Examination of life cycle cost in nZEB design

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Abstract. In this paper, the feasibility and net present value of life cycle cost (LCC(NPV)) of nZEB under the meteorological conditions of Sapporo, Japan was examined for the model building. The procedure for examining the feasibility of nZEB is as follows. First, a building with envelope and equipment that meets the performance standards of the Japanese Building Energy Conservation Law is set as a reference building. Then the energy performance improvement measures of strengthening the thermal insulation performance, installing energy-saving lighting equipment, improving the efficiency of the heat source, installing the total heat exchanger, a combined heat and power and PV power generation were applied in order of cost effectiveness. And the change in LCC(NPV) was calculated. When all measures except PV power generation and ground source heat pump were adopted, the primary energy consumption was reduced by about 53%, which reached the level of ZEB Ready in Japan's ZEB evaluation. Furthermore, the installation of PV power generation reduced the primary energy consumption to about 25%. This is a nearly ZEB in Japan's ZEB evaluation. The point of becoming the cost optimum (minimum LCC(NPV)) was the level at which the primary energy consumption was about 50%. From this result, it was possible to show the importance of deciding the policy of ZEB while considering energy consumption and LCC(NPV) at the same time.

Keywords. Life cycle cost, nZEB, Net present value.
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1. Introduction

International joint research by the Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) and The Society of Heating, Air-Conditioning and Sanitary Engineers of Japan (SHASE) started in April 2018. In this joint research, we are conducting research on the comparison of energy performance of nearly zero energy buildings (hereinafter, nZEB) in countries with different climates.

So far, we have examined the methods of comparing the energy performance of nZEB and confirmed the difference in the conditions of energy performance evaluation between Europe and Japan. Then, a model building was defined, and a method for comparing the energy requirement performance of nZEB under different conditions was examined [1)].

The move toward a carbon-free society has become a global trend, with the EU Green Deal “Achieving Climate Neutrality in 2050” in 2019, the “Net Zero Emissions of Greenhouse Gases by 2050” in the Byden Plan and China's “carbon neutrality by 2060” in 2020. And in Japan, in October 2020, former Prime Minister Suga declared that "Japan aims to reduce greenhouse gas emissions to zero as a whole by 2050, that is, to realize a carbon-neutral, carbon-free society in 2050."

At COP26 held in Glasgow, England in 2021, in order to pursue efforts to limit the temperature increase to 1.5℃ above pre-industrial levels, contracting parties were urged to take measures against carbon neutrality in the middle of this century and ambitious climate change toward 2030. In parallel with these, the greenhouse gas or CO_2 reduction targets of each country were strengthened, and in October 2021, the Global Warming Prevention Headquarters decided the strengthened Nationally Determined Contribution (NDC) of Japan, as "Japan aims to reduce its greenhouse gas emissions by 46 percent in fiscal year 2030 from its fiscal year 2013 levels, setting an ambitious target which is aligned with the long-term goal of achieving net-zero by 2050. Japan will continue strenuous efforts in its challenge to meet the lofty goal of cutting its emission by 50 percent. "The breakdown of 46% is 51% in the Commercial and others sectors and 66% in the

Residential sector, and these reduction targets are very strict compared to other sectors. Furthermore, in the "Green Growth Strategy for 2050 Carbon Neutral" announced in December 2020, " The houses/building field is a key field for carbon neutrality in the home/business sector, and once built, becomes a long-term stock; and is a field that should be addressed immediately." Then the spread of ZEH and ZEB is mentioned as a priority issue.

ZEB's design flow begins with reducing the load of air conditioning, lighting, etc. as much as possible by making full use of architectural energy saving measures (passive measures) while maintaining indoor thermal comfort. Building service such as highly efficient air conditioning systems and artificial lighting is applied to this reduced load and active renewable energy utilization (energy creation) to aim net zero level. And in the actual design, while these flows are the basis, various energy saving methods should be introduced after careful consideration of cost benefits in order to realize nZEB at an appropriate cost. In addition, the final decision should be made after understanding the optimal cost level while considering changes in energy consumption and life cycle cost.

Based on the above background, this paper examined the feasibility and life cycle cost of nZEB under the meteorological conditions of Sapporo, Japan, for the model building adopted in previous paper [1)] as part of the international joint research.

2. Method

2.1 model building, input data and BEI

Figure 1 shows a reference building model [1)], which has a net floor, envelope and window areas of 4451.8 m^2, 3993.9 m^2 and 1326 m^2, respectively. The reference building is used as an office building in Sapporo , Japan and its input data is shown in Table 1. The heating degree day of Sapporo is 2,267 (2021,IWEC weather data) and the cooling degree day is 687.

Figure 2 shows the definition of Japanese ZEB according to the present regulation. Energy performance requirements in Japan are regulated by BEI indicator, which is the ratio of design and standard value representing so-called reference-building method. BEI = 1.0 is the minimum requirement and BEI = 0.5 is set for ZEB Ready with the aim to reduce primary energy by 50% compared to the present energy requirement. Primary energy includes energy uses for HVAC, domestic hot water and lighting. The standard value of primary energy is determined by multiplying the reference factor by each floor area and summing them. The reference factor for each energy use has been defined depending on the 8 climate regions, 8 building types, and 201 room types. The reference value for HVAC is estimated according to the heat load calculated based on the input data as shown in Table 1. Official tool, WEBPRO is used to simulate the standard value as well as the designed value. WEBPRO has been produced by the Japanese National Building Research Institute [2)3)].

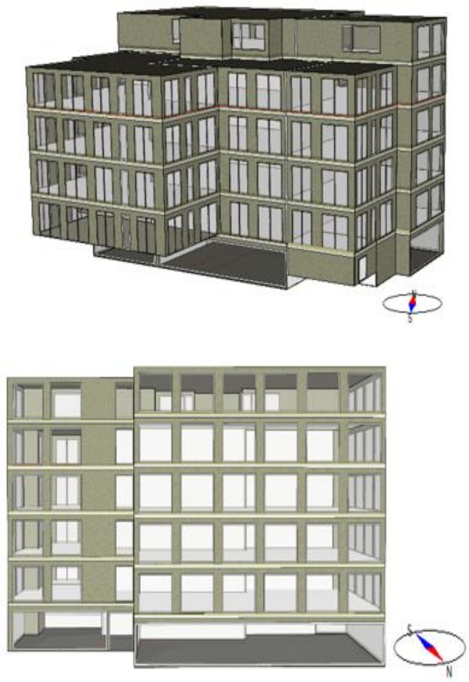

Fig.1 Views of simulated reference building model

Tab. 1 Input data for the reference building

Input data	[a]Japan (Sapporo)
Occupant, m^2/person	10
Appliances, W/m^2	12
Lighting, W/m^2	[b]16.3/7.5
Air volume flow by re-circulation, m^3/h. m^2	[c]17.1
Appliances & lighting operation hour	8:00-21:00
Usage factor	0.89
DHW, l/m^2 a	91.58
Fan operation hour	7:00-21:00
Ventilation rate, l/m^2 s	1.39
Heating set point, °C	22
Cooling set point, °C	26

[a] Relative humidity during heating season should not be less than 40% and not more than 50% during cooling season;
[b] Lighting power for 2016 and ZEB ready are 16.3 and 7.5 W/m^2, respectively;
[c] Re-circulation was used only with 2016 regulation and was not applied to Japanese nZEB

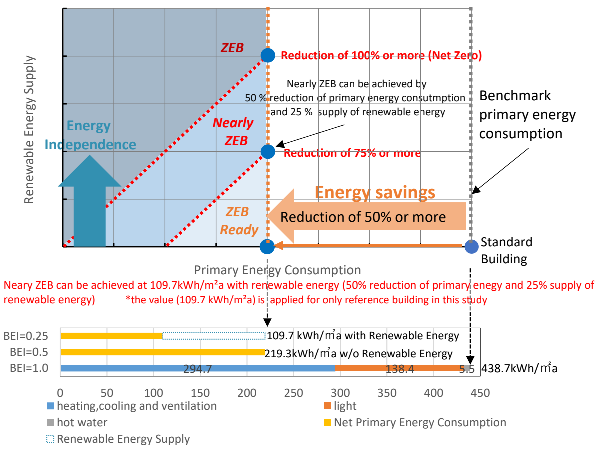

Fig. 2 Energy performance of reference building according to present regulation

2.2 calculation method for energy consumption

In this subsection, the reference building and system specification and the energy conservation measures are described.

Energy performance of the reference building were estimated with using the WEBPRO. Table 2 shows the building and system specifications for baseline calculation with input data listed in table 1. BEI for the baseline for further analysis is 0.98.

Tab. 2 Building properties and system specification for baseline with BEI=0.98

Building properties	
U- value (Outer wall) [W/㎡K]	0.32
U-value (Roof)	0.61
U value (Windows)	2.8
Solar radiation heat acquisition rate [-]	0.79
Systems	
specifications	**Installed number**
Air- source heat pump Cooling/Heating capacity: 252 kW/513kW COP for cooling/Heating : 3.23/2.95 Primary circulation pump: 11.7 kW	2
Secondary pump 31.4㎥/h, 4.8kW (constant water flow)	2
Outdoor air handling unit Cooling/Heating capacity: 106kW/280kW 13268㎥/h (CAV), 11kW for fan Total heat exchanger efficiency:60%	1
Fan coil unit Cooling/heating capacity:2.5kW/4.2kW	225
Gas-fired hot water supplier Capacity: 2.0 kW, primary energy efficiency: 0.66	6

In this study, 10 energy conservation measures are applied to the design building; 1) better performance of insulation and windows, 2) lower hot water supply temperature for heating, 3) LED lighting and its control, 4) installing higher performance of domestic hot water supplier, 5) installing higher performance of heat source equipment, 6) installing higher efficiency of total heat exchanger, 7) variable volume control of secondary pump, 8) installing CHPs, 9) installing PV on the roof, and 10) installing ground source heat pump (hereafter, GSHP).

1) Insulation and windows

The U-value of the outer wall and roof for the baseline is 0.61 w/㎡K and 0.32 W/㎡K respectively. The improved value for the outer wall and roof is 0.27 and 0.18 W/㎡K respectively.

The U-value of windows for the baseline is 2.8 W/㎡K, and the solar radiation heat acquisition rate is 0.79. The improved U- value and solar radiation heat acquisition rate are 0.82 and 0.33 respectively.

2) Lower hot water supply temperature for heating

The setpoint of hot water supply temperature for heating for baseline case and energy conservation case is 45℃ and 40℃ respectively.

3) LED lighting and its control

As shown in Table 1, the internal heat gain from lighting equipment was reduced from 16.3W/m² to 7.5 W/m². In this study, time schedule control, illuminance control, human presence control, and function of illuminance initial correction are installed as energy conservation measures.

4) Higher performance of domestic hot water supplier

The primary-energy- based efficiency of the gas-fired hot water heater is improved from 0.66 to 0.9. In addition, the piping is insulated as energy conservation measures.

5) Higher performance of heat source equipment

Table 3 listed the specification of the heat source for energy conservation case. For the baseline case, two air-source heat pumps are installed shown in table 2. For the energy conservation case, 10 air-source module heat pumps are adopted in order to operate with higher efficiency when the cooling/heating heat load is small.

Tab. 3 Specification for the heat source for the energy conservation case

Specifications	**No.**
Air-source module heat pump Cooling/Heating capacity: 53.6 kW/53.6kW COP for cooling/Heating : 4.12/4.19 Primary circulation pump: 0.375 kW	10

6) Higher efficiency of total heat exchanger

For the baseline case, the efficiency of total heat exchanger is 60%. To achieve high efficiency of total heat exchanger, the bigger size of the total heat exchanger is selected and the face velocity is reduced. The value is improved to 77% for the energy conservation case.

7) Variable volume control of secondary pump

For the baseline case, the variable volume control of secondary pump is not installed, in other word, the water flow volume of secondary pumps is constant. For the energy conservation case, the variable volume control of the secondary pumps is installed and its minimum frequency ratio is set at 30%.

8) CHPs

For the baseline case, CHPs are not installed. For the energy conservation case, a CHP is installed listed in table 4. The exhaust hot water from a CHP is utilized for heating in winter. In summer, exhaust hot water from the CHP is not used.

Tab. 4 specifications of CHP

Installed number	1
Electricity [kW]	34
Power generation efficiency [%]	33.5
Exhaust hot water generation efficiency [%]	54.5

9) PV on the roof

Crystalline photovoltaics on the roof are installed for the case, the capacity of which is 131kW, facing the south. Its angle of inclination is 43°. The efficiency of the power conditioner is 0.93.

10) GSHP

Two out of 10 air source module heat pumps are replaced with GSHP. Table 5 shows the specification of GSHP. The length of the total ground source heat exchanger is 2000m with 25 boreholes (80m/each borehole).

Tab.5 Specification of GSHP

Installed number	2
Capacity (cooling/heating) [kW/each]	41.2/46.4
COP (cooling/heating)	5.42/4.18
Circulation volume of chilled/hot water [l/min/each]	118/133
Circulation volume for ground sour heat exchanger (cooling/heating) [l/min/each]	139/101
Electricity consumption of primary pump [kW/each]	0.4
Electricity consumption for ground source heat exchanger pump [kW/each]	0.75

For the estimation of energy consumption for the case with GSHP, LCEM tool [4)5)6)] is used for considering the actual performance of GSHP based on the cooling and heating load provided by the WEB-Based program.

2.3 Cost-effectiveness calculation

The cost-effectiveness of different energy conservation measures was estimated with net present value of life cycle cost (hereafter, LCC(NPV)) defined with eq.(1) to eq.(3). In the paper [7)], maintenance cost was not included in the economic calculation, however, in this study, maintenance cost is considered for each conservation measure.

$$C_{g(t)} = C_i + \sum_{i=1}^{15} \left(C_{ao,i} \times R_d(i)\right) + C_m \qquad eq.(1)$$

where t means the calculation period (in this study 15 years), $C_{g(t)}$ is total cost over the calculation period t [YEN], C_i is initial investment cost for a measure or a set of measures [YEN], $C_{ao.i}$ is annual operation energy cost during year i [YEN], Rd(i) is a discount factor for year i, C_m is maintenance cost [YEN].

Depending on the refurbishment of the systems, the cost-effectiveness calculation period was chosen to be 15 years.

$$C_m = K0 \times C_i \qquad eq.(2)$$

where K0 is the maintenance cost factor (=0.02).

The cost-effectiveness of the additional costs related to each energy conservation measure that was needed to meet the requirement of the nearly ZEB was assessed in these calculations.

$$\nabla \mathrm{LCC(NPV)} = \frac{\left(C_{g(t)}^{nZEB} - C_{g(t)}^{ref}\right)}{A_{floor}} \qquad \mathrm{eq.}\,(3)$$

where, $C_{g(t)}^{nZEB}$ is global energy performance related cost included in the calculations of nZEB [YEN], $C_{g(t)}^{ref}$ is global energy performance related cost included in the calculations of reference building [YEN], and cooled/heated net floor are [㎡].

Initial additional costs compared to the baseline case for each conservation measure are estimated as follows.

1) Insulation and windows

$$dC_{ins} = (C1_{ins} - C0_{ins}) \times S \times (1 + k1) \times (1 + k2) \mathrm{eq.}\,(4)$$

where, dC_{ins} is an additional cost for insulation [Yen], $C1_{ins}$ is a unit price with insulation 100mm [Yen/㎡], $C0_{ins}$ is a unit price with insulation 50mm [Yen/㎡], S is an area of outer walls and ceiling, K1 is delivery cost ratio (0.1) and K2 is expense ratio (0.2).

$$dC_{wind} = (C1_{wind} - C0_{wind}) \times S \times k3 \quad \text{eq. (5)}$$

where, dC_{wind} is an additional cost for window glazing and flame [Yen], $C1_{wind}$ is a unit price with both windows and its sash for baseline case [Yen/㎡], $C0_{wind}$ is unit price with both window glazing and its flame for improved case [Yen/㎡], K3 is expense ratio.

Improving the thermal performance of the building envelope is expected to decrease the heat load and thus HVAC equipment capacity. However, this study does not consider the cost reduction due to the reduction in equipment capacity.

2) Lower hot water supply temperature for heating

There is no additional cost for this energy conservation measure.

3) LED lighting and its control

The additional cost for LED lighting and its control is set with the reference to the result of a similar project.

4) Higher performance of domestic hot water supplier

The additional cost for higher performance of domestic hot water supplier is set with the reference to the result of a similar project.

5) Higher performance of heat source equipment

The additional cost for higher performance of heat source equipment is set with the reference to the result of a similar project.

6) Higher efficiency of total heat exchanger

The additional cost for higher efficiency of the total heat exchanger is provided based on the quotation by the general contractor.

7) Variable volume control of secondary pump,

The additional cost for higher efficiency of the total heat exchanger is provided based on the quotation by the general contractor.

8) CHPs

$$dC_{CHP} = C1_{CHP} \times CAP_{CHP} \quad \text{eq. (6)}$$

where, dC_{CHP} is the additional cost for CHP [Yen], $C1_{CHP}$ is the unit price per capacity of CHP, CAP_{CHP} is the electrical capacity of CHP .

9) PV on the roof

$$dC_{PV} = C1_{PV} \times CAP_{PV} \quad \text{eq. (7)}$$

where, dCpv is the additional cost for PV [Yen], C1pv is the unit price per capacity of PV, CAPpv is the capacity of PV.

10) Ground source HP

$$dC_{gshp} = C1_{gshp} + C1_{boreholes} \times L_{boreholes} + C1_{hspump} \quad eq.(8)$$

where, dC_{gsgp} is the additional cost for GSHP, $C1_{gshp}$ is the cost for ground source HP itself, [Yen], $C1_{boreholes}$ is the unit price for digging boreholes, pile construction and piping work [Yen/m], $L_{boreholes}$ is the total length of the boreholes [m] and $C1_{hspump}$ is an additional cost for circulation pump of heat source water.

$C1_{gshp}$ is assumed to be zero because, as indicated in section 2.2. 10), two out of ten air source heat pump is replaced with ground heat source, therefore, there is no additional cost for GSHP itself.

2.4 Evaluation Indices

BEI and primary-energy-based energy consumption are the indices to evaluate the building energy performance. In this study, the order of applying energy conservation measures is followed by the philosophy of nZEB that passive design measures must be prioritized. In the evaluation, the energy conservation measure for building property including better insulation and windows is the first measure to apply. Then, the energy conservation measure will be adopted in the order of the lowest pay-back year.

The cost-effectiveness of different solutions was estimated using LCC(NPV) described in 2.3.

3. Results and discussion

Figure 3 shows the results of BEI for baseline case and energy conservation cases. The value in parentheses shows the annual unit energy consumption [kWh/m^{2}year]. The number in the square brackets from one to ten means applied set of energy conservation measures as listed in table 6. The effect of the energy consumption is accumulated from baseline (BL), that is, in the example, the value 0.92 is the results of installing better insulation and windows and lower hot water supply temperature for heating.

The figure indicates that a set of the energy conservation measures including better performance of insulation and windows, lower hot water supply temperature for heating, LED lighting and its control, high performance of domestic hot water supplier, high performance of heat source equipment, and high efficiency of total heat exchanger does not achieve BEI=0.5 (ZEB ready). In addition to the above measures, when the energy conservation measures including variable volume control of secondary pump, installation of CHP, PV and GSHP can achieve BEI=0.26 which is certified by almost Nearly ZEB. These results show that it is necessary to apply the further energy conservation measure to achieve nZEB requirement [BEI=0.25] in

Japan. In other words, it shows that Japanese nZEB requirement is ambitious requirement.

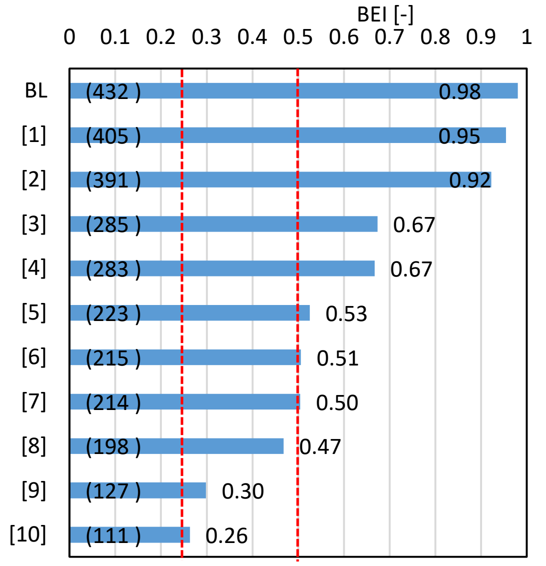

Fig. 3 Results of the BEI

Tab. 6 List of the set of energy conservation measures

Num.	set of energy conservation measures
[1]	Higher insulation and better windows
[2]	[1] and lower hot water supply for heating
[3]	[2] and LED lighting and its control
[4]	[3] and higher performance of domestic hot water supplier
[5]	[4] and higher performance of hear source
[6]	[5] and higher efficiency of total heat exchanger
[7]	[6]and variable volume control of secondary pump
[8]	[7] and CHPs
[9]	[8] and PV on the roof
[10]	[9] and GSHP

Table 7 shows the summary of the BEI, simple pay-back years, energy reduction cost of operation, construction cost, operation cost for 15 years and maintenance cost.

As shown in 2.4, although the simple pay-back years for better insulation and windows (27 years) is longer than some of the other energy conservation measures, it is first adopted to the baseline case as priority. The longest simple pay-back years is marked at installing GSHP because the digging cost is calculated based on a conservative unit price which might be significantly lower due to technological innovation, in addition because of the underestimating of energy-saving amount by replacing conventional heat source equipment to GSHP, because the ASHP module of the LCEM-tool used in this study does not consider the performance characteristic while the ASHP is under the defrost operation. As indicated in section 2.3, the calculation period in this study is 15 years. Insulation, windows and boreholes for GSHP have longer lifespan than 15 years, therefore these simple pay-back years are underestimated. Figure 4 shows the relation between accumulated reduction of operation cost and accumulated initial cost. From the case introducing lower hot water supply temperature for heating to the case installing CHP, their effects on accumulated reduction of operation cost is relatively high. PV on the roof has large impact both initial cost and operation cost.

Figure 5 shows the relation between LCC(NPV) and primary energy consumption. The lowest value of LCC(NPV) is marked at almost BEI=0.5, which means it would be certified by ZEB ready. In this study, the non-energy benefits of the improved thermal performance of the building envelope regarding thermal comfort are not considered. If these benefits are considered, the increase in LCC(NPV) due to that in the figure may be different. And the BEI with minimum LCC(NPV) was 0.5 as a result of prioritizing the installing enhanced thermal performance of building envelope, but different results would be derived depending on this priority.

From the viewpoint of the balance between BEI and LCC(NPV), construction of buildings with the level of ZEB ready is estimated by the lowest LCC(NPV). And it is expected that Nearly ZEB would be achieved at the similar level of LCC(NPV) of BL case.

As for the level of Nearly ZEB with BEI=0.25, the value of LCC(NPV) gets high because of the increase of initial cost. So, it should be needed that LCC(NPV) considers not only energy-benefits but also none energy-benefits to encourage the motivation to achieve ZEB further

4. Conclusion

In this paper, as part of the international joint research, the feasibility and LCC(NPV) of nZEB under the meteorological conditions of Sapporo, Japan was examined for the model buildings.

The procedure for examining the feasibility of nZEB is as follows. First, a building with envelope and equipment that meets the performance standards of the Japanese Building Energy Conservation Law is set as a reference building. Then the energy performance improvement measures of strengthening the thermal insulation performance, installing energy-saving lighting equipment, improving the efficiency of the heat source, installing the total heat exchanger, a combined heat and power, and PV power generation were applied in order of cost effectiveness. And the increase of LCC(NPV) was calculated.

When all measures except PV power generation and GSHP were adopted, the primary energy consumption was reduced about 53%, which reached the level of ZEB Ready in Japan's ZEB

Tab. 7 summary of the BEI, simple pay-back years, energy reduction cost of operation, operation cost for 15 years, and maintenance cost. The vaues of cost for BL are the reference, therefore each cost is to be zero.

	primary energy consu-mption	BEI	Invest-ent: P	Effect: M	P/M	Accumul-ated initial cost	Accum-ulated reducti-on cost of operati-on	Operati-on cost for 15 years	Mai-ntenan-ce cost	SUM
			Additio-nal initial cost	Reducti-on cost of operati-on	Simple pay-back years					
	kWh/m² a	-	Yen/m²	Yen/m²	year	Yen/m²	Yen/m²	Yen/m²	Yen/m²	Yen/m²
BL	432	0.98	0	0	0	0	0	0	0	0
a[1]	405	0.95	6014	220	27	6014	220	-3,051	120	3,083
a[2]	391	0.92	0	108	0	6014	328	-4,548	120	1,586
a[3]	285	0.67	570	836	1	6584	1164	-16,145	132	-9,429
a[4]	283	0.67	27	21	1	6611	1185	-16,435	132	-9,692
a[5]	223	0.53	884	476	2	7495	1662	-23,040	150	-15,395
a[6]	215	0.51	840	64	13	8335	1726	-23,925	167	-15,424
a[7]	214	0.50	100	5	19	8435	1731	-23,997	169	-15,394
a[8]	198	0.47	1910	124	15	10345	1855	-25,713	207	-15,161
a[9]	127	0.30	17656	568	31	28001	2423	-33,593	560	-5,032
a[10]	112	0.26	6811	114	60	34812	2537	-35,177	696	331

[a] the number in brackets are listed in table 6

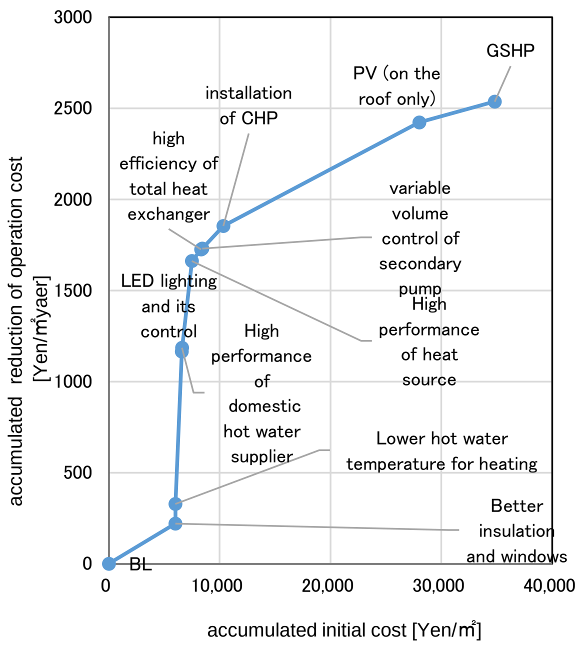

Fig. 4 the relation between accumulated initial cost and accumulated reduction of operation cost

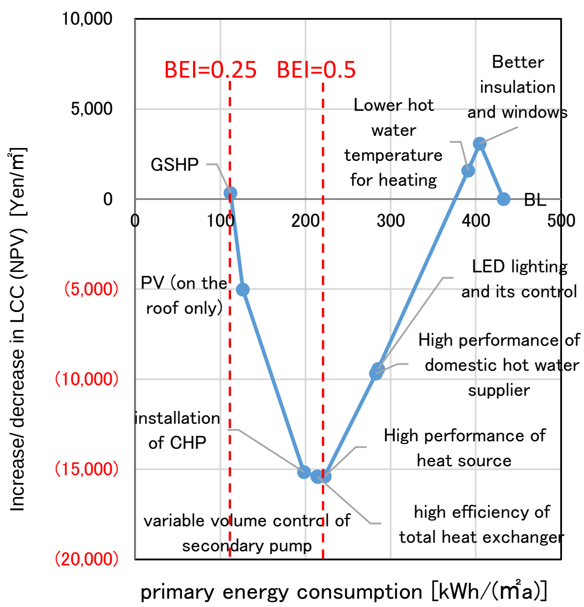

Fig. 5 relation between increase/decrease in LCC(NPV) and primary energy consumption.

evaluation. Furthermore, the installation of PV power generation reduced the primary energy consumption to about 25%. This is a nearly ZEB in Japan's ZEB evaluation.

The point of achieving the cost optimum (minimum LCC(NPV)) was the level at which the primary energy consumption was about 50%, marked at almost BEI=0.5, which means it would be certified by ZEB ready. And it is expected that Nearly ZEB would be achieved at the similar level of LCC(NPV) of BL case. From this result, it could be said that policy initiatives such as financial support are needed to raise motivation to achieve ZEB. Several research is also being conducted on the multiple benefits of energy efficiency improvement and the co-benefit of ZEB[8)9)10)]. Therefore, as the next step of the study, in addition to the LCC(NPV) composed of initial cost and energy cost, the co-benefits such as thermal comfort, air quality, increased productivity, lower staff turnover, and reduced sick leaves will be considered for the evaluation of ZEB.

The specific values of energy performance and cost shown in this study depend on the conditions of the country or region such as weather conditions, material costs, labor costs, and manufacturing costs. On the other hand, these results show that the feasibility study and the LCC(NPV) analysis are very helpful measure to qualitatively and quantitatively understand how ambitious ZEB requirement are under the different climate and other conditions. In addition, these analyzes can be performed by utilizing simulation tools that are usually used in each country.

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