Supplementary Materials

Rooftop-PV-Driven Air-Source Heat Pumps in Mechanically Ventilated Broiler Houses: An Integrated Assessment of Thermal Environment, Energy, and Carbon Emissions in South Korea

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Text S1. Economic assessment of the PV coupling (methods, price assumptions, operating modes, and results)

Methods.

The economics were examined as a supplementary analysis to support the practical feasibility of the solar-driven ASHP substitution. Matching the rooftop-PV generation with the house electricity consumption on an hourly basis, the self-consumed amount (generation consumed directly in the house) and the surplus (generation exceeding consumption) were analysed. Specifically, (i) the grid-electricity purchase cost avoided by self-consumption, (ii) the grid-sale revenue of the surplus, and (iii) the annual operating cost of each cooling/heating method were calculated, and the annual benefit relative to the baseline (without PV) was compared by region and weather. A simple payback period was then estimated from the annual benefit relative to the initial capital cost.

The grid purchase price applied was 0.048 USD·kWh^{-1}, the highest summer/winter energy charge among the agricultural high-voltage tariffs (Korea Electric Power Corporation, effective 1 August 2026). The export price of the PV-generated electricity was computed by summing the system marginal price (SMP) and the revenue from Renewable Energy Certificates (RECs): SMP was the recent 12-month mainland monthly average of approximately 0.081 USD·kWh^{-1}, and the REC the spot-market average of approximately 49.2 USD·REC^{-1} with a building-mounted rooftop-PV weight of 1.5, giving a combined export price of approximately 0.155 USD·kWh^{-1} (Korea Power Exchange, 2026 basis). Each PV condition was evaluated in its realistic operating mode. Because the ECP scenario has a very small electricity demand, ECP+PV can realise value only by exporting essentially all of its generation, and it was therefore treated as a full-export power-generation business receiving both SMP and REC, with the house electricity purchased entirely from the grid. The ASHP scenario, with a large electricity demand, was operated as a self-use facility that first allocates generation to the house's hourly demand and exports only the surplus, easing policy constraints such as summer grid saturation and output curtailment; under this self-use classification the REC does not apply, so only the SMP is received for the surplus. The kerosene price applied was approximately 0.98 USD·L^{-1}, the national average retail price of tax-exempt agricultural indoor kerosene (Korea National Oil Corporation, Opinet, 5 August 2026 basis). The initial capital cost was assigned by condition: ECP+PV carries only the rooftop-PV cost (approximately 219,000 USD), whereas ASHP+PV carries both the PV and the heat-pump cost (approximately 317,000 USD). The PV installation cost was taken as approximately 913 USD·kW^{-1} (2026 domestic industry average; range approximately 773–1,265 USD·kW^{-1}), giving approximately 219,000 USD for 240 kWp, and the air-source heat-pump cost as approximately 4,920 USD per unit; for the 20 units installed to meet the peak cooling load, this gave approximately 98,300 USD. The existing evaporative cooling pad and kerosene heater were treated as already installed and excluded from the initial capital cost.

Results.

Without PV, the ASHP conversion (Condition 1) had an annual operating cost of 9,200–9,800 USD, similar to or slightly lower than that of the baseline (ECP, 9,300–14,400 USD), even though the electricity demand

increased greatly (192–204 MWh) (Table S1). This is because the domestic agricultural electricity tariff (agricultural (B) high voltage, 0.048 USD·kWh^{-1}) is cheap relative to the kerosene fuel cost (0.98 USD·L^{-1}), so replacing kerosene heating with electricity roughly offsets the increased demand. Considering the heat-pump investment of approximately 98,300 USD, however, the resulting saving (at most 5,200 USD·year^{-1}) gives a very long, strongly region-dependent payback of approximately 19–248 years, or no payback in Jinju (T_Max), because the saving hinges on the avoided kerosene. Combined with the fact that ASHP conversion without PV increases carbon emissions (main text, Section 3.4), the heat-pump conversion is justified only when coupled with rooftop PV.

Coupling rooftop PV turns the house into a net-revenue structure (Table S1). In its realistic full-export mode, ECP+PV (Condition 2) earned an annual net revenue of approximately 43,500 USD (35,300–48,700 USD), with a simple payback of approximately 4 years (3.7–4.4 years) against its PV-only added investment of approximately 219,000 USD. ASHP+PV (Condition 3), in its self-consumption mode, earned approximately 17,100 USD (14,800–19,200 USD), with a payback of approximately 11 years (10.3–12.5 years) against its combined PV and heat-pump investment of approximately 317,000 USD.

This does not mean ECP+PV is the better system; it monetises the same rooftop PV differently. ECP+PV sells its entire generation with the REC premium as a power-generation business, whereas ASHP+PV self-consumes much of the generation (earning no REC on that part) and exports less. If ASHP+PV instead sold all of its generation under full export, it would earn approximately 45,800 USD, which is more than ECP+PV earns, so by operating in the self-consumption mode it forgoes roughly 28,700 USD per year. This forgone revenue can be regarded as the private cost of on-site decarbonisation and of the potential grid benefit of self-consumption, as discussed in the main text (Section 4.5).

Table S1. Net annual operating cost and simple payback period by region, weather, and condition. Each cell gives the net operating cost (10^3 USD·year^{-1}; negative = net revenue) with the simple payback period in parentheses (years); "–" denotes not applicable (baseline).

Region	Weather	Baseline (ECP)	Condition 1 (ASHP)	Condition 2 (ECP+PV)	Condition 3 (ASHP+PV)
Chuncheon	T_Max	13.26 (–)	9.19 (24.2)	−41.63 (4.0)	−17.44 (10.3)
Chuncheon	T_Min	14.40 (–)	9.22 (19.0)	−35.33 (4.4)	−14.78 (10.9)
Daejeon	T_Max	10.22 (–)	9.78 (221.2)	−45.64 (3.9)	−17.26 (11.5)
Daejeon	T_Min	10.13 (–)	9.48 (150.9)	−48.67 (3.7)	−19.18 (10.8)
Jinju	T_Max	9.34 (–)	9.38 (no payback)	−43.31 (4.2)	−16.01 (12.5)
Jinju	T_Min	9.75 (–)	9.35 (248.4)	−46.58 (3.9)	−17.98 (11.4)

Text S2. Sensitivity to market weight

Methods.

The Daejeon T_Max scenario, which showed the largest ECP exceedance, was additionally simulated for a heavier market weight of approximately 2.5 kg. Each flock was reared for 41 days, from placement at 1 day of age to shipment at 42 days of age (2.56 kg; main text, Eq. 2), followed by the same 14-day downtime, giving six flocks and 5,904 occupied hours per year. The setpoint schedule was the same as in the main analysis, decreasing to 21 °C at 28 days of age and then maintained until shipment. The number of birds was reduced to 21,902 to maintain the stocking density of 39 kg·m^{-2}. Because the 2.5 kg case was simulated without rooftop

PV, Conditions 2 and 3 were estimated for both market weights by matching the PV output computed in the no-PV runs with the house electricity demand on an hourly basis. The shading effect of the PV modules on the indoor temperature (approximately 0.02 °C on average; main text, Table 4 note) was therefore neglected, and the 1.5 kg values of Conditions 2 and 3 in Table S2 differ slightly from those in Table 7 of the main text and Table S1.

Results.

With the heavier market weight, the longer finishing period increased the ECP exceedance of 2 °C or more from 562 to 759 h·year^{-1} and the THI ≥ 78 hours from 275 to 419 h·year^{-1}, whereas the ASHP recorded 0 h for both indicators. The ASHP electricity demand increased by approximately 10%, mainly in cooling, while the heating demand of both systems decreased because the number of brooding periods fell from eight to six. ASHP+PV remained net-negative under the export-credit approach, and its simple payback lengthened from approximately 12 to 14 years. The comparative conclusions of the main text were therefore unchanged.

Table S2. Comparison of the 1.5 kg and 2.5 kg market-weight scenarios (Daejeon, T_Max). Conditions 2 and 3 were estimated from the no-PV runs for both market weights (Text S2). Exceedance and THI hours are counted over the occupied hours and the late rearing period (from 21 days of age), respectively.

Item	1.5 kg	2.5 kg
Market weight (kg)	1.50	2.56
Rearing period (days of age)	1–31	1–42
Number of birds	36,504	21,902
Flocks per year	8	6
Occupied hours (h·year^{-1})	5,760	5,904
Late rearing hours (h·year^{-1})	1,920	3,024
ECP exceedance ≥ 1 / 2 / 3 / 4 °C (h·year^{-1})	774 / 562 / 383 / 260	1,070 / 759 / 583 / 465
ASHP exceedance ≥ 1 °C (h·year^{-1})	0	0
ECP THI ≥ 78 (h·year^{-1})	275	419
ASHP THI ≥ 78 (h·year^{-1})	0	0
ECP electricity (MWh·year^{-1})	18.0	23.1
ECP kerosene (L·year^{-1})	9,548	6,197
ASHP electricity (MWh·year^{-1})	203.7	224.2
Cooling / heating (MWh·year^{-1})	184.0 / 17.3	211.2 / 11.0
ASHP+PV self-sufficiency (%)	38.2	37.4
Baseline (ECP) emissions (tCO_2·year^{-1})	32.0	26.0
Condition 1 (ASHP) emissions (tCO_2·year^{-1})	93.6	103.0
Condition 2 (ECP+PV) net emissions (tCO_2·year^{-1})	−134.5	−140.5
Condition 3 (ASHP+PV) net emissions (tCO_2·year^{-1})	−73.0	−63.6
Baseline (ECP) cost (10^3 USD·year^{-1})	10.22	7.18
Condition 1 (ASHP) cost (payback, years)	9.78 (221.2)	10.76 (no payback)
Condition 2 (ECP+PV) cost (payback, years)	−45.92 (3.9)	−48.96 (3.9)
Condition 3 (ASHP+PV) cost (payback, years)	−17.02 (11.6)	−15.83 (13.8)