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Application of net zero extended exergy buildings concept for sustainable buildings analysis

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ABSTRACT

Different Zero-Energy Building (ZEB)-related definitions considering its four main dimensions, such as zero energy, zero carbon, zero exergy and zero cost, have been proposed by different investigators. Among these, exergy-based definitions are relatively low in numbers. In this regard, the main objective of this present study is to propose net zero extended exergy buildings as a new concept, which combines extended exergy and net zero exergy building concepts and is a measure of the exergetic footprint. This concept setups a balance between extended exergy accounting of electricity from the grid and electricity generated in building. The proposed methodology is applied to a building available in the literature for heating and cooling seasons. Results show that $450W_p$ peak power and 44.181 kWh electrical energy must be obtained for meeting the electricity demand of the building. Another novel result is that the extended exergy accounting of the electricity generated by PV panels is bigger than the extended exergy of the electricity taken from the gird meaning that exergetic footprint of the electricity generated by PV panels is bigger. However, this result must be interpreted for the whole life time of the system.

Nomenclature

A	Area of the PV panel (m^2)
C	Capital ($)
CExC	Cummulative exergy consumption (kJ)
$\dot{E}x_D$	Exergy destruction rate (kW)
EEx_{EN}	Extended exergy associated with the environmental remediation (MJ,PJ)
EEx_K	Extended exergy amount of capital (MJ,PJ)
EEx_L	Extended exergy amount of labor (MJ,PJ)
$\dot{E}x_F$	Fuel exergy (or exergetic fuel) rate (kW)
G	Irradiation rate (kJ/m^2)
$\dot{E}x_P$	Product exergy (or exgergetic product) rate (kW)

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EExA	Total extended exergy account (MJ,PJ)
$EExA_{PV}$	Total extended exergy account (MJ,PJ)
$EExA_{GRID}$	Total extended exergy account (MJ,PJ)
$\dot{E}x_{in}$	Total input exergy rate (kW)
EEA_{Grid}	Extended exergy for grid power (kJ)
ee_{GRID}	Specific extended exergy cost ($TWh/TWh_{electricity}$)
ee_K	Specific extended exergy rate of capital (kJ/$)
ee_L	Specific extended exergy rate of labor (kJ/Nwh)
ee_{PV}	Specific extended exergy of the PV panel (kJ/m^2)
H	Working hours (h)
L	Energy load supplied by PV system (kJ)
N	Number of PV panels
N*	Number of PV panels calculated using net extended exergy methodology
P_{PV}	Power of the PV system (kW)
$\dot{W}_p$	*Photovoltaic plant peak power (W)*

Greek letters

φ	*Exergy efficiency of the system*
η	*PV panel efficiency (%)*
α	Fraction of the primary exergy embodied into labor
β	Amplification factor for the creation of wealth due to financial activities

Abbreviations

EExA	Extended Exergy Accounting
GHG	Greenhouse gases
PV	Photovoltaic
ZEB	Zero-Energy Building

1. Introduction

Buildings are of great importance due to energy consumption all over the world because building sector significantly affects the total natural resource consumption and is considered a significant contributor to Greenhouse Gases (GHG) [1]. Exergy indicates the maximum work potential of a system or a process under certain conditions. Exergy demand of a building represents the minimum work for maintaining the indoor conditions [2] and exergy-based analyses and assessments have played an essential role to increase the total efficiencies of energy-related systems and technologies [3].

The concept of "Zero-Energy Building (ZEB)" was firstly used in 1976 [1,2] and since then, various definitions have been proposed by different investigators, as also reviewed in Refs. [4–6]. The definitions used aim at applying passive and active design strategies to build environments for minimizing energy demand and fossil fuel consumption while maximizing energy efficiency and installing renewable energy-related systems in an integrated or holistic way [7]. These definitions also have four main dimensions, such as zero energy, zero carbon, zero exergy and zero cost while the period is categorized as one year and life cycle [4].

As far as some studies on ZEBs are concerned, Kylili and Fokaides [8] reviewed how the ZEB principle could contribute to achieving smart cities in Europe while what kinds of actions could be needed to develop the methodologies for the building assessment. Sangi and Müller [9] proposed three approaches to compare non-renewable and renewable building energy systems solely from the exergy point of view. Based on their results, these three approaches could be successfully used for comparing these types of systems. Pernetti et al. [10] used a differential the elementary effects and sensitivity analysis methods for assessing the impact of various boundary conditions and building features on life cycle cost evaluation for eleven net ZEBs across Europe. Luo [11] proposed an integrated design process for determining optimal retrofitting solutions and achieving life-cycle net-zero while a real-world office building was adopted for demonstrating the approach proposed. The maximum lifetime payback cost reductions of 116.3% and 103.5% for life-cycle net-zero energy and carbon were achieved for the building considered in the research. From the exergy-based ZEBs point of view, the energy along with its quality, namely its exergy, was considered in a study done by Kilkis [12]. In exergy-based ZEBs concept sum of zero exergy transfer across the building-district boundary in a district energy system, during all electric and any other energy transfer that is taking place in a certain period of time [12], which overcome weakness of energetic approach. Two new definitions, "Net-Zero Exergoeconomic Building" and "Net-Zero Exergoenvironmental Building" were also proposed by Ahmadi et al. [13]. They integrated these definitions with the net ZEB regulations and applied to a grid-connected office building equipped with a PV power plant for indicating the effectiveness of the proposed definitions. Ahmadi et al. [14] used the extended exergy accounting, which considered exergetic equivalent of the labor, capital, environmental remediation costs and resource consumptions, concept and applied it to a district in the central part of Iran. This method can be called net zero extended exergy building concept. The difference between exergy-based ZEBs and net zero extended exergy building concept is that exergy-based ZEBs take into account only energy transfer while net zero extended exergy building concept considers capital, labor, environmental and resource consumption effects as well to evaluate sustainability in a better way during the same period. They also compared the outcomes obtained from the net-zero extended exergy approach with the net-zero source energy and net zero exergy methods in terms of sensitivity and technical analyses. Another advantage of the exergetic approach is that it can help us understand environmental impacts better than the energy analysis performs. Measures to increase energy efficiency can reduce environmental impact by reducing energy losses. Within the scope of exergy methods, such activities lead to increased exergy efficiency and reduced exergy losses (both waste exergy emissions and internal exergy consumptions) [15].

As shown in the review of the state of the art and in the literature survey, various ZEB-related definitions, in which the 'zero' is referred to the energy, the CO_2 emissions, the exergy, and the energy costs exist in the literature. In this context, the exergy-based definitions include Life Cycle Nearly Zero Exergy Building, Life Cycle Net-zero Exergy Building, Life Cycle Positive Exergy Building, Net-zero Exergoeconomic Building and Net-zero Exergoenvironmental Building. The present research applies concept of Net Zero Extended Exergy Buildings that differs from the previously conducted studies mentioned above which combines extended exergy and net zero exergy building concepts. A building where PV panels are used to generate its own electricity is considered and a net zero extended energy method was performed. Some important aspects are highlighted for the correct application of the technique and discussed. In addition, a methodology is presented for determining solar energy capacity based on the net extended exergy methods. This method can be varied and used for other renewable energy conversion systems.

2. Conventional and extended exergy analyses

2.1. Conventional exergy analysis

The magnitudes and locations of loss power connected with irreversibilities, in other words, entropy production in any system is determined through conventional exergy analysis. Some improvements can also be conducted by means of results of conventional exergy analysis. The equations of conventional exergy analysis are given in Table 1.

2.2. Extended exergy analysis

Exergy (to find total exergy destruction) is only connected with energy flows and does not consider all the effects to obtain products, such as effects of human, monetary, resource consumption and environmental issues. All the material and energy consumed (that are related to equipment setup, operation and production), human/monetary contribution and environmental impacts in processes should be added to the calculations in all analysis methods. Exergetic life cycle analysis, cumulative exergy consumption, exergoeconomic and exergoenvironmental analyses are used to calculate the whole life effects. Extended exergy analysis, extension of traditional exergy analysis, shows the main factors with the economic and human parameters, material contents, exergy and environmental remediations [16,17]. So, the extended exergy accounting is assumed in evaluating sustainability of the considered item, which combines social, economy, energy and environment as explained below. Therefore, the extended exergy accounting can be considered as exergetic input consumed to obtain an output, which consists of social, labor, economic, energetic and environmental aspects, or the so-called exergetic footprint of the system.

3. System description and data used

As a case study of the reference used for making easier the calculations, the extended exergy results were used from Ref. [18], which was related to the extended exergy analysis of the Chinese society. A building with 200 m^2 base area in Beijing/China located in 39° 54′20 "N and 116° 23′29″ E was chosen for the application. Analyses were conducted for the building generating its electricity during day time through Photovoltaic (PV) panels. When there is no sun light (namely associated solar production), the required electricity is bought from the grid. The first step of calculations is to determine the electricity load of the considered building. In the second step, energy calculation is made to meet the electricity consumption of the building and define how many panels will be used. In the third step, the extended exergy analysis is conducted for the PV system and the corresponding extended exergy value is calculated by using the values given in Ref. [19]. As shown in Tables 2 and 3, two different loads were determined for the calculations in the heating and cooling seasons.

Fig. 1 shows the heating and cooling loads during a typical day for each period. For the PV panel calculation, the days with the least irradiation rate were chosen for heating and cooling seasons to guarantee that the required electricity was generated by PV panels, which were determined on 31st October and 9th June while average ambient temperatures were 8.89 °C and 20.45 °C, respectively.

Because electricity generation during these days must be met for system permanence and extended exergy values of the electricity generated by PV panels will be already equal or bigger than the electricity taken from the grid for other days, which is already the desired output. Irradiation rates for these dates are indicated in Fig. 2.

Table 1
Conventional exergy analysis equations used in exergy method.

Equation	Parameter
$\dot{E}x_D = \dot{E}x_F - \dot{E}x_P$	$\dot{E}x_D$: Exergy destruction rate $\dot{E}x_F$: Fuel exergy rate $\dot{E}x_P$: Product exergy rate
$\varphi = \frac{\dot{E}x_P}{\dot{E}x_F}$	φ: Exergy efficiency of the system

Table 2
Explanation of the load for the heating season (adapted from Ref. [20]).

	Room Heater	Refrigerator	Computer (Laptop)	CFL Lamp (5 item)	Microwave Oven	Television (LED)	Vacuum Cleaner	Washing Machine	Air Conditioner
	(W)	(W)	(W)	(W)	(W)	(W)	(W)	(W)	(W)
	2200	300	100	75	1400	40	1400	1000	1600
Hours									
0–1									
1–2	X	x							
2–3	X	x							
3–4	X	x							
4–5	X	x							
5–6	X	x							
6–7	X	x							
7–8	X	x							
8–9	X	x							
9–10		x							
10–11		x							
11–12		x							
12–13		x							
13–14		x							
14–15		x							
15–16		x							
16–17		x							
17–18		x							
18–19		x							
19–20	X	x		x					
20–21	X	x	x	x	x	x	x		
21–22	X	x	x	x		x		x	
22–23	X	x	x	x		x			
23–24	X	x		x		x			

(*x* presents the operation of the device).

Table 3
Explanation of the load for the cooling season (adapted from Ref. [20]).

	Room Heater	Refrigerator	Computer (Laptop)	CFL Lamp (5 item)	Microwave Oven	Television (LED)	Vacuum Cleaner	Washing Machine	Air Conditioner
	(W)	(W)	(W)	(W)	(W)	(W)	(W)	(W)	(W)
	2200	300	100	75	1400	40	1400	1000	1600
Hours									
0–1		x							
1–2		x							
2–3		x							
3–4		x							
4–5		x							
5–6		x							
6–7		x							
7–8		x							
8–9		x							
9–10		x							
10–11		x							
11–12		x							
12–13		x							
13–14		x							
14–15		x							
15–16		x							
16–17		x							
17–18		x							
18–19		x							x
19–20		x	x		x	x	x		x
20–21		x	x	x		x		x	x
21–22		x	x	x		x			x
22–23		x		x		x			x
23–24		x		x		x			x

(*x* presents the operation of the device).

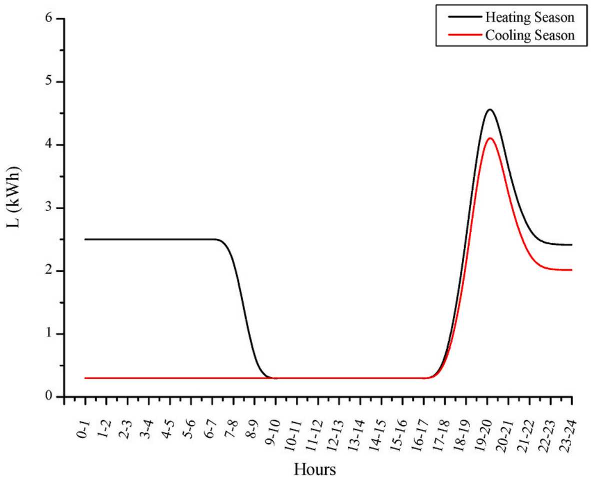

Fig. 1. Loads for heating and cooling seasons.

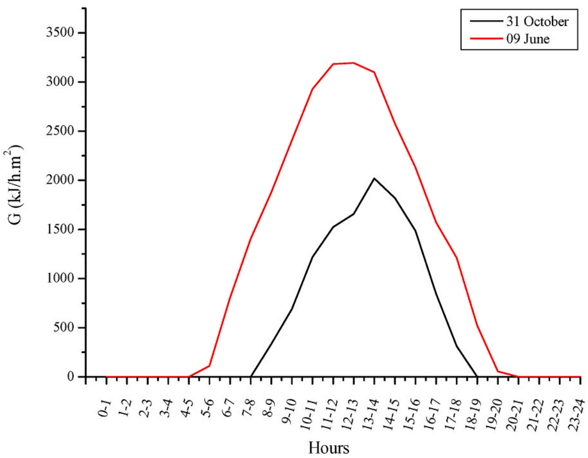

Fig. 2. Irradiation rates.

4. Methodology applied along with assumptions made

Extended exergy analysis equations for energy generation are presented in Fig. 3, which also explains the methodology applied. In calculations, the required power of the PV panel system (P_{PV}) is calculated as below.

$$P_{PV} = \eta \times A \times G \tag{1}$$

where η is the panel efficiency, A is the area of the panel (m^2) and G is the irradiation rate (kJ/m^2) and N is number of panels. In this research only electricity energy is taken into account because electric energy is equal to exergy of the electricity and therefore energy/exergy terms are equally used. Net zero exergy balance can be written as given below:

$$P_{PV} \times N = L \tag{2}$$

where L is the load (kJ) which is met by PV. Extended exergy balance is as follows where N* represents the new number of PV panels calculated by using Net Extended Exergy approach proposed by this research:

$$EExA_{PV} - EExA_{GRID} \geq 0 \tag{3a}$$

or

$$ee_{PV}A \cdot N * - ee_{GRID}.L \geq 0 \tag{3b}$$

Extended exergy values are based on the extended exergy results for the conversion sector where the electricity need of China is generated. Exergetic equivalent of the labor (1012.4 PJ), cumulative exergy consumption (35130.8 PJ), capital exergy equivalent

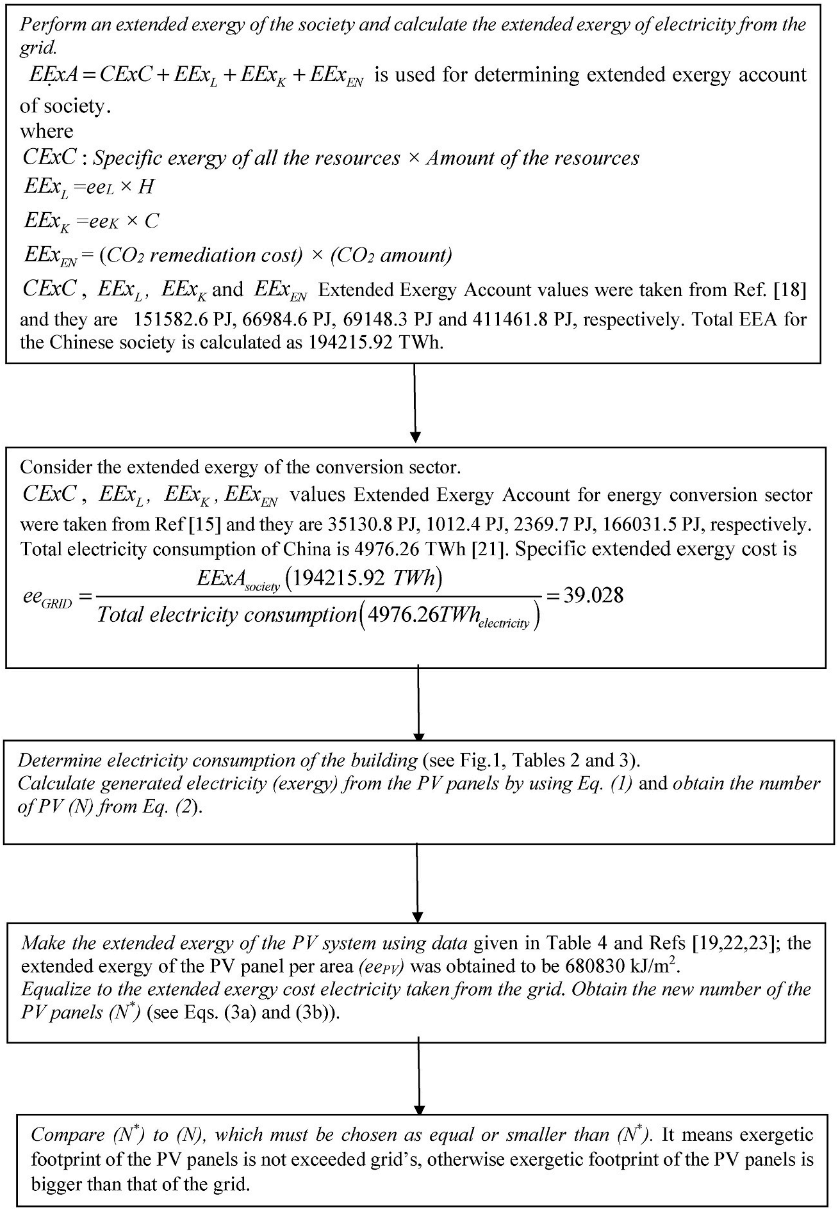

Fig. 3. Methodology for the net zero extended exergy calculation.

(2369.7 PJ) and environmental remediation costs (166031.5 PJ) for the conversion sector were taken from Ref. [18]. Using these values, the extended exergy of the generated electricity per total electricity consumption was determined while this value was used to calculate the extended exergy cost of the electricity taken from the grid, which was called as the specific extended exergy cost. At the final step, the extended exergy of the PV system was equalized with the extended exergy of the electricity of the grid and hence, the number of the required PV was determined. If this number of the required PV modules was bigger than that of the PV obtained from the energy analysis, a higher one was chosen as the real number of the PV panels. Otherwise, the number of the PV panels already obtained was chosen as the real number of the PV system.

Some assumptions made in this study are listed as follows.

a) The efficiency and the surface area of PV panels were taken as 20% and 1.95 m^2, respectively [22].
b) The yearly working hours were assumed to be 365 in calculating the exergetic equivalent of the labor.
c) The cost of one PV panel was assumed as 0.25 $/Wp [23].
d) Materials of the PV panel were taken from Ref. [19].
e) Only CO_2 emissions were taken into account in the calculations.

Parameters used in extended exergy calculations are given in Table 4. As highlighted before, extended exergy results are taken from Ref. [18] and α, β, ee_K and ee_L values were calculated for the performed analysis (see Appendix for calculations) and $\dot{E}x_{in}$ total input exergy.

The fraction of the primary exergy embodied into labor is described by α, which is used for calculating specific exergy of the labor (ee_L) in a country [24]. In this paper, ee_L is found as 0.666 MJ/Nwh being Nwh the net working hours, which can be described as exergetic equivalent of the labor per work hours in the country. Similarly, β accounts for the creation of wealth due to exclusively financial activities and is an amplification factor [24] and exergetic equivalent of the capital is obtained by means of it. It is calculated as 0.277 MJ/$ which is equivalent exergy per capital (ee_K). The specific extended exergy cost (ee_{GRID}) was calculated 39.028 TWh/$TWh_{electricty}$, which is the rate of total extended exergy to total electricity generated (see Ref. [18]) and the extended exergy of the PV panel per area (ee_{PV}) was obtained to be 680830 kJ/m^2.

5. Results and discussion

The concept of The Net Zero Extended Exergy buildings that are presented in this article is a new methodology to evaluate energy consumption in buildings. Different approaches, definitions and methods, such as zero energy buildings and net zero exergy buildings, were proposed in the literature before but no previous research exists for the present methodology. All of these focused on only one output, such as energy, exergy, economy or environmental issues or combination of them, such as exergo-economic or exergo-environmental. However, extended exergy analysis method, because of nature, consists of exergetic equivalent of material consumption, labor, capital and environment. The purpose of this methodology is to setup a balance between extended exergy of electricity from the grid and electricity generated in building. As mentioned above, the extended exergy is utilized as a measure of the sustainability and represents exergetic footprint. In this paper, exergetic footprints of the electricity generated by the PV cell and electricity from the grid are compared.

Results for the heating season can be seen in Table 5. As explained above, it is assumed that the considered building generates its electricity during the day time, except these times the required electricity is taken from the grid.

Energy (exergy) generated per area is calculated and then the required total area of PV panels is obtained. The results are listed in the fourth column as Total Energy (Exergy) Generated and the total PV required area is determined as 58.295 m^2, as seen in Table 6. This is equal to $N = 30$ (29.895) PV panel and is required to meet the electricity load in day time under the sunlight. In other words, it is calculated on the net zero energy (exergy) basis. This value is achieved for the net zero exergy method.

However, the net extended exergy approach should be checked if it is achieved or not and when someone setups the extended exergy balance using Eq. (3), the new panel number (N^*) is fixed as 16 (15.513, see Table 6). It means only 16 PV panels are enough to meet the extended exergy of the electricity from the grid. In other words, if PV panels are more than 16, its exergetic footprint is bigger than that of the electricity taken from the grid. It is concluded that N can be chosen as panel number meet the zero net exergy, however, meeting electricity by means of PV panels causes much more exergetic foot print than meeting electricity from the grid.

After calculation of the heating season, the balance for the cooling season must also be done. The results for the cooling season are illustrated in Table 7. The same methodology was applied to the previous paragraph for extended exergy balance.

According to the results, the number of panels (N) calculated by using net exergy approach is equal to 66. The number of panels (N^*) calculated by using net extended exergy approach proposed in this paper is obtained as 7 (6.278, as shown in Table 8). The results show that the number of PV panel should be chosen as N. Finally, comparing the results for heating and cooling seasons, the number of PV panels is chosen to be 34.

However, the same conclusion is obtained as given in the previous paragraph, which means exergetic footprint of the PV panel is much greater than the electricity from the grid. The most important point is that because PV panels are mounted, their exergetic footprint is taken into account and only exergetic footprint is this value during its life cycle. However, electricity taken from the grid causes continuous exergetic footprint. In this study, calculations have been conducted for the maximum and minimum conditions and it means that 68 PV panels have more exergetic footprints than the grid, yet it is much more advantageous during its life time.

Figs. 4–6 along with Tables 5 and 7 illustrate a comparison of the results of heating and cooling seasons.

The delivered energy/exergy values in the heating period are bigger than those in the cooling period. So, it shows that energy taken from the grid is bigger for the heating season. When taking a look into the energy generation, one can see that much more electricity is generated. It is an expected result since solar irradiation reaches the maximum in the summer time. EEA_{Gird} values are similar to the delivered energy values, which are the extended exergy.

Here, a brief discussion is made. In the literature, there are various methods, such as nearly zero energy building, net zero site energy building, net zero energy emissions building, net zero source energy building, net zero energy costs building, net zero exergy building, net zero exergy district, net zero exergoeconomic building and net zero exergoenvironmental building and we need a better understanding on exergy-based approaches. In Ref. [13], net zero exergy building concept was claimed not to be technically feasible because of requiring large surface area. It is also stated that it is not sensitive to the grid/renewable energy and energy consumption pattern. Net zero exergoenvironmental building method was not found suitable since it has problems in terms of sensitivity to energy

Table 4
Parameters used in calculations.

A	β	ee_K (MJ/$)	ee_L (MJ/Nwh)	Ex_{in} (PJ)
0.0066	2.341	0.277	0.660	153413.4

Table 5
Results for the heating season.

Hours	Load (kJ)	Energy (Exergy) Generated (kJ/m^2)	Total Energy (Exergy) Delivered (kJ)	Total Energy (Exergy) Generated (kJ)	EEA_{Grid} Total (kJ)
0	9000	0	9000	0	351252.000
1	9000	0	9000	0	351252.000
2	9000	0	9000	0	351252.000
3	9000	0	9000	0	351252.000
4	9000	0	9000	0	351252.000
5	9000	0	9000	0	351252.000
6	9000	0	9000	0	351252.000
7	9000	0	9000	0	351252.000
8	1080	66.629	0	4397.512	0
9	1080	138.092	0	9114.085	0
10	1080	243.950	0	16100.670	0
11	1080	304.866	0	20121.177	0
12	1080	331.297	0	21865.595	0
13	1080	403.674	0	26642.458	0
14	1080	363.673	0	24002.426	0
15	1080	297.262	0	19619.264	0
16	1080	168.853	0	11144.273	0
17	1080	62.354	0	4115.335	0
18	8550	0	8550	0	333689.400
19	19134	0	19134	0	746761.752
20	12654	0	12654	0	493860.312
21	9054	0	9054	0	353359.512
22	8694	0	8694	0	339309.432
23	8694	0	8694	0	339309.432

Table 6
Number of PV panels calculated for the heating season.

	Required Total Area (m^2)	Number of PV
Energy/Exergy Balance	58.295	29.895 *(N)*
EEA Balance	7.955	15.513 *(N*)*

Table 7
Results for the cooling season.

Hours	Load (kJ)	Energy/Exergy Generated (kJ/m^2)	Total Energy/Exergy Delivered (kJ)	Total Energy/Exergy Generated (kJ)	EEA_{Grid} Total (kJ)
0	1080	0.000	1080.000	0	42150.240
1	1080	0.000	1080.000	0	42150.240
2	1080	0.000	1080.000	0	42150.240
3	1080	0.000	1080.000	0	42150.240
4	1080	0.000	1080.000	0	42150.240
5	1080	22.320	0.000	1473.120	0.000
6	1080	160.679	0.000	10604.828	0.000
7	1080	281.306	0.000	18566.178	0.000
8	1080	375.036	0.000	24752.389	0.000
9	1080	481.457	0.000	31776.140	0.000
10	1080	585.731	0.000	38658.261	0.000
11	1080	636.590	0.000	42014.911	0.000
12	1080	638.733	0.000	42156.356	0.000
13	1080	619.840	0.000	40909.432	0.000
14	1080	515.626	0.000	34031.348	0.000
15	1080	425.976	0.000	28114.449	0.000
16	1080	313.963	0.000	20721.553	0.000
17	1080	242.275	0.000	15990.166	0.000
18	6840	104.470	0.000	6895.000	0.000
19	17424	0.000	17424.000	0	680023.872
20	11214	0.000	11214.000	0	437659.992
21	7614	0.000	7614.000	0	297159.192
22	7254	0.000	7254.000	0	283109.112
23	7254	0.000	7254.000	0	283109.112

Table 8
Number of PV panels calculated for the cooling season.

	Required Total Area (m^2)	Number of PV
Energy/Exergy Balance	127.673	65.899 *(N)*
EEA Balance	3.219	6.278 *(N*)*

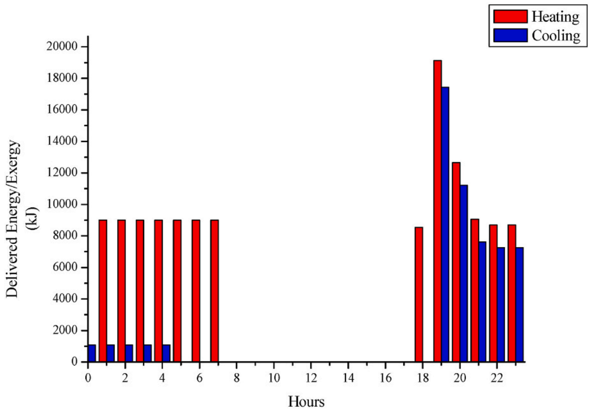

Fig. 4. Energy/exergy values delivered for the heating and cooling seasons.

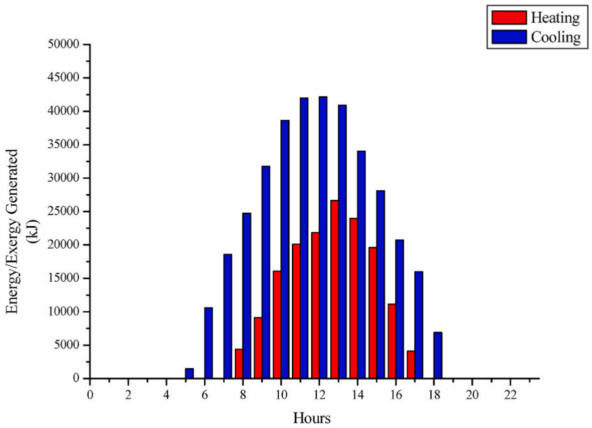

Fig. 5. Energy/exergy generated for the heating and cooling seasons.

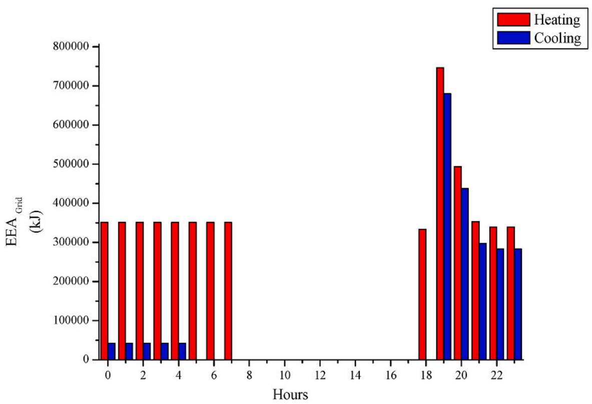

Fig. 6. EEA_{Grid} values for the heating and cooling seasons.

consumption patterns and grid emission factor [13]. Net zero exergoconomic building concept was found more suitable for developing sustainable buildings in terms of adapting energy consumption parameters, technical feasibility, variations in grid/renewable energy parameters, economic profitably and environmental impact [13]. In Ref. [14], it was reported that the net zero extended exergy approach was sufficiently sensitive to changes in the energy load profile and the energy network and renewable energy system parameters and it can be said that it is the best approach for developing sustainable buildings in all methods. However, it should be careful when using these methods. Considering the net zero extended exergy method proposed in this paper, based on the results, the number of the PV panel may not meet the electricity need instantly. These methods should be applied after checking if energy need of the building is met. The desired methods should be utilized and all the results must be interpreted together. In addition, if exergetic footprint of any renewable energy system is more than the electricity from the grid, the values during the life time must be compared to each other. Another aspect is that the extended exergy method provides a better point of view to assess sustainability. As seen above, the extended exergy method enables us to compare any system's exergetic footprint with another one.

6. Conclusions

This study aims at presenting a new methodology, the so-called Net Zero Extended Exergy buildings. The method includes exergetic equivalent of the material consumption, labor, capital and environmental aspects as a whole while the target is to setup a balance in all these aspects. The proposed methodology is applied to a building in Beijing, China for heating and cooling seasons. Calculations are made for the least irradiation rate conditions to guarantee that the required electricity is generated by PV panels.

Some concluding results drawn from the results of the present study may be listed as follows.

a) For heating season, N and N^* are determined as 30 and 16, respectively.
b) For cooling season, N and N^* are calculated as 66 and 7, respectively.

According to these results N should be chosen as 66 because it is the maximum number of the PV panels. This number of PV panels is adequate to meet electricity of the building. This also concludes that the extended exergy of the electricity generated by PV panels is bigger than the extended exergy of the electricity taken from the gird. These means more than all the aspects including material consumption, labor, capital and the environmental impact are met. Although, the extended exergy method shows that using PV panels to meet electricity is not as sustainable as meeting electricity from the grid because the exergetic footprint of the PV panels is much higher than the electricity taken from the grid in first glance, this value is just for one time (when it was mounted), however exergetic footprint of the electricity is exposed every time it is used. equivalent to meet energy taken from the grid. The maximum value of the extended exergy account taken from the grid reaches about 750000 kJ. Some advantages and disadvantages of this method can be listed as follow.

- It can provide a better and deep sight and results in terms of sustainability, since it consists of many parameters like environmental, economic, social and natural resource consumption.
- It enables to determine exergetic footprint of any considered system, since all parameters mentioned above are converted into exergetic equalivents and it enables us a cumulative approach.
- Some Disadvantages of the system can be mentioned as calculation of the methodology is a bit complex because of many parameters taken into account and it must be careful about if the system meets provide power enough.

For future research and studies, it is recommended that this methodology should be utilized for buildings with different renewable energy generation while the results should be compared to other similar methods in the literature.

CRediT author statement

Emin Açikkalp: Conceptualization, Methodology, Software, Writing, Original Draft Preparation. **Arif Hepbasli**: Conceptualization, Methodology, Software, Writing, Original Draft Preparation. **Ana I. Palmero-Marrero**: Writing, Validation, Original draft preparation. **David Borge-Diez**: Writing, Original draft preparation, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix

Calculations of α, β, ee_K and ee_L [18] are performed for the values taken from Ref. [18] as follows:

$$\alpha = \frac{EEx_L}{Ex_{in}} = \frac{1012.4}{153413.4} = 0.0066$$

$$\beta = \frac{EEx_K}{EEx_L} = \frac{2369.7}{1012.4} = 2.341$$

$$ee_L = \frac{\alpha \times Ex_{in}}{Nwh} = \frac{0.0066 \times 153413.4}{767040000 \times 2000} = 0.660 \frac{MJ}{Nwh}$$

where *Nwh* cumulative number of work-hours generated by a society. It is obtained by multiplying total number of workers in society (767040000 [21]) and working hours per year which is assumed as 2000 h/year.

$$ee_K = \frac{\alpha \times \beta \times Ex_{in}}{M2} = \frac{0.0066 \times 2.341 \times \left(153413.4 \times 10^9\right)}{8539584000000} = 0.277 \frac{MJ}{\$}$$

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