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PROPOSING BUILDING DRIVEN-ENERGY PAYBACK TIME AS A NEW LIFE CYCLE ASSESSMENT INDICATOR

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ABSTRACT

This study proposes building driven-energy payback time (BD-EPBT) as a new life cycle assessment indicator. The BD-EPBT is the time required to outrun the total life cycle energy used in a power system-integrated building with annual surplus energy. As a result of a case study, it was shown that the BD-EPBT is highly associated with the embodied energy of construction materials. Also, by increasing the power system capacity (i.e., PV system) from 3 kW to 5 kW, BD-EPBT can be reduced by one fifth. The BD-EPBT is a novel concept capable of providing comprehensive analytics solutions to energy decision problems for building owners.

Keywords: energy payback time (EPBT), life cycle assessment (LCA), life cycle energy (LCE), renewable energy resources, energy conservation in buildings, energy systems for power generation

NONMENCLATURE

Abbreviations	
DB-EPBT	Building driven-EPBT
D&D	Demolition and Decomposition
EPBT	Energy Payback Time
LCA	Life Cycle Assessment
LCE	Life Cycle Energy
O&M	Operation and Maintenance
PV	Photovoltaic
RMC	Ready Mixed Concrete

1. INTRODUCTION

Energy payback time (EPBT) is a common metric used in the life cycle assessment (LCA) of a power system to compare the environmental impact of different energy sources [1,2]. EPBT refers to the time needed for a power system to generate the energy equal to the energy spent in manufacturing and operating during its lifetime.

Meanwhile, a life cycle energy (LCE) analysis of a building is generally expressed as the sum of the energy used for construction, operation and maintenance (O&M), and demolition & decomposition (D&D), as an energy consumer [3,4]. Recently, a variety of renewable energy systems have been installed on buildings to cover their energy consumption, which has in turn led to a new concept of energy prosumer. Thus, energy generation in buildings is now a matter of academic concern.

Instead of the existing EPBT concept that focuses only on the renewable energy system, this paper proposes a “building driven-EPBT (BD-EPBT)” that focuses on the building with a renewable energy system as an energy prosumer. Using this new proposed BD-EPBT, the building owner can then calculate the time required for the installed renewable energy system to outrun the total energy used during the life cycle of the building and the system.

2. MATERIALS AND METHODS

This study proposed a framework to calculate the BD-EPBT. (i) Step 1: disassembling energy for a building; (ii) Step 2: disassembling energy for a power system; and (iii) Step 3: calculation of BD-EPBT.

2.1 Step 1: Disassembling energy for a building

The total energy consumed for a building can be calculated by totaling the following four types of energy spent during the life cycle of the building: (i) embodied energy of building materials; (ii) energy consumption in construction stage; (iii) energy consumption in O&M stage; and (iv) energy consumption in D&D stage.

2.1.1 Step 1-1: Embodied energy of building materials

By using the embodied energy intensity and the quantity of material from the construction statement, the total embodied energy of building materials can be calculated (refer to Eq. (1)).

$$E_{EMB\_T} = \sum \frac{Q_M}{D_M} \times I_M \qquad (1)$$

Here, E_{EMB_T} refers to the total embodied energy (GJ), Q_M refers to quantity of material, D_M refers to density of material, and I_M refers to embodied energy intensity of material.

2.1.2 Step 1-2: Energy consumption in construction stage

Various types of construction equipment are used in the building construction stage. A large amount of energy is consumed from the construction equipments, such as trucks, tower cranes, dozers, and truck mixers. The total energy spent from the equipment can be calculated using Eq. (2).

$$E_{CON\_T} = \sum \frac{Q_M}{L_T} \times \frac{S}{F_T} + \sum Q_M \times e_E \qquad (2)$$

Here, E_{CON_T} refers to the total construction energy (GJ), Q_M refers to the quantity of the material, L_T refers to the load capacity of the transportation, S refers to distance, F_T refers to the fuel efficiency of the transportation, and e_E refers to the efficiency of the equipment.

2.1.3 Step 1-3: Energy consumption in O&M stage

To calculate the energy consumption during the building O&M stage, the building energy consumed for heating & cooling and for other building facilities such as computers, lighting, and ventilation should be considered as shown in Eq. (3).

$$E_{ONM\_A} = E_H + E_C + E_F \qquad (3)$$

Here, E_{ONM_A} refers to the annual building O&M energy (GJ/yr), E_H refers to heating energy, E_C refers to cooling energy, and E_F refers to facility energy.

2.1.4 Step 1-4: Energy consumption in D&D stage

The energy for transporting discarded material and operating heavy equipment for landfill and incineration are calculated for the energy consumed in the building D&D stage using Eq. (4).

$$E_{DND\_T} = \sum \frac{Q_D}{L_T} \times \frac{S}{F_T} + \sum Q_D \times e_E \qquad (4)$$

Here, E_{DND_T} refers to the total D&D energy (GJ), and Q_D refers to the quantity of discarded material.

2.2 Step 2: Disassembling energy for a power system

A power system, particularly renewable energy systems, can be installed in buildings to cover their energy consumption. A power system both consumes and produces energy during its lifetime. Depending on the power system, the amount of energy consumed and produced by the system can vary.

2.2.1 Step 2-1: Energy consumption of a power system

The LCE of a power system can be calculated based on the embodied energy, manufacturing energy, maintenance energy, and disposal energy using Eq. (5).

$$E_{LCS\_T} = E_{EMB\_T} + E_{MAN\_T} + E_{MTN\_T} + E_{DND\_T} \qquad (5)$$

Here, E_{LCS_T} refers to the total life cycle energy of a power system (GJ), E_{MAN_T} refers to the total manufacturing energy of a power system (GJ), and E_{MTN_T} refers to the total maintenance energy of a power system (GJ).

2.2.2 Step 2-2: Energy generation of a power system

The annual energy generation of a power system can be calculated by totaling the monthly energy generation as shown in Eq. (6).

$$E_{GEN\_A} = \sum_{i=1}^{12} E_{GEN\_i} \qquad (6)$$

Here, E_{GEN_A} refers to the annual energy generation of a power system (GJ/yr) and E_{GEN_i} refers to the monthly energy generation of a power system in a month i.

2.3 Step 3: Calculation of BD-EPBT

The BD-EPBT is the time required for the annual surplus energy, which is the annual energy generated from the power system minus the annual energy consumed in the building, to outrun the total energy used in the building with a renewable energy system. The BD-EPBT can be calculated using Eqs. (7)-(9). E_{ONM_A} is not included in E_{LCB_T} since this study considered E_{ONM_A} in calculating E_{SUR_A}, which is required for calculating BD-EPBT.

$$E_{LCB\_T} = E_{EMB\_T} + E_{CON\_T} + E_{DND\_T} + E_{LCS\_T} \qquad (7)$$

$$E_{SUR\_A} = E_{GEN\_A} - E_{ONM\_A} \qquad (8)$$

$$BD(EPBT) = E_{LCB\_T} / E_{SUR\_A} \qquad (9)$$

Here, E_{LCB_T} refers to the total life cycle energy of a building with a renewable energy system (GJ), E_{SUR_A} refers to the annual surplus energy of a building with a renewable energy system (GJ), and *BD(EPBT)* refers to the building driven-energy payback time (year).

3. RESULTS

3.1 Case study description

This study conducted a case study to calculate the BD-EPBT of different scenarios. It then selected a single-family house in Seoul with a photovoltaic (PV) system as a renewable energy system for the case study. Based on the target building selected above, this study generated four scenarios according to the building material, building operation strategy, and PV system capacity: using 100% conventional material and conventional operation strategy (A) or replacing 30% of the total material with reused material and 30% energy saving operation strategy (B) with two different PV system capacity, a 3kW system (1) or a 5kW system (2). The BP-EPBT of four combined scenarios (Scenarios A1, A2, B1, and B2) are calculated and analyzed.

3.1.1 Disassembling energy for the target building

The target building, a single-family house for four people in Seoul, is a single story building with a gross floor area of 200m^2.

3.1.1.1 Embodied energy of building materials

Since the purpose of the case study is to compare the LCE of the target building using conventional material with that using reused material, this study focused on the concrete and steel bar among the construction materials. The quantity of the materials required are shown in Table 1 based on the preliminary estimate by gross area [4].

Table 1

Material	Unit per gross area (m^2)	Q_M	Unit
Concrete	0.55	110	m^3
Steel bar	0.057	9.12	m^3

The embodied energy intensity of each material is shown in Table 2. Since there is no formal information of embodied energy intensity in South Korea, this study used the relevant information from verified researches [5,6].

Table 2

Material	D_M (kg/m^3)	Unit	I_M (GJ/unit)
Concrete	2400	m^3	5.48
Steel bar	7850	t	85.46

3.1.1.2 Energy consumption in construction stage

Ready mixed concrete (RMC) trucks (concrete) and 1-ton trucks (steel bar) are used to transport materials, and the detailed information is shown in Table 3 [7].

Table 3

Transport	L_T (t)	S (km)	F_T (km/ℓ)
RMC truck	13.110	20	2.440
1-ton truck	1	20	11.200

Pump trucks (concrete) and hoists (steel bar) are used to construct the building, and the detailed information is shown in Table 4 [7].

Table 4

Equipment	e_E (energy/t)	GJ/energy
Pump truck	0.238	0.036
Hoist	0.553	0.0036

3.1.1.3 Energy consumption in O&M stage

Based on the official report of the actual energy consumption of a household in South Korea, this study assumed that the target building consumes 352.3 kWh per month on average [8].

3.1.1.4 Energy consumption in D&D stage

By applying the discard conversion factor, the quantity for discarded materials is calculated, and the detailed information is shown in Table 5 [9].

Table 5

Material	Conversion factor	Q_D	Unit
Concrete	2.364 (t/m^3)	264	t
Steel bar	2.000 (t/m^3)	18.24	t

The backhoe and Giant breaker are used to discard materials from the target building, and the detailed information is shown in Table 6 [10].

Table 6

Equipment	e_E (ℓ/m^3)	GJ/ℓ
Backhoe & Giant Breaker	4.735	0.036

A 24-ton truck (concrete) and 15-ton truck (steal bar) are used to transport the discarded materials, and the detailed information is shown in Table 7 [10].

Table 7

Transport	L_T (t)	S (km)	F_T (km/ℓ)
24-ton truck	19.2	20	3.4
15-ton truck	16	20	3.1

3.1.2 Disassembling energy for the target power system

The target power system is a PV system with two different capacities: (i) 3 kW; and (ii) 5 kW. The LCE of the PV system was calculated using data from the relevant previous studies [5]. The energy generation of the PV system was calculated using RETScreen, a clean energy management software.

3.2 *Case study results*

3.2.1 Results of case study building

Using Eqs. (1)–(4), four different types of energy consumed by the target building for each scenario are calculated as Table 8.

Table 8

Scenarios	E_{EMB_T}	E_{CON_T}	E_{ONM_T}	E_{DND_T}
A	6,721 GJ	13 GJ/y	15.22 GJ	37 GJ
B	4,705 GJ	13 GJ/y	10.66 GJ	37 GJ

3.2.2 Results of case study power system

Using Eqs. (5) and (6), the energy consumed and produced by the target power system for each scenario are calculated as Table 9.

Table 9

Scenarios	E_{LCS_T}	E_{GEN_A}
1	40 GJ	12.85 GJ/y
2	64 GJ	21.41 GJ/y

3.2.3 Results of case study DB-EPBT

Using Eqs. (7)–(9), the BD-EPBTs for each scenario are calculated as Table 10.

Table 10

Scenarios	E_{LCB_T}	E_{SUR_A}	*BD(EPBT)* (yr)
A1	6,811	-2.37	-
A2	6,835	6.19	1,105
B1	4,795	2.19	2,189
B2	4,819	10.75	449

4. DISCUSSION

E_{EMB_T} occupies 98.3% to 98.7% of E_{LCB_T}. Applying new technologies that can decrease the embodied energy of materials are critical to reduce BD-EPBT. Also, reused material can significantly decrease BD-EPBT. The results of Scenarios A2 and B2 show that only replacing 30% of conventional materials with reused materials can lead to a 60% decrease in BD-EPBT. Using energy conservation strategies are also an effective way to reduce BD-EPBT. While Scenario A1 could not reach any BD-EPBT, reducing 30% of the energy consumption enabled it to reach BD-EPBT. Similarly, using PV system with larger capacity can be a solution. Comparing Scenarios B1 and B2 showed that using a PV system with 2 kW larger capacity resulted in 5 times less BD-EPBT.

In fact, the BD-EPBT more than the lifespan of a building, usually 50 to 60 years, could be regarded as meaningless. Thus, by excluding the embodied energy of building materials, the DB-EPBT can be decreased to 11 years, which leads to a meaningful result.

5. CONCLUSIONS

BD-EPBT is an efficient way to show the importance of the technology, material, operation strategy and power system when constructing buildings. As a decision maker, the building owner should be aware of these ideas to change owner from an energy consumer into an energy producer.

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REFERENCE

[1] Lu L, Yang HX. Environmental payback time analysis of a roof-mounted building-integrated photovoltaic (BIPV) system in Hong Kong. Appl Energy 2010; 87(12):3625-3631.

[2] Mousa OB, Kara S, Taylor RA. Comparative energy and greenhouse gas assessment of industrial rooftop-integrated PV and solar thermal collectors. Appl Energy 2019;241:113-123.

[3] Stephan A, Stephan L. Life cycle energy and cost analysis of embodied, operational and user-transport energy reduction measures for residential buildings. Appl Energy 2016;161:445-464.

[4] Public Procurement Service. Basic guideline. PPS 2017, Korea.

[5] Aye L, Ngo T, Crawford RH, Gammampila R, Mendis P. Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules. Energy Build 2012;47:159-168.

[6] Treloar GJ, Crawford RH. Database of embodied energy and water values for materials. Melbourne 2010: The University of Melbourne.

[7] Korea Institute of Civil Engineering and Building Technology. Standard of estimate. KICT 2017, Korea.

[8] Ministry of the Interior and Safety. A Study on the Establishment of Basic Energy Usage. PRISM 2019, Korea.

[9] Ministry of Environment. A Study on the Separation and Discharge of Construction Waste and Estimation of Generation Unit. ME 2004, Korea.

[10] Cha GW, Son BH, Hong WH. A Study on CO_2 Emissions of Construction Wastes by Types from Demolition Phase of Buildings to Final Disposal Phase of Construction Wastes Generated from Urban Renaissance Project Area. J Architect Inst Korea Plan Design 2010;26(7):311-320.