems etc. which could operate up to 24/7. Occupancy varies upon the specific work done in a space, between 2 m^2/person for conference rooms and 19 m^2/person for private offices where a high concentration level is demanded;

for usual office activity, the average occupancy is approximately 7 m^2/person [28].

(d) *Air pollution and odour control* must be addressed besides indoor air temperature and relative humidity, defining the thermal comfort [29] that supports better performances of the occupants. Depending on the occupancy and on the type of equipment used in office buildings, rates of 4–10 air changes per hour must be insured, with maximum allowed air speed of 0.13–0.23 m/s [26, 27].

Overall, depending on the geographic location and on the above described characteristics, the total yearly energy demand of office buildings varies between 100–1,000 kWh/m^2 [30]. In order to reach the nZEB status, this yearly energy demand must be as low as economically feasible. In some European Member States there are already in-force requirements for the yearly energy demand between 60 and 150 kWh/m^2 [31] upon the geographic location and type of use.

After applying the measures required to reduce the yearly energy demand of the building, renewable energy systems (RES) must be designed to cover this. For existent buildings having already implemented RES, the energy provided by RES should be assessed and, if the energy demand is not covered “to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby” as stipulated in the recast of the energy performance of buildings directive [1], then the exiting RES capacity should be increased if possible; if not, new types of RES must be considered according to the renewable energy sources potential and available space for installation. In the case of office buildings, there are constraints both on potential and available space. Thus, due to their location in areas with high buildings density and restrictive construction permits, usually solar, geothermal and wind (only for higher buildings) sources of renewable energy can be taped. Among these RES, the best use of available space for installation is attained for air to air or vertical ground coupled heat pumps [32], followed by solar thermal collectors [33], photovoltaic modules [34, 35] installed on the buildings’ rooftops or facades, and wind turbines [36]. Optimum results can be achieved if each RES is analysed not only as an entity, but also as part of an integrated and flexible energy mix able to meet the energy needs based on fluctuant renewable sources of energy [37, 38]. One important advantage of using RES on office buildings is given by the willingness of companies operating these office buildings to decrease operating costs, to improve employees’ productivity and its “green” image.

The paper presents a method to evaluate the specific initial cost of a renewable energy mix (expressed in €/m^2 for the entire building), aiming at covering a given value of RES share in the total energy demand, and to offer an easy to use instrument to evaluate the feasibility of such renewable energy mixes for office buildings having different values of yearly specific energy demand.

2 Method

The method used in this paper rely on an algorithm previously developed in general terms to improve the renewable energy mix for a building toward the nZEB status [37], meshed on the particular case of office building types. The first two steps of the above mentioned algorithm (the assessment of the current energy status and the decrease of the energy demand) are skipped, considering a given range of values for the yearly specific energy demand for domestic hot water and space heating. The focus is on the third step: the selection of the optimal, feasible and affordable renewable energy mix.

The yearly energy demand for domestic hot water and space heating is calculated with:

$$E_{DHy} = e_{DHy} \cdot S \ [\text{kWh/year}] \quad (1)$$

where:

e_{DHy} is the given value of the yearly specific energy demand [kWh/(m^2 year)];
S is the entire floor surface of the building [m^2].

This yearly energy demand must be monthly divided as significant differences occur. To this end, the yearly energy demand for domestic hot water and space heating is separately calculated.

The yearly energy demand for heating domestic hot water is calculated with:

$$E_{Dy} = n_p \cdot q \cdot \rho \cdot c \cdot \Delta t \cdot N_{wdy}/3{,}600{,}000 \ [\text{kWh/year}] \quad (2)$$

where:

n_p is the number of persons occupying the office building [person];
q is the daily specific hot water demand [L/(person day)];
ρ is the density of water [kg/L];
c is the specific heat of the water [J/(kg K)];
Δt is the temperature difference between the hot and cold water [°C];
N_{wdy} is the number of working days in a year [days/year].

The yearly energy demand for space heating is calculated with:

$$E_{Hy} = E_{DHy} - E_{Dy} \ [\text{kWh/year}] \quad (3)$$

The monthly energy demand for domestic hot water heating is calculated with:

$$E_{Dm} = n_p \cdot q \cdot \rho \cdot c \cdot \Delta t \cdot N_{wdm}/3{,}600{,}000 \ [\text{kWh/month}] \quad (4)$$

where:
N_{wdm} is the number of working days in a month [days/month].

The monthly energy demand for space heating is calculated with:

$$E_{Hm} = \frac{E_{Hy} \cdot H_{DDm}}{H_{DDy}} \ [\text{kWh/month}] \tag{5}$$

where:
H_{DDm} is the monthly heating degrees days [° days/month];
H_{DDy} is the yearly heating degrees days [° days/year].

Both, monthly and yearly heating degrees days are calculated based on the average monthly outdoor temperature. The monthly thermal energy demand for domestic hot water and space heating is calculated with:

$$E_{DHm} = E_{Dm} + E_{Hm} \ [\text{kWh/month}] \tag{6}$$

Next, different mixes of RES are evaluated for an imposed share of yearly energy demand to be covered by RES (f_{RES}). For each RES component, the installed capacity and associated costs are calculated based on an algorithm presented in this paper for a solar thermal system (STS), a heat pump system (HPS) and a photovoltaic system (PVS) which provides the yearly electrical energy needed to drive the heat pump system.

Solar thermal systems (STS) are evaluated based on a methodology previously proposed [38], to cover different shares (f_{STS}) between 0 and 100 % of yearly energy demand for domestic hot water and space heating; the results are the installed power (P_{STS}) and the investment cost (C_{STS}). The STS specific cost (sc_{STS}) is calculated with:

$$sc_{STS} = \frac{C_{STS}}{S} \quad [€/\text{m}^2] \tag{7}$$

where:
C_{STS} is the investment cost for STS [€].

Heat pump systems (HPS) are evaluated based on the same methodology, to cover different shares (f_{HPS}) between 100 and 0 % of yearly energy demand for domestic hot water and space heating (complementary to STS); the results are the installed heating power (P_{hHP}), the investment cost (C_{HPS}) and the yearly electric energy demand to drive the HPS (E_{eHPy}). Due to the specific characteristic of implementation sites, for office buildings (usually located in places with less available ground surface) vertical ground heat exchangers are recommended, usually increasing the initial investment cost in comparison with horizontal ones. The cost of the vertical ground heat exchanger is calculated with:

$$C_{VHX} = l \cdot L \; [€] \tag{8}$$

where:

l is the average market cost of vertical ground heat exchanger [€/m];
L is the depth of the vertical ground heat exchanger [m].

The L value is calculated with:

$$L = P_{hHP} \cdot \frac{COP - 1}{COP} \cdot \frac{1}{h} \; [\mathrm{m}] \tag{9}$$

where:

P_{hHP} is the installed heating power of the heat pump [W];
COP is the coefficient of performance of the heat pump [−];
h is the amount of heat that can be transferred from the ground [W/m].

The HPS specific cost, considering both the heat pump and the vertical ground heat exchanger (sc_{HPS}), is calculated with:

$$sc_{HPS} = \frac{C_{HPS} + C_{VHX}}{S} \; [€/\mathrm{m}^2] \tag{10}$$

where:

C_{HPS} is the investment cost for HPS [€];
C_{VHX} is the investment cost for the vertical ground heat exchanger [€].

Photovoltaic systems (PVS) should cover the yearly energy demand to drive the HPS and is designed based on the methodology proposed in [38], resulting the installed power (P_{PVS}) and the investment cost (C_{PVS}). The PVS specific cost (sc_{PVS}) is calculated with:

$$sc_{PVS} = \frac{C_{PVS}}{S} \; \left[€/\mathrm{m}^2\right] \tag{11}$$

where:

C_{PVS} is the investment cost for PVS [€].

The specific cost of the entire RES mix is calculated for different combinations of shares covered by each component with:

$$sc_{RES} = sc_{STS} + sc_{HPS} + sc_{PVS} \; \left[€/\mathrm{m}^2\right] \tag{12}$$

3 Case Study

The calculation method is applied considering the following hypotheses:

- One large office buildings (S = 1,350 m^2) occupied by 56 persons, 5 days/week with a schedule of 8 h/day (form 8:00 to 16:00);
- Iterative yearly specific thermal energy demand for space heating between 10 and 100 kWh/m^2/year and a constant daily specific hot water demand of 5 L/(person day);
- For the latitude corresponding to the implementation location (45.65°) and based on the solar radiation monitored over two years, it was concluded that the yearly collection efficiency of the solar radiation (obtained in simulation calculations) was 55 % for the fixed horizontal STS and 67.5 % for optimal fixed tilt STS at 37°;
- Continental temperate climatic profile, with winter and summer peak temperatures of −28 and 32 °C respectively, and values evaluated based on on-site measurements for: monthly available global horizontal solar radiation G_h, monthly average outdoor air temperature T_E, monthly heating and cooling degree-days H_{DDm} and C_{DDm}, as presented in Table 1.

In these conditions, the yearly energy demand for domestic hot water and space heating were calculated with Eqs. (1–3), and the results are presented in Table 2.

Based on the separately calculated values of the yearly energy demand for domestic hot water and space heating, monthly values are calculated using Eq. (4) and (5). The monthly energy demand for domestic hot water heating depends on the number of working days in the month, resulting 326, 349, and 360 kWh/month for the months with 28, 30 and 31 days respectively. The results obtained for the monthly energy demand for space heating are presented in Table 3.

Based on these results, the monthly thermal energy demand is calculated with Eq. (6), and the results are presented in Table 4.

Solar thermal systems (STS) are evaluated in following hypotheses:

- overall conversion efficiency of the STS 60%
- current average market prices for STS 750 €/kW

Based on these values, the installed power (P_{STS}), the investment cost (C_{STS}) and the specific cost (sc_{STS}) of the STS were calculated, Table 5.

Heat pump systems (HPS) are evaluated in following hypotheses:

- average coefficient of performance (COP) 4.50
- current average market prices for vertical ground heat exchanger (l) including the borehole, the U-tube and the grout: 50 €/m
- the heat that can be transferred from the ground (h) 50 W/m
- current average market prices for heat pumps based on the trend line equation presented in Fig. 1, where the significant dependence between the specific cost (sc_{HP}) of the heat pumps and its installed heating power is outlined.

Table 1 Monthly climatic parameters

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
G_h, [kWh/m^2]	37.20	50.40	83.70	105.00	145.70	156.00	169.88	142.60	90.00	71.30	51.00	24.80
T_e, [°C]	−4.90	−2.50	2.60	8.50	13.30	16.10	17.50	17.00	13.40	7.90	2.80	−1.90
H_{DDm}, [° days]	772	630	539	345	47	0	0	0	53	375	516	679
C_{DDm}, [° days]	0	0	0	0	30	183	233	217	34	0	0	0

Table 2 Yearly energy demand for DHW (E_{Dy}) and space heating (E_{Hy}) [kWh/year]

e_{DHy}*	10	20	30	40	50	60	70	80	90	100
E_{DHy}	13,500	27,000	40,500	54,000	67,500	81,000	94,500	108,000	121,500	135,000
E_{Dy}	4,244	4,244	4,244	4,244	4,244	4,244	4,244	4,244	4,244	4,244
E_{Hy}	9,256	22,756	36,256	49,756	63,256	76,756	90,256	103,756	117,256	130,756

* e_{DHy}—yearly specific energy demand for domestic hot water and space heating [kWh/(m^2 year)]

Table 3 Monthly energy demand for space heating, E_{Hm} [kWh/month]

Month	e_{DHy}*									
	10	20	30	40	50	60	70	80	90	100
January	1,806	4,440	7,074	9,708	12,343	14,977	17,611	20,245	22,879	25,513
February	1,474	3,624	5,774	7,924	10,074	12,224	14,373	16,523	18,673	20,823
March	1,262	3,103	4,943	6,784	8,625	10,466	12,306	14,147	15,988	17,829
April	807	1,985	3,162	4,339	5,516	6,694	7,871	9,048	10,226	11,403
May	110	270	430	590	750	910	1,070	1,230	1,390	1,550
June	0	0	0	0	0	0	0	0	0	0
July	0	0	0	0	0	0	0	0	0	0
August	0	0	0	0	0	0	0	0	0	0
September	124	304	484	664	844	1,024	1,205	1,385	1,565	1,745
October	878	2,158	3,438	4,718	5,998	7,278	8,558	9,838	11,118	12,398
November	1,207	2,968	4,729	6,490	8,251	10,012	11,773	13,533	15,294	17,055
December	1,588	3,905	6,222	8,539	10,856	13,172	15,489	17,806	20,123	22,439

* e_{DHy}—yearly specific energy demand for domestic hot water and space heating [kWh/(m^2 year)]

Table 4 Monthly thermal energy demand, E_{DHm} [kWh/month]

Month	e_{DHy}*									
	10	20	30	40	50	60	70	80	90	100
January	2,166	4,801	7,435	10,069	12,703	15,337	17,971	20,605	23,240	25,874
February	1,800	3,949	6,099	8,249	10,399	12,549	14,699	16,849	18,999	21,149
March	1,622	3,463	5,304	7,145	8,985	10,826	12,667	14,508	16,348	18,189
April	1,156	2,333	3,511	4,688	5,865	7,043	8,220	9,397	10,575	11,752
May	470	630	790	950	1,110	1,270	1,430	1,591	1,751	1,911
June	349	349	349	349	349	349	349	349	349	349
July	360	360	360	360	360	360	360	360	360	360
August	360	360	360	360	360	360	360	360	360	360
September	472	653	833	1,013	1,193	1,373	1,553	1,734	1,914	2,094
October	1,238	2,518	3,798	5,078	6,358	7,638	8,918	10,198	11,478	12,758
November	1,556	3,317	5,078	6,839	8,600	10,360	12,121	13,882	15,643	17,404
December	1,949	4,266	6,582	8,899	11,216	13,533	15,850	18,166	20,483	22,800

* e_{DHy}—yearly specific energy demand for domestic hot water and space heating [kWh/(m^2 year)]

Table 5 Specific cost of the STS covering a share of f_{STS} in the energy mix [€/m^2]

f_{STS} (%)	e_{DHy}*									
	10	20	30	40	50	60	70	80	90	100
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.54	1.12	2.21	3.62	5.09	7.01	9.48	13.22	20.19	35.57
20	1.12	3.26	6.14	9.03	12.53	16.48	22.81	30.67	46.48	77.86
30	2.05	5.78	10.11	14.44	19.97	26.19	36.14	48.40	72.77	120.15
40	2.98	8.30	14.08	19.85	27.41	35.91	49.47	66.12	99.06	162.44
50	4.03	10.83	18.04	25.26	34.85	45.62	62.80	83.84	125.35	204.73
60	5.08	13.35	22.01	30.77	42.29	55.34	76.13	101.57	151.65	247.01
70	6.13	15.87	25.98	36.29	49.73	65.05	89.46	119.29	177.94	289.30
80	7.18	18.40	29.94	41.81	57.17	74.76	102.79	137.01	204.23	331.59
90	8.23	20.92	33.91	47.33	64.60	84.48	116.12	154.74	230.52	373.88
100	9.28	23.44	37.88	52.85	72.04	94.19	129.45	172.46	256.81	416.17

* e_{DHy}—yearly specific energy demand for domestic hot water and space heating [kWh/(m^2 year)]

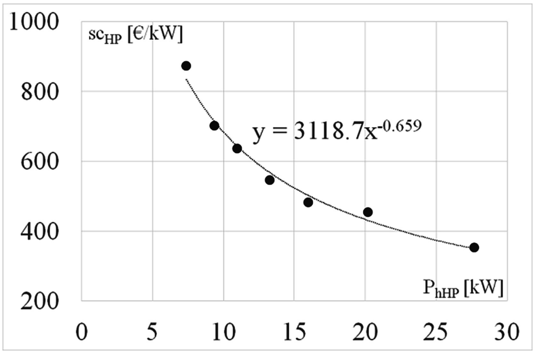

Fig. 1 The dependence between the specific cost of heat pumps and its installed heating power

Based on these values, the installed power (P_{hHP}) and the investment cost (C_{HPS}) of the HPS were calculated, along with the investment cost (C_{VHX}) of the vertical ground heat exchanger and, accordingly, the specific cost (sc_{HPS}) of the HPS; the results are presented in Table 6.

Photovoltaic systems (PVS) are evaluated in following hypotheses:

– overall conversion efficiency of the PVS 15 %
– current average market prices for PVS 1,500 €/kW

Based on these values, the installed power (P_{PVS}) and the investment cost (C_{PVS}) of the PVS were calculated and, accordingly, the specific cost (sc_{PVS}) of the PVS, the results being presented in Table 7.

The nZEB status requires to cover a significant share of the energy demand by using RES. Now-a-days it is usually considered that "significant" referred to a share (f_{RES}) above 50 %. Therefore, two cases were considered to discuss the optimal energy mix: f_{RES} = 70 % and f_{RES} = 50 %.

Table 6 Specific cost of the HPS covering a share of f_{HPS} in the energy mix [€/m^2]

f_{HPS} (%)	e_{DHy}*									
	10	20	30	40	50	60	70	80	90	100
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	1.31	1.72	2.04	2.39	2.79	3.15	3.47	3.82	4.22	5.00
20	1.72	2.39	3.06	3.70	4.28	4.82	5.33	5.99	6.69	8.08
30	2.04	2.99	3.92	4.75	5.51	6.23	6.94	7.86	8.86	10.82
40	2.39	3.55	4.69	5.69	6.63	7.53	8.44	9.60	10.90	13.41
50	2.70	4.07	5.39	6.58	7.69	8.75	9.87	11.27	12.86	15.92
60	2.98	4.55	6.05	7.41	8.70	9.94	11.25	12.89	14.76	18.36
70	3.25	5.01	6.69	8.23	9.68	11.09	12.60	14.47	16.62	20.76
80	3.50	5.45	7.30	9.01	10.64	12.21	13.92	16.02	18.45	23.13
90	3.74	5.87	7.90	9.78	11.58	13.32	15.22	17.55	20.26	25.47
100	3.97	6.28	8.49	10.54	12.50	14.40	16.50	19.06	22.05	27.78

* e_{DHy}—yearly specific energy demand for domestic hot water and space heating [kWh/(m^2 year)]

Table 7 Specific cost of the PVS covering a share of f_{HPS} in the energy mix [€/m^2]

f_{HPS} (%)	e_{DHy}*									
	10	20	30	40	50	60	70	80	90	100
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.24	0.48	0.72	0.96	1.20	1.45	1.69	1.93	2.17	2.41
20	0.48	0.96	1.45	1.93	2.41	2.89	3.37	3.85	4.34	4.82
30	0.72	1.45	2.17	2.89	3.61	4.34	5.06	5.78	6.50	7.23
40	0.96	1.93	2.89	3.85	4.82	5.78	6.74	7.71	8.67	9.63
50	1.20	2.41	3.61	4.82	6.02	7.23	8.43	9.63	10.84	12.04
60	1.45	2.89	4.34	5.78	7.23	8.67	10.12	11.56	13.01	14.45
70	1.69	3.37	5.06	6.74	8.43	10.12	11.80	13.49	15.18	16.86
80	1.93	3.85	5.78	7.71	9.63	11.56	13.49	15.42	17.34	19.27
90	2.17	4.34	6.50	8.67	10.84	13.01	15.18	17.34	19.51	21.68
100	2.41	4.82	7.23	9.63	12.04	14.45	16.86	19.27	21.68	24.09

* e_{DHy} - yearly specific energy demand for domestic hot water and space heating [kWh/(m^2 year)]

Eight different mixes can be obtained for f_{RES} = 70 %, using iterative shares for STS (f_{STS}) between 70 and 0 % with 10 % steps (and accordingly for HPS (f_{HPS}) between 0 and 70 %). The case considering f_{RES} = 50 % will follow the same approach. The specific costs obtained are presented in Table 8 and their graphical representation in Fig. 2.

Table 8 Specific cost of the RES mix

RES mix			Yearly specific energy demand, e_{DHY}, [kWh/(m^2 year)]									
			10	20	30	40	50	60	70	80	90	100
f_{RES} [%]	f_{STS} [%]	f_{HPS} [%]	STS + HPS + PVS specific cost [€/m^2]									
70	70	0	6.13	15.87	25.98	36.29	49.73	65.05	89.46	119.29	177.94	289.30
	60	10	6.63	15.56	24.77	34.13	46.28	59.93	81.29	107.31	158.04	254.43
	50	20	6.24	14.18	22.55	30.89	41.54	53.33	71.50	93.68	136.38	217.62
	40	30	5.74	12.74	20.17	27.49	36.53	46.47	61.47	79.76	114.43	180.49
	30	40	5.40	11.26	17.69	23.99	31.42	39.50	51.32	65.71	92.35	143.20
	20	50	5.03	9.74	15.15	20.42	26.24	32.46	41.11	51.58	70.18	105.82
	10	60	4.97	8.57	12.60	16.82	21.02	25.62	30.85	37.67	47.96	68.39
	0	70	4.94	8.38	11.75	14.97	18.11	21.20	24.40	27.96	31.80	37.62
50	50	0	4.03	10.83	18.04	25.26	34.85	45.62	62.80	83.84	125.35	204.73
	40	10	4.53	10.51	16.84	23.21	31.40	40.50	54.63	71.87	105.46	169.85
	30	20	4.25	9.13	14.62	20.07	26.66	33.90	44.84	58.24	83.80	133.05
	20	30	3.89	7.69	12.24	16.67	21.66	27.05	34.81	44.31	61.85	95.91
	10	40	3.89	6.60	9.79	13.17	16.54	20.32	24.66	30.53	39.76	58.62
	0	50	3.90	6.48	9.00	11.39	13.71	15.98	18.30	20.91	23.70	27.96

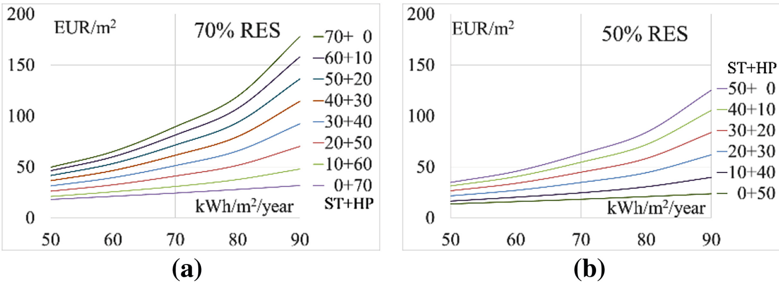

Fig. 2 **a** 70 % RES share; **b** 50 % RES share out of thermal energy demand

4 Results and Discussions

There is a direct correlation between the initial investment costs to implement renewables and the thermal energy demand of the building. The results show that specific RES cost increase exponentially starting from a threshold of 80 kWh/(m^2 year). Therefore, the first steps in developing Nearly Zero Energy Buildings, before implementing RES, should be made towards decreasing the specific energy demand of the building.

The lowest specific cost were obtained for systems based on HPS only, both when considering a RES share of 50 % and of 70 % respectively, due to the smaller specific energy demand for domestic hot water than space heating. This is characteristic to office buildings, having smaller DHW need, 5 L/(person day), as compared to residential buildings, 90 L/(person day).

For highly efficient buildings, with specific energy demand lower than 50 kWh/(m^2 year), the share of domestic hot water in the yearly energy demand increases, making almost no difference between different RES mixes.

A specific RES cost under 50 €/m^2 can be considered affordable for new buildings considering the average office building costs of 500–750 €/m^2. This threshold can be respected if the specific energy demand is lower than 90 kWh/(m^2 year).

Future developments will consider the increase of the building cost when improving its envelope thermal characteristics, the operating and maintenance cost of RES mix and finally the cost - benefit ratio.

5 Conclusions

It is common knowledge that the thermal resistance of the building envelope and consequently its specific energy demand have a major influence on the RES mix feasibility, but the extent of this influence is usually not outlined. Therefore, the paper proposes a calculation model that correlates the yearly specific thermal energy demand of a building with the costs of the installed renewables.

The results outline the need to follow a stepwise development of Nearly Zero Energy Buildings, first by increasing the energy efficiency (and significantly cutting the thermal losses) and only afterwards to consider the implementation of renewables-based energy mixes.

Even so, covering 50 % of the thermal energy demand with RES represents a feasible and affordable path in the current development conditions, and well justifies the targeted values proposed for nZEBs.

Acknowledgement This paper is supported by the Sectoral Operational Programme Human Resources Development (SOP HRD), financed from the European Social Fund and by the Romanian Government under the project number POSDRU/159/1.5/S/134378.

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