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Transition Pathways of Electrified Buildings Toward Carbon Neutrality: Comparative Assessment with Gas–Based ZEBs and the Role of PV Integration

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Abstract

This study evaluates the energy performance, operational carbon emissions, and energy autonomy of electrified residential buildings compared to a conventional gas-based Zero-Energy Building (ZEB) under Korea's ZEB certification framework. A detached single-family house was modeled with three configurations: a gas-based ZEB, a Packaged-Terminal Heat Pump (PTHP) ZEB, and an Air-to-Water Heat Pump (AWHP) ZEB. A 3-kW rooftop photovoltaic (PV) system was applied to all cases, representing a typical residential-scale installation for energy self-sufficiency. The results show that full electrification increases primary energy consumption—from 148.3 to 201.6 kWh/m^2·yr—under the current source energy conversion factor (2.75 for electricity), making it difficult for electrified ZEBs to satisfy the present 90 kWh/m^2·yr threshold. Although the electricity emission factor (EF) of the Korean grid is projected to decline significantly from 0.4781 to 0.0480 kgCO_2eq/MWh by 2050, this reduction reflects grid decarbonization, not changes in building performance. When building operational emissions are recalculated using the future EF values, electrified ZEBs show substantially lower annual emissions than the gas-based case, highlighting the long-term benefits of electrification under a decarbonized power system. PV-based energy autonomy analysis reveals that the load cover ratio (LCR) and self-consumption ratio (SC) remain within 38–67%, while the self-sufficiency ratio (SS) exceeds the 20% threshold required for ZEB certification. Nevertheless, the high loss of power supply probability (63–78%) underscores the necessity of storage or load-shifting strategies. Overall, electrification represents a viable transition pathway toward carbon–neutral ZEBs, contingent upon continued grid decarbonization and expanded renewable integration.

Keywords Building electrification · Carbon neutrality · Energy autonomy · Thermodynamic performance · Zero-energy building

Extended author information available on the last page of the article

1 Introduction

The international community has set the achievement of carbon neutrality by 2050 as a top priority, and is making various efforts to achieve carbon neutrality. The building sector accounted for 39% of global greenhouse gas emissions in 2019 [1]. Electrification is attracting attention as a strategy for reducing greenhouse gas emissions in the building sector. Building electrification refers to designing and operating buildings in which all energy-related functions rely on electricity. These buildings have heating, cooling, lighting, appliances and other functions powered by environmentally friendly electrical energy, replacing traditional fossil fuel–based systems.

Countries around the world are promoting policies related to electrification of buildings for decarbonization. The European Union has committed to phase out heating from fossil fuels by direct combustion in the building sector by 2040 [2]. Some Member States are banning the use of fossil fuel–based boilers in new and retrofitted buildings and actively adopting electrification technologies [3]. Each state has introduced various policies and programs related to electrification in the United States. California has introduced legislation banning the use and emission of natural gas in all new buildings from 2023 and converting space and water heating systems to electrical systems [4]. New York State seeks to approve and implement the All–Electric Building Act, which would ban the use of gas in all new buildings by 2027 [5]. In Canada, provincial and municipal governments are promoting the electrification of buildings by providing economic support for the adoption of electrification technologies [6]. Many other countries are adopting electrification strategies to achieve carbon neutrality.

Through previous studies, various advantages of building electrification such as energy saving, reducing greenhouse gas emissions, public health impact, and securing economic feasibility have been revealed. Li et al. [7] proposed a heat pump system combined with thermal energy storage to reduce the peak load and reduce the overall electrical load, since installing solar panels on the roof for electrification of single–family houses cannot solve the high heating and cooling loads. As a result, in the case of using thermal storage, the annual electrical load could be reduced by 50 to 80% by climate zone compared to the case of using only heat pump. Padovani et al. [8] found that combining PV with heat pumps can reduce life cycle cost and greenhouse gas emission in residential buildings in a cold climate with high heating load. Fournier et. al revealed that the community's greenhouse gas emissions can be reduced by electrifying gas devices [9]. In addition, it was found that there was an advantage of public health due to a reduced in PM–2.5 μ emission in housing. It was confirmed that power generation was helpful not only in terms of energy conservation but also in improving the health of residents. It was found that the electrification of buildings could have a similar effect to the renovation of existing buildings as well as newly built ones. The paypack period was shorter to heat using a heat pump than to renovate deeply with a gas boiler or to use an electric boiler [10]. Earle et al. [11] confirmed that the electrification at a community scale reduce greenhouse gas emissions like individual building units, and there was no negative impact on the bill impact. However, as distributed energy systems had to be installed on a community scale, the initial investment cost was high and the payback period was long, which acted as a barrier. Ryan et al. [12] used ground source heat pumps with thermal energy storage for electrification of heating and cooling for a large campus consisting of a complex building group for various purpose in a cold climate. Thermal storage is effective in reducing peak load, and the electrified system would be reduced CO_2 emission by 30% compared to fossil fuel–based CHP. Through this, it was confirmed that electrified heat supply is possible in large campus. In this way, electrification of buildings has various advantages, and is being actively applied to both individual buildings and community scales.

While many countries are proposing the electrification of heating and cooking energy sources to achieve carbon neutrality in the building sector, the Korean government is proposing energy efficiency improvement, supply of high–efficiency devices, smart energy management, low–carbon clean energy supply, and behavior improvement. Low–carbon clean energy supply means expanding the proportion of renewable energy use in buildings and expanding district heating. In other words, although electrification is being promoted through decarbonization of the energy sector and conversion to renewable energy, electrification to replace fossil fuel consumption in buildings with other energy sources is slow.

Korea's climate is mostly in the humid continental climate (Dwa), and the heating degree days amount to 3061 HDD (base 18 °C) [13], which means that heating energy consumption is higher. The heating system of residential buildings in Korea uses a radiant floor heating system that uses hot water above 55 °C [14]. Most heating systems in residential buildings use fossil fuel–based boilers or district heating to supply hot water to floor radiant coils. While 52% of commercial buildings' heating and hot water energy use is electrical energy [15], only 2.6% of residential buildings use electric boilers [16]. In other words, the era of electrification of residential buildings is almost never achieved.

Achieving carbon neutrality requires transforming energy production and end–use across all sectors. Direct combustion of fossil fuels in buildings and transport inevitably emits carbon, making net–zero unattainable without eliminating such fuels. Electricity, by contrast, can be progressively decarbonized through renewable integration, nuclear expansion, and carbon capture, which is why electrification of end–uses is considered central to net–zero strategies [17].

Electrification also delivers efficiency gains. Heat pumps, for example, can supply three or more units of heat per unit of electricity, far outperforming gas boilers [18]. Furthermore, electricity enables the integration of variable renewable resources with demand–side flexibility, storage, and smart controls, enhancing both efficiency and grid stability [19]. Consequently, major international roadmaps—including those of the EU, the United States, and Korea—highlight electrification, together with a decarbonized power sector, as an indispensable pathway toward carbon neutrality [20].

This study aims to evaluate the energy and carbon performance of electrified buildings as a pathway toward carbon neutrality in residential zero energy buildings (ZEBs). The analysis compares a conventional gas-based ZEB, which utilizes both gas and electricity, with two fully electrified configurations employing a packaged-terminal heat pump (PTHP) and an air-to-water heat pump (AWHP). The research is structured in three parts. First, the building energy consumption of each ZEB type is analyzed to identify the influence of electrification on-site and source energy use. Second, PV integration and energy autonomy are evaluated using key indicators. Finally, the carbon neutrality potential of electrified buildings is examined under different power mix scenarios, including the current grid composition and the projected 2050 decarbonized electricity mix. Through this comparative approach, the study provides quantitative insights into how electrification and renewable integration contribute to achieving carbon–neutral operation in residential ZEBs.

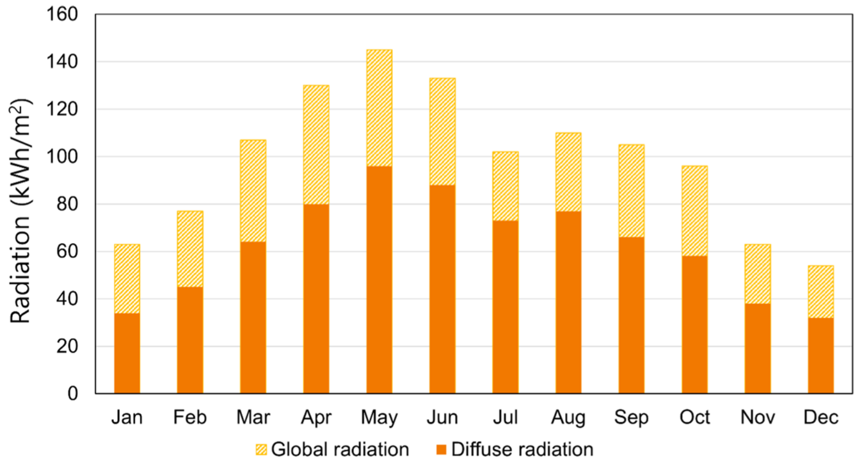
2 Methodology

2.1 Building Description

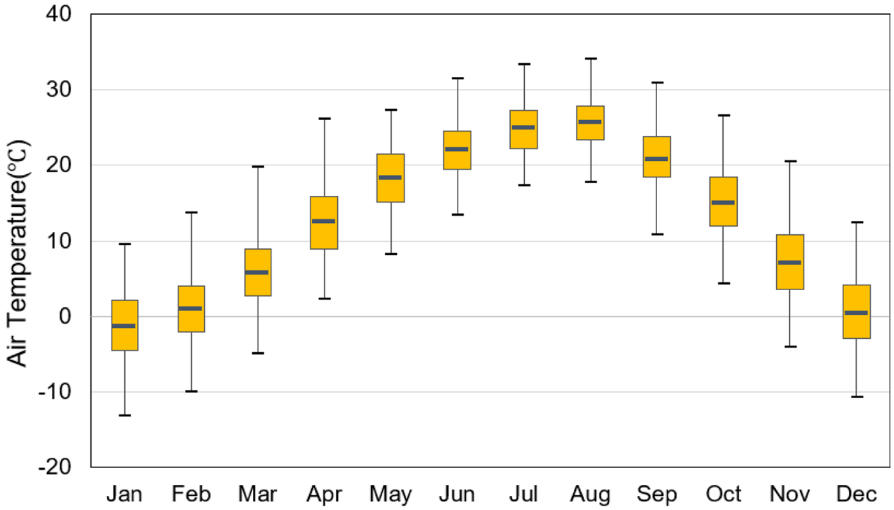
The case study building is a single-family residence located in Seoul, Korea. According to the Köppen climate classification, Seoul has a humid continental (Dwa) climate. Figure 1 illustrates monthly temperature and solar radiation profiles. Annual global radiation is 1,185 kWh/m^2, with temperature ranging from – 13.1 °C to 34.1 °C.

The building was set up as a single–story single–family house, and the floor plan and outline of the building are shown in Fig. 2 and Table 1. Although multi-family housing dominates the residential building stock in Korea, single-family houses were chosen because they allow clearer evaluation of energy autonomy and more direct application of on-site renewable systems without shared infrastructure or metering constraints. This approach enables an independent assessment of building-level energy performance and facilitates quantitative comparison between gas-based and electrified ZEB configurations.

As shown in Table 1, input variables related to energy analysis were set to comply with current legal standards. Residential buildings in Korea use a gas-based radiant floor heating system as a heating system and a fan or air conditioner as a cooling system. The base model (gas-based ZEB) used gas for heating and electricity for cooling, reflecting the typical configuration of Korean residential buildings, and electrified buildings were set to use electricity for both cooling and heating (Table 2). In this study, two types of heat pump systems were considered for the electrified building scenarios: a PTHP and an AWHP system. The selection of these systems reflects both technical diversity in electrification pathways and the characteristics of Korean residential heating practices. The PTHP system represents a direct air-based heating and cooling solution, which is widely applicable to small- and medium-sized buildings undergoing partial electrification. In contrast, the AWHP system was included to reflect Korean residential heating characteristics, where radiant floor heating using gas boilers (ondol system) is the dominant form of space heating. The AWHP enables the use of low-temperature hot water to maintain floor-slab radiant heating, thereby serving as a technically feasible replacement for conventional gas boilers under full electrification. By comparing PTHP and AWHP



(a) Solar radiation



(b) Air temperature

Fig. 1 Monthly weather conditions of Seoul, S. Korea; **a** solar radiation and **b** air temperature

ZEBs with a gas-boiler-based baseline, this study evaluates how different electrification approaches affect energy consumption, energy autonomy, and carbon emissions in the transition toward carbon–neutral buildings in Korea.

It was assumed that a 3-kW PV system would be installed on the roof for energy independence. The selected capacity represents a typical residential-scale PV installation in Korea, which is generally adopted to support partial energy autonomy in detached houses. This capacity is sufficient to meet a significant portion of household electricity demand under favorable solar conditions, aligning with the practical

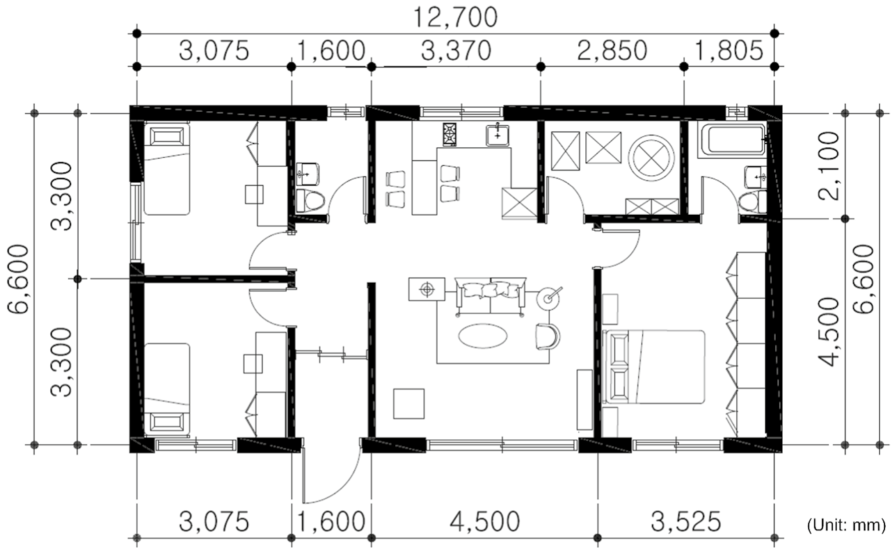


Fig. 2 Plan of the target building

Table 1 Building parameters and input variables used for the energy simulation

Input variables		Value
Building type		Detached house
Location		Seoul, South Korea
Longitude		126.97°
Latitude		37.57°
Orientation		South
Floor area (m^2)		83.82
Number of floors		1
Floor & ceiling height (m)		3.0 / 2.3
Roof type		Flat roof
External wall U–value ($W/m^2 \cdot K$)		0.150
Roof U–value ($W/m^2 \cdot K$)		0.150
Floor U–value ($W/m^2 \cdot K$)		0.150
Window	Total solar transmission (SHGC)	0.430
	Light transmission	0.400
	U–value ($W/m^2 \cdot K$)	0.800
Infiltration (ACH_{50})		1.5
Occupancy density ($people/m^2$)		0.0229
Lighting density (W/m^2)		5.5
Miscellaneous power density (W/m^2)		6.40
Mechanical ventilation rate (ACH)		0.5

Table 2 Facility system–related input variables

System	Parameter	Gas-based ZEB	PTHP ZEB	AWHP ZEB
Heating system	System type	Floor radiant heating with boiler	Packaged-terminal heat pump	Air-to-water heat pump
	System efficiency (or COP)	92%	3.0	4.5
	Fuel type	Natural gas	Electricity	Electricity
	Heating setpoint temperature	20 °C	20 °C	20 °C
	Operation period	November–March	November–March	November–March
Cooling system	System type	Packaged-terminal DX air–conditioner	Packaged-terminal heat pump	Air-to-water heat pump
	Fuel type	Electricity	Electricity	Electricity
	COP	3.5	3.5	4.5
	Cooling setpoint temperature	26 °C	26 °C	26 °C
	Operation period	June–August	June–August	June–August
Domestic hot water	System type	Gas boiler	Instant water heater	Instant water heater
	Fuel type	Natural gas	Electricity	Electricity
	System efficiency	90%	90%	90%
	Operation period	January–December	January–December	January–December

objectives of residential ZEB design rather than complete off-grid operation. Therefore, the 3-kW system was deemed an appropriate baseline for assessing the effect of electrification and PV integration on energy self-sufficiency and carbon reduction. The specifications of the installed PV system are summarized in Table 3. The PV system was assumed to be a grid-tied configuration without battery storage.

In this study, DesignBuilder based on Energyplus, which allows hourly detailed analysis, was used. Climate data for the Seoul area provided by Meteonorm V. 7.3 was applied.

2.2 Performance Metrics

To evaluate the matching performance between the building's energy demand and electric generation by the PV system, the energy self-sufficiency ratio (ESSR), annual load cover ratio (LCR), self–consumption (SC), self–sufficiency (SS) and loss of power supply probability (LPSP) of energy supplied through a PV system were used.

In accordance with the Korean ZEB certification system established by the Ministry of Land, Infrastructure and Transport (MOLIT) and the Korea Energy Agency (KEA), the ESSR quantifies the share of on-site renewable energy generation relative to the total primary energy demand of a building. This indicator serves as a key criterion for determining ZEB certification grades, ranging from Level 5 (20%) to Level 1 (100%). The ESSR is calculated using the following equation:

$$ESSR = \frac{E_{G,source}}{E_{demand,source}} \times 100 \tag{1}$$

where, $E_{G,source}$ is annual source energy equivalent of on-site renewable energy generation (kWh/m^2·yr); $E_{demand,source}$ is annual total source energy consumption of the

Table 3 Specification of the PV system

Category	Parameter	Value
PV module	Cell type	Monocrystalline silicon
	Capacity	3-kW
	Size of module	2,124 × 1,134 × 35 mm
	Active area of a module	2.27 m^2
	Power at max power (P_{MPP})	500 W
	Short–circuit current (I_{sc})	13.88 A
	Module current at max power (I_{MPP})	13.18 A
	Temperature coefficient of short circuit current (α)	0.04%/K
	Open–circuit voltage (V_{oc})	45.62 V
	Module voltage at max power (V_{MPP})	37.95 V
	Temperature coefficient of short–circuit voltage (β)	-0.27%/K
	Array slope	35°
	Azimuth	0°
Inverter	Efficiency	95%

building, including heating, cooling, domestic hot water, lighting, and ventilation (kWh/m^2·yr).

The primary energy conversion coefficients for natural gas and electricity consumed in the building were 1.1 and 2.75, respectively. According to the certification guidelines, a building is classified as a ZEB when its total source energy consumption is under 90 kWh/m^2·yr, and the ESSR exceeds 20% (Level 5). Higher certification levels correspond to greater renewable energy coverage, culminating in Level 1 for 100% or higher energy self-sufficiency.

The LCR ratio represents the ratio of the energy production of the PV system to the annual electrical energy consumption of the building, as shown in Eq. 2 [21].

$$LCR = \frac{E_G}{E_L} \tag{2}$$

where, E_G is the annual generated energy of the on–site PV system (kWh); and E_L is the annual power demand of the building (kWh).

SC is the ratio of the amount of power consumed on its own rather than supplied to the grid among self–generated power. In other words, a SC value of 100% means that the electricity produced was totally consumed in the building. SS refers to the ratio of the amount of electricity consumed by self–generation to the amount of electricity consumed. In other words, it measures how much of the power needed within the building was supplied by the PV system. A SS value of 100% means that the building's energy demand and power generation completely match. SC and SS are expressed as Eq. 3 and 4 [21–23].

$$SC = \frac{\int_{t_1}^{t_2} Min[G(t), L(t)]dt}{\int_{t_1}^{t_2} G(t)dt}; 0 \le SC \le 1 \tag{3}$$

$$SS = \frac{\int_{t_1}^{t_2} Min[G(t), L(t)]dt}{\int_{t_1}^{t_2} LD(t)dt}; 0 \le SS \le 1 \tag{4}$$

where, G(t) is the PV system at hour t; and LD(t) is the building power consumption at hour(t).

LPSP is the probability that the available generation capacity is insufficient to meet the building's demand at any given time, it can be calculated as [24, 25]. In this study, LPSP is calculated as the ratio of hours during which the on-site PV system without energy storage fails to satisfy the electric load, to the total hours in the analysis period. LPSP quantifies the proportion of time during which the self-generation and storage systems cannot meet the building's load demand. Hence, it serves as a suitable indicator for assessing the energy autonomy and supply reliability of zero-energy buildings under a renewable generation. A higher LPSP indicates a greater risk of supply shortfall and highlights the need for supplementary resources such as grid connection in electrified buildings. In this study, LPSP was calculated under grid-connected, no-storage conditions, considering PV output only.

$$LPSP = \frac{\sum_{t=1}^{T} LD(t) - G(t)}{\sum_{t=1}^{T} LD(t)} \tag{5}$$

When $G(t) \geq LD(t)$, the numerator becomes zero, indicating that the supply adequately meets the demand during that period.

2.3 Assessment of Carbon Emissions under Power Mix Scenarios

This study evaluates the carbon emissions associated with building electrification. Conventional ZEBs use both natural gas and electricity, whereas electrified ZEBs rely solely on electricity to meet all final energy demands. Greenhouse gas emissions from electricity use were assessed by applying multiple energy mix scenarios, including the current power mix and the 2050 carbon–neutral mix, to analyze changes in emissions under different scenarios. The system boundary encompasses space heating, cooling, domestic hot water, lighting, ventilation, and plug loads.

For the fuel sector, the "2021 Approved National Greenhouse Gas Emission and Absorption Factors" published by the Greenhouse Gas Inventory and Research Center of Korea was employed [26]. Based on this source, the emission factor (EF) for natural gas (LNG) combustion was set at 56.0 tCO_2/TJ (0.2013 tCO_2eq/MWh). For electricity, the national average EF of 0.4781 tCO_2eq/MWh from the same source was applied.

The amount of carbon emissions emitted from natural gas and electricity consumed in buildings is calculated according to Eqs. 6 according to the greenhouse gas reduction calculation method presented by the Ministry of Environment [27].

$$Emissions_{GHG} = \sum E_i \times EF \tag{6}$$

where, $Emissions_{GHG}$ is total greenhouse gas emission (tCO_2eq) by electricity consumption and gas combustion; Ei denotes the energy consumption by each energy source; and EF represents the greenhouse gas EF for each energy source. EF for electricity at the point of consumption stage is 0.4781 tCO_2eq/MWh, and the EF for natural gas is 0.2013 tCO_2eqMWh [26] that was derived by converting the original value of 15.236 tC/TJ [26] using the IPCC AR6 GWP100.

As listed in Table 4, the power mix scenarios were derived from the "Korea 2050 Carbon Neutral Scenario (K–Map 2.0) [28]." Specifically, the annual shares of generation by source (e.g., renewables, nuclear, coal, LNG) presented in K–Map 2.0 were reflected in constructing each scenario. The carbon EF of electricity was calculated as the weighted average of the generation shares. Since the government does not officially provide generation–specific emission factors, this study referred to internationally recognized literature, including IPCC and UNECE reports, which present life cycle assessment (LCA) based GHG intensities for major generation technologies such as coal, natural gas, oil, nuclear, solar PV, and wind. This approach compensates for the absence of officially disclosed values in Korea while appropriately capturing the influence of generation mix changes on the carbon intensity of electricity.

Table 4 Power mix scenario for carbon neutrality in Korea and emission factor

Power generation source (%)	2022	2030	2040	2050
Coal	32.7	3.9	0	0
Natural gas	27.7	42.4	4.1	0
Nuclear	29.8	26.1	19.3	15.6
Oil	0.3	0	0	0
Solar PV	4.6	15.8	33.2	37.5
Wind	0.6	9	24.0	23.5
Hydrogen turbines	0	0	17.3	22.5
Others	4.3	2.7	2.1	1.0

The GHG intensity of electricity generation by power source is shown in Table 5. The 'other' category includes minor domestic renewable generation technologies such as biomass, geothermal, small hydro, and waste–to–energy. Since official emission factors are not separately provided for these technologies, this study refers to published life cycle GHG emission studies: dedicated biomass power (~ 130–230 kgCO_2eq/MWh) [29], geothermal (~ 11–47 kgCO_2eq/MWh) [30], and small hydro/run–of–river (~ 1–24 kgCO_2eq/MWh) [29]. Considering the heterogeneity and low penetration share, we adopt a representative EF of ~ 100 kgCO_2eq/MWh for the 'other' category and conduct sensitivity analysis within the range of 50–150 kgCO_2eq/MWh. The EF of electricity was calculated as a weighted average based on the generation mix, with a transmission and distribution loss rate of 5% applied to adjust the value to the final consumption stage. The resulting EF was 0.4702 kgCO_2eq/MWh, which is in close agreement with the officially reported consumption–based factor of 0.4781 kgCO_2eq/MWh, thereby validating the methodological approach.

Table 5 GHG emissions intensity of electricity generation source

Power generation source	Lifecycle GHG emission intensity (kg$CO_{2\text{-eq}}$/MWh)	Reference
Coal	888	[31]
Natural gas	499	[31]
Nuclear	29	[31]
Oil	733	[31]
Solar PV	85	[31]
Wind	26	[31]
Hydrogen turbines	10	[32–34]
Others	100	[29, 30]

3 Results & Discussion

3.1 Building Energy Consumption

In this study, to ensure a reliable analysis model, the gas–based ZEB (conventional system) was set as the reference building, and the energy consumption of the reference building was compared with energy consumption statistical data. The reference model was compared to the energy consumption of an apartment complex that was completed in 2019 and received zero energy certification (Fig. 3). The criterion for a ZEB is that the source energy consumption for heating, cooling, domestic hot water, lighting, and ventilation does not exceed 90 kWh/m^2·yr.

The energy consumption of actual zero-energy residential buildings was converted to primary energy by averaging the energy consumption from 2020 to 2022 provided by the Apartment Housing Management Information System [35]. The energy consumption of the reference model was compared with the monthly source energy use intensity. The mean bias error (MBE) and coefficient of variation (CV) for the root-mean-square error (RMSE) for the simulation results were 5% and 9%, respectively, which were considered reliable because they satisfied the MBE and CVRMSE standards of ± 10% and ± 30% from ASHRAE Guideline 14–2014 [36].

Figure 4 compares site and source energy consumption among three ZEB configurations: the Gas-based ZEB using both gas and electricity, the PTHP ZEB adopting a packaged-terminal heat pump, and the AWHP ZEB utilizing an air-to-water heat pump. Under the current energy mix and source energy conversion factors (2.75 for electricity, 1.1 for gas), electrified buildings exhibit higher source energy consumption compared to the gas-based baseline.

Under the current ZEB certification scheme in Korea, buildings are required to satisfy a source energy consumption threshold of 90 kWh/m^2·yr for regulated loads including heating, cooling, lighting, ventilation and DWH. The gas-based ZEB

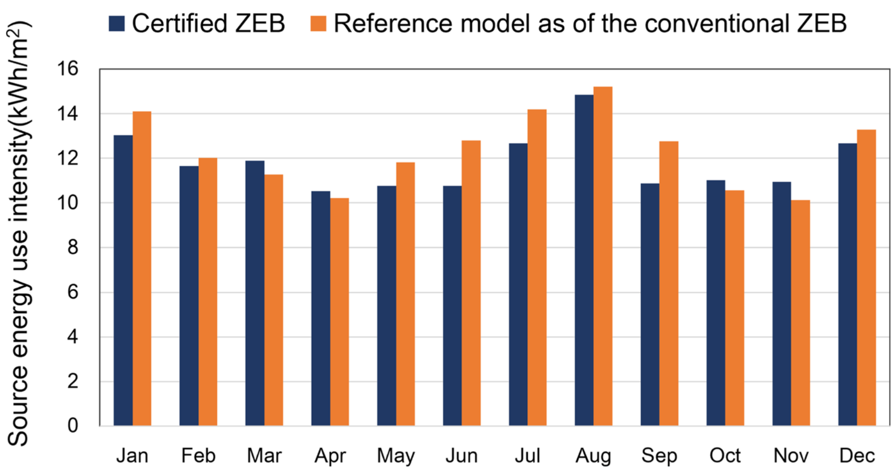


Fig. 3 Comparison of monthly source energy use intensity

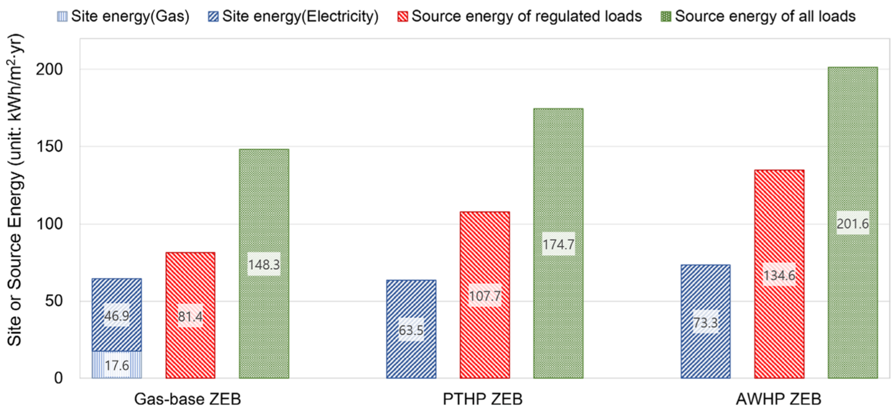


Fig. 4 Energy consumption comparison of ZEBs with different heating systems

records a regulated source energy consumption of 81.35 kWh/m^2·yr, meeting the certification requirement. However, both electrified ZEBs exceed the 90 kWh/m^2·yr threshold, thereby failing to satisfy the minimum ZEB requirement under the current source energy conversion factors.

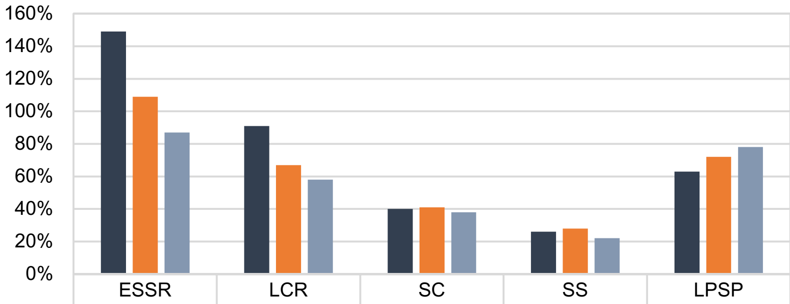
The results clearly demonstrate that while full electrification is desirable for long-term decarbonization, it is at a structural disadvantage under the current certification framework. The higher source energy conversion factor assigned to electricity inflates the calculated source energy consumption, making it nearly impossible for fully electrified building to achieve the regulatory target, even when high-efficiency heat pump systems are applied.

Therefore, unless the source energy conversion factor for electricity is revised downward to reflect the decarbonization of the national grid, electrified ZEBs will remain ineligible for certification, despite their lower direct CO_2 emissions and higher compatibility with renewable energy integration.

3.2 PV Integration and Energy Autonomy

The energy autonomy and reliability indicators for the gas-based and electrified ZEBs integrated with PV systems are summarized in Fig. 5. The ESSR, LCR, SC, SS, and LPSP were analyzed to assess the extent to which each building configuration achieves energy independence through on-site solar generation.

The energy self-sufficient rate, defined by the Korean ZEB certification as the ratio of on-site renewable energy generation to total primary energy consumption, records 149% for the gas-based ZEB, 109% for the PTHP ZEB, and 87% for the AWHP ZEB. All configurations therefore meet the minimum 20% requirement stipulated in the national ZEB certification standard, confirming that even fully electrified buildings can achieve compliance under the given PV capacity. The higher value for the gas-based ZEB reflects its smaller total source energy demand, owing to partial gas use.



	ESSR	LCR	SC	SS	LPSP
Gas-based ZEB	149%	91%	40%	26%	63%
PTHP ZEB	109%	67%	41%	28%	72%
AWHP ZEB	87%	58%	38%	22%	78%

Fig. 5 Comparison of energy autonomy and reliability metrics

The LCR, which indicates the proportion of electrical demand met directly by PV generation, is 91% for the gas-based ZEB, 67% for the PTHP ZEB, and 58% for the AWHP ZEB. The decline with increasing electrification results from higher total electrical loads, particularly from heating operations, which reduce the share of PV-covered demand. When gas consumption is included in the total load of the gas-based case, the LCR decreases to approximately 66%, becoming comparable to that of the electrified ZEBs.

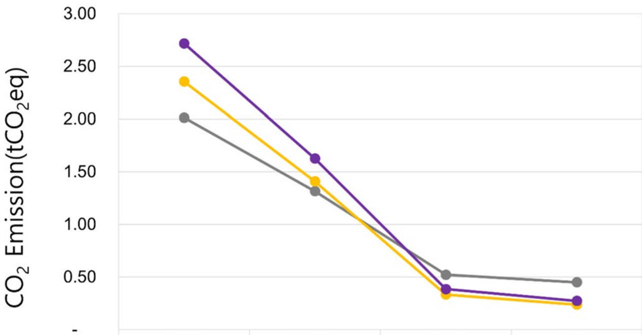
The SC remains within a narrow range of 38–41%, suggesting that the temporal mismatch between PV output and building demand, rather than heating system configuration, dominates energy-use patterns. The SS declines as electrification increases—26% for gas-based, 28% for PTHP, and 22% for AWHP—showing greater reliance on external grid supply in fully electric systems.

The LPSP rises sharply from 63% (Gas-based) to 72% (PTHP) and 78% (AWHP), implying reduced supply reliability and greater vulnerability to renewable intermittency as electrification progresses. These high LPSP values highlight that current PV capacity alone cannot guarantee energy security in electrified ZEBs without additional measures such as energy storage or demand-side management.

Overall, while electrification increases dependency on electricity and slightly lowers reliability indicators, all configurations meet Korea's ZEB certification criteria. The results reaffirm that transitioning to fully electrified buildings remains a feasible and policy-aligned pathway toward carbon–neutral operation, particularly as the national power mix continues to decarbonize.

3.3 Carbon neutrality potential of electrified buildings according to the power mix

Figure 6 presents the projected carbon emissions of three ZEB configurations from 2022 to 2050, under power mix scenarios aligned with Korea's 2050 Carbon Neutrality Roadmap (K-Map 2.0). The EF for 2030, 2040, and 2050 were 0.2859 kgCO_2eq/MWh, 0.0676 kgCO_2eq/MWh, and 0.0480 kgCO_2eq/MWh, respectively,



	2022	2030	2040	2050
Gas-based ZEB	2.01	1.31	0.52	0.45
PTHP ZEB	2.36	1.41	0.33	0.24
AWHP ZEB	2.72	1.62	0.38	0.27

Fig. 6 Projected carbon emissions under evolving power mix scenarios

and these values were derived based on the data presented in Table 4 and Table 5. The EF for electricity is expected to decline substantially, from 0.4781 kgCO_2eq/MWh in 2022 to 0.0480 kgCO_2eq/MWh by 2050, reflecting the progressive decarbonization of the national grid.

Under the current EF, electrified ZEBs exhibit higher building operational emissions than the gas-based baseline. Specifically, the AWHP ZEB emits 2.72 tCO_2eq, followed by the PTHP ZEB (2.36 tCO_2eq) and the Gas-based ZEB (2.01 tCO_2eq). This outcome is consistent with earlier findings that electrified buildings are disadvantaged under the current grid, primarily due to the high carbon intensity of electricity relative to natural gas.

As the electricity grid transitions toward renewables, however, the building-level operational emissions for electrified ZEBs decrease sharply. By 2030, emissions from all ZEB types converge around 1.3–1.6 tCO_2eq, indicating reduced differences between systems. By 2040, the AWHP and PTHP ZEBs emit 0.38 and 0.33 tCO_2eq, respectively, outperforming the gas-based ZEB (0.52 tCO_2eq). Finally, by 2050, all–electric ZEBs become the most carbon–efficient configurations, with emissions reduced to 0.24–0.27 tCO_2eq, compared to 0.45 tCO_2eq for the gas-based ZEB.

These results demonstrate a clear turning point around 2040, beyond which electrification becomes advantageous in terms of total carbon emissions. Therefore, while electrified ZEBs currently face challenges under existing EFs, they hold significant long–term potential for carbon neutrality, particularly when combined with on–site renewable generation such as a PV system.

3.4 Discussion

The results indicate that building electrification, while currently disadvantaged by higher source energy conversion factors and electricity emission intensities, provides a clear long-term advantage under the projected decarbonized grid. Although electrification increases total site and source energy use, it enhances compatibility with renewable generation and enables future carbon-free operation. The results also highlight that the Korean ZEB certification framework, which uses a fixed source energy conversion factor of 2.75 for electricity, does not fully reflect the evolving energy system. Updating these conversion factors to align with the progressive decarbonization of the power sector would allow electrified ZEBs to be properly recognized for their environmental performance.

In terms of PV-based autonomy, the LCR, SC, and SS values suggest that the current 3-kW PV capacity is insufficient for full self-sufficiency in electrified configurations. The high LPSP values (72–78%) indicate that incorporating battery storage or implementing load-shifting strategies is essential to maintain a stable power supply and reduce the temporal mismatch between generation and demand. This aligns with previous studies emphasizing that renewable-based electrified buildings must be supported by distributed storage and smart control systems to achieve both energy autonomy and reliability.

The AWHP represents radiant floor heating, which is widely used in Korean homes. Its inclusion highlights the importance of designing systems that reflect local heating practices for practical electrification. The results confirm that PTHP systems are more energy-efficient for direct air heating and cooling, while AWHP systems ensure comfort consistency with traditional ondol-based heating but at the cost of higher electricity consumption. These findings suggest that the optimal strategy for Korea's residential electrification should combine heat pump selection, PV integration, and grid interaction strategies depending on the building typology and user behavior.

Ultimately, as the power mix shifts toward renewables and hydrogen-based generation, electrified ZEBs are expected to outperform gas-based systems in both operational emissions and life cycle carbon intensity. Therefore, electrification is not merely a technological substitution but a transitional mechanism bridging current fossil-dependent buildings to future carbon–neutral communities. Taken together, the study underscores that the effectiveness of building electrification is tightly coupled to national grid decarbonization, and policies that simultaneously promote clean electricity and building-sector electrification will be essential to achieving deep carbon reductions.

4 Conclusion

This study examined the energy consumption, energy autonomy, and carbon neutrality potential of residential ZEBs under different electrification configurations. Three ZEB types—a gas-based ZEB, a PTHP-based ZEB, and an AWHP-based ZEB—were compared using identical operational and PV conditions.

Results show that the source energy consumption increases from 148.3 kWh/m^2·yr in the gas-based ZEB to 201.6 kWh/m^2·yr in the AWHP ZEB, primarily due to the conversion of thermal loads to electricity and the higher primary energy factor for electricity (2.75). Under the current certification framework, only the gas-based ZEB satisfies the regulated threshold of 90 kWh/m^2·yr, while both electrified ZEBs fail to meet the requirement, despite employing efficient heat pump systems.

In terms of energy autonomy, the gas-based and PTHP ZEBs exhibited comparable LCR (≈66–67%) and SC (~40%), while the AWHP ZEB showed a lower LCR (58%) due to greater electrical load for radiant heating. When total loads including gas are considered, the gas-based ZEB's LCR decreases to about 66%, indicating similar on-site generation coverage among systems. All configurations, however, achieved an ESSR above 20%, meeting Korea's minimum ZEB certification criterion.

Carbon emission analysis indicates that although electrified buildings currently exhibit higher operational emissions due to the carbon-intensive electricity grid, their performance improves substantially as the grid decarbonizes. The electricity emission factor decreases from 0.4781 to 0.0480 $kgCO_2eq/MWh$ by 2050, and when this cleaner grid is applied to the simulated energy demand, electrified ZEBs are projected to achieve more than an 80% reduction in their annual operational emissions under the assumed future grid conditions. By 2050, the AWHP and PTHP ZEBs emit only 0.27 and 0.24 tCO_2eq per year, respectively, outperforming the gas-based ZEB, which emits 0.45 tCO_2eq.

In summary, although full electrification currently leads to higher primary energy demand and potential supply instability, it represents a viable long-term pathway toward achieving carbon neutrality under a decarbonized energy system. Future research should explore integrating energy storage, predictive control, and dynamic power tariffs with electrified ZEBs to enhance system resilience and maximize renewable self-consumption. Policy frameworks, including Korea's ZEB certification, should also evolve to reflect the decarbonizing electricity grid, ensuring that electrified buildings receive fair assessment and support in the national transition toward net-zero.

This study has several limitations. The analysis was based on a single detached house, which may not fully represent Korea's predominantly high-rise residential stock. Battery storage and detailed occupant behavior were not modeled, and the carbon emission assessment relied on projected future emission factors that are subject to uncertainty. In addition, the PV capacity was fixed at 3-kW without exploring optimal system sizing. Despite these limitations, the study provides important insights by quantitatively demonstrating how the relative performance of electrified ZEBs evolves under Korea's decarbonizing electricity grid. The findings highlight the conditions under which electrification becomes advantageous and clarify the policy and technical adjustments needed to support a transition toward carbon–neutral residential buildings.

5 Conflict of interest

The authors declare no competing interests.

Author Contributions Bo Rang Park: Conceptualization, Investigation, Software, Writing—original draft, Min Hee Chung: Data curation, Methodology, Visualization, Writing—original draft, Jin Woo Moon: Supervision, Funding acquisition, Writing—review & editing.

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References

1. Global Alliance for Buildings Construction, International Energy Agency, the United Nations Environment Programme, 2019 global status report for buildings and construction: towards a zero-emission, efficient and resilient buildings and construction sector. (United Nations Environment Programme Nairobi, Kenya, 2019)
2. European Commision, Proposal for a directive of the european parliament and of the council on the energy performance of buildings (recast). (Brussels, 2021)
3. European Commission, REPowerEU Plan. (2022)
4. California Building Standards Commission, california code of regulations title 24. (2023)
5. Environmental Advocates NY
6. Electrifying Canada, (International Institute for Sustainable Development, 2022)
7. Y.Y. Li, G. Rosengarten, C. Stanley, A. Mojiri, J. Energy Storage **56**, 105873 (2022). https://doi.org/10.1016/j.est.2022.105873
8. F. Padovani, N. Sommerfeldt, F. Longobardi, J.M. Pearce, Energy Build. **250**, 111284 (2021). https://doi.org/10.1016/j.enbuild.2021.111284
9. E.D. Fournier, F. Federico, R. Cudd, S. Pincetl, A. Ricklefs, M. Costa, M. Jerrett, D. Garcia-Gonzales, Sustain. Cities Soc. **86**, 104128 (2022). https://doi.org/10.1016/j.scs.2022.104128
10. Y.H. Wang, K. Qu, X.J. Chen, X.X. Zhang, S. Riffat, Energy **241**, 122935 (2022). https://doi.org/10.1016/j.energy.2021.122935
11. L. Earle, J. Maguire, P. Munankarmi, D. Roberts, Appl. Energy **329**, 120256 (2023). https://doi.org/10.1016/j.apenergy.2022.120256
12. E. Ryan, B. McDaniel, D. Kosanovic, Appl. Energy **328**, 120147 (2022). https://doi.org/10.1016/j.apenergy.2022.120147
13. S. Park, J. Shim, D. Song, Renew. Sustain. Energy Rev. (2021). https://doi.org/10.1016/j.rser.2020.110211
14. J. Cho, B. Park, T. Lim, Appl. Therm. Eng. (2019). https://doi.org/10.1016/j.applthermaleng.2019.114360
15. Korea Energy Economics Institute, Korea energy agency, 2020 energy consumption survey. (Ministry of Trade, Industry & Energy, 2022)
16. Korea Research Institute for Human Settlements, 2020 Residential survey. (Ministry of land, infrastructure and transport, 2021),
17. H. Kim, H. McJeon, D. Jung, H. Lee, C. Bergero, J. Eom, Energy Clim. Change **3**, 100075 (2022)
18. A. Nyers, J. Nyers, Energies **16**(7), 2981 (2023)
19. L. Göke, J. Weibezahn, M. Kendziorski, Energy **278**, 127832 (2023)
20. M. Cook, F.T. Davidson, H. Fell, J. Glynn, M. Lott, J.D. Rhodes, Columbia University Center on Global Energy Policy, New York, (2022)
21. J. Ge, C. Shen, K. Zhao, G.Q. Lv, Energy Convers. Manage. (2022). https://doi.org/10.1016/j.enconman.2022.115485
22. S.L. Cao, A. Hasan, K. Sirén, Energy Build. **64**, 423 (2013). https://doi.org/10.1016/j.enbuild.2013.05.030
23. R. Luthander, J. Widén, D. Nilsson, J. Palm, Appl. Energy **142**, 80 (2015). https://doi.org/10.1016/j.apenergy.2014.12.028
24. T. Khatib, I.A. Ibrahim, A. Mohamed, Energy Convers. Manag. **120**, 430 (2016)
25. J. Lian, Y. Zhang, C. Ma, Y. Yang, E. Chaima, Energy Convers. Manag. **199**, 112027 (2019)
26. National Greenhouse Gas Inventory Management Center, (Greenhouse gas inventory and research center of korea, carbon tracking & information system (CTIS), 2022)
27. Ministry of Environment, ed. by ministry of environment (2022)
28. Green Energy Strategy Institute, Institute for green transformation, NEXT group, Agora Energiewende, (2024)

29. Intergovernmental Panel on Climate Change, (2014), p. 1335
30. National Renewable Energy Laboratory, (U.S. Department of Energy, 2017)
31. World Nuclear Association, (World Nuclear Association, London, 2011)
32. U.S. Environmental Protection Agency, (U.S. Environmental Protection Agency, 2023)
33. European Monitoring and Evaluation Programme, European Environment Agency, (European Environment Agency, 2023)
34. M. Alhuyi Nazari, M. Fahim Alavi, M. Salem, M.E.H. Assad, Int. J. Low-Carbon Technol. **17**, 513 (2022). https://doi.org/10.1093/ijlct/ctac025
35. Ministry of Land Infrastructure and Transport, Korea Real Estate Board
36. American Society of Heating Refrigerating and Air-Conditioning Engineers, Guideline 14–2014: Measurement of energy and demand savings. (ASHRAE, Atlanta, GA 2014),

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