

Design, Analysis and Comparative Case Study of PV-Integrated Horizontal Ground Source and Air-to-Water Heat Pump Systems

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Abstract - This paper presents a unified design and performance-evaluation framework for photovoltaic (PV)-integrated heat pump systems, examining two complementary configurations: a horizontal closed-loop ground source heat pump (GSHP) and an air-to-water heat pump, both powered by rooftop PV generation. The objective is to consolidate loop-field sizing and thermal-electrical power-calculation procedures into a single design methodology that can guide the selection between ground-coupled and air-coupled renewable heating solutions. The methodology combines heat-load estimation and soil-conductivity-based trench sizing for the horizontal loop field with mass-and-specific-heat-based power sizing for the air-to-water configuration, supported by a comparative case study contrasting standard PV, photovoltaic-thermal (PVT), and battery-backed PV integration strategies, together with their component inventories and installed costs. The results indicate that standard PV integration with a horizontal GSHP offers the most favourable balance between capital cost and long-term energy savings, PVT collectors deliver superior thermal yield at a substantially higher cost, and battery-backed PV integration with an air-to-water heat pump offers greater siting flexibility where loop-field land is unavailable. These findings provide practical guidance for sizing and selecting PV-integrated heat pump systems in new-build and retrofit applications aimed at zero-energy performance.

Key Words: ground source heat pump, air-to-water heat pump, photovoltaic integration, loop-field design, renewable energy systems, energy cost savings.

1. INTRODUCTION

Rising expectations for decarbonised space and water heating have pushed building services toward hybrid arrangements that pair a heat-upgrading device with an on-site renewable electricity source. A heat pump does not generate heat directly; instead, it withdraws low-grade thermal energy from an available reservoir — the surrounding air, the shallow subsurface, or a water body — and raises it to a usable temperature through a vapour-compression cycle, consuming considerably less primary energy than a combustion boiler for an equivalent heat output. Ground-coupled units draw on the comparatively stable temperature found a few metres below grade, which keeps their performance largely insensitive to outdoor air conditions, whereas air-coupled units exchange heat directly with ambient air and therefore respond more directly to seasonal swings but avoid the excavation and land footprint that ground coupling requires.

Photovoltaic panels complement either heat pump type by converting incident sunlight into direct-current electricity, which is then inverted to alternating current to run the compressor, circulation pumps and controls. Wiring PV output into the heat pump's electrical supply — with or without battery buffering — shifts a meaningful share of the heating load away from the grid, reducing both the operating cost and the associated carbon intensity of the delivered heat.

This paper treats the horizontal closed-loop GSHP and the air-to-water heat pump as two design variants of one underlying PV-integration approach rather than as

separate technologies. The loop-field sizing method, the electrical power-sizing method, the component architecture, the case-study cost data and the future-development roadmap originally documented for each variant separately are consolidated here into a single design reference, and standard PV, photovoltaic-thermal (PVT) and battery-backed PV integration strategies are compared on cost and performance grounds to inform configuration selection.

2. SYSTEM OVERVIEW AND DESIGN METHODOLOGY

2.1 Current Scenario

Heat pumps are already being coupled with a range of renewable and low-carbon energy sources, each bringing a distinct set of integration challenges. The principal combinations reported in practice are summarised below.

- Biomass-assisted heating, in which a heat pump operates alongside a biomass boiler; fuel sourcing logistics and emissions control remain the main constraints.
- Wind-assisted heat pumps, which draw electricity from an on-site or grid-connected wind turbine; the intermittent and variable nature of wind output complicates matching supply to heating demand.
- Geothermal-coupled systems, in which a ground source heat pump exchanges heat with the subsurface; performance is strong but installation cost and land or site suitability can be limiting.

- Solar-thermal-assisted systems, which pre-heat the working fluid using collected solar thermal energy; the added collector loop increases system complexity.
- Tidal-assisted systems, which harness the kinetic energy of tidal movement to generate the electricity that drives the heat pump.
- Hydrogen fuel-cell-assisted systems, which use hydrogen as a clean electricity source for the heat pump's electrical load.
- Combined heat and power (CHP) integration, where a single fuel source is used to generate both electricity and useful heat alongside the heat pump.
- Bioenergy-assisted systems, which use biogas or other biofuels derived from organic matter as a heat or electricity source.

Across these options, high upfront capital cost, supply intermittency, and site- or fuel-sourcing constraints are the recurring barriers, which is what motivates the narrower and more predictable pairing of heat pumps with directly wired PV electricity examined in this paper.

2.2 System Description

In both design variants considered here, PV panels supply direct-current electricity that is converted to alternating current by an inverter and used to run the heat pump's compressor, circulation pumps, fans and controls; any surplus generation can be buffered in a battery bank or, for the ground-coupled variant, offset against a photovoltaic-thermal (PVT) collector option. A comparison of the two PV strategies shows a clear cost-performance trade-off: PVT collectors raise the delivered thermal yield of the system but do so at a markedly higher per-panel cost than standard PV modules, which makes plain PV electrical coupling the more cost-effective default for most installations even though PVT retains an efficiency advantage where roof area is limited.

Horizontal GSHP variant. For the ground-coupled configuration, heat is exchanged with the subsurface through a horizontal closed loop buried below the frost line, where, under typical central-US conditions, ground temperature remains in the region of 10-15 °C at a depth of roughly 30 feet. The loop pipework is formed from high-density polyethylene (HDPE) or cross-linked polyethylene (PEXa); the Slinky™ coiling technique packs additional pipe length into a shorter trench, reducing excavation and installation cost relative to a straight-run layout. A typical horizontal field requires on the order of 150-180 metres of pipe per ton of installed capacity and between a quarter and three-quarters of an acre of land, depending on soil conditions.

Air-to-water variant. Where land for a loop field is unavailable, an air-to-water heat pump extracts heat directly from outdoor air through a refrigeration cycle and delivers it to a hydronic distribution loop serving radiators, underfloor heating and a domestic hot water

(DHW) tank, avoiding excavation entirely at the cost of some seasonal performance variation.

Common component architecture. Both variants share the same five functional groups of equipment, distinguished mainly in the fourth and fifth groups by whether the heat source is the ground or outdoor air:

- Heat pump unit — compressor and refrigerant-to-water heat exchanger.
- Indoor distribution equipment — DHW storage tank, circulator pump, expansion vessel, and terminal units such as radiators or underfloor heating.
- Control system — pressure sensors, thermostat, an energy management system, and a smart meter for monitoring generation and consumption.
- PV generation equipment — PV panels, roof or ground mountings, and an inverter (with an optional battery bank for the air-to-water variant).
- Heat-source-side equipment — for the horizontal GSHP, HDPE ground loop pipework and manifolds; for the air-to-water unit, the outdoor air-source evaporator coil and fan assembly.

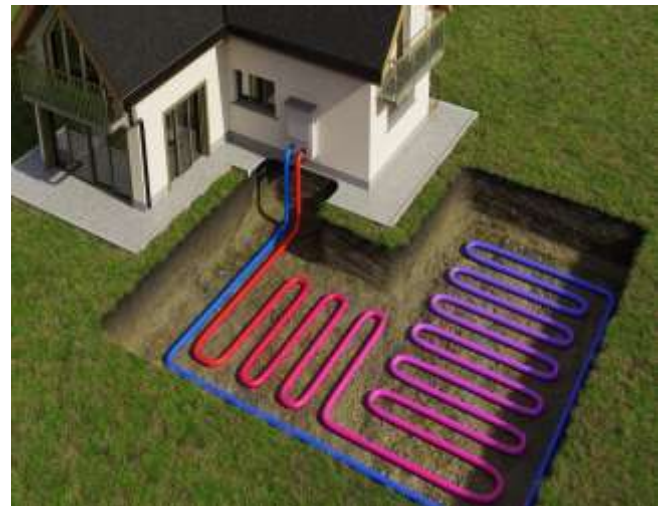


Fig-1: Horizontal closed-loop GSHP with PV integration – system schematic

Fig-2: PV-integrated air-to-water heat pump – system schematic (CAD MODEL)

2.3 Design Methodology and Calculations

Two sizing procedures are presented below: loop-field sizing for the horizontal GSHP variant, and electrical power sizing for the air-to-water variant. Both begin from a defined heating and hot-water demand and proceed to a physical or electrical sizing result.

2.3.1 Case A – Horizontal GSHP loop-field sizing

Step 1 – Total heat load. The total heat load Q_o is the sum of the space-heating demand (Q_h), the domestic-water-heating demand (Q_w) and the ventilation demand (Q_v):

$$Q_{\Sigma} = Q_h + Q_w + Q_v = Q_o$$

Step 2 – Condenser output. The total energy demand at the condenser is derived from Q_o and the heat pump's coefficient of performance, giving the thermal output the ground loop must be sized to reject or extract.

Step 3 – Loop-field sizing. For a representative dry-clay soil with a specific heat-extraction capacity q_E of 25 W/m² and a total heat load Q_o of 10,000 W, the required ground area A follows from $A = Q_o / q_E$:

$$A = 10,000 / 25 = 400 \text{ m}^2$$

With 32 mm diameter pipe laid at a rate of 1.5 m of pipe per m² of ground area, the required pipe length is:

$$L = 400 \times 1.5 = 600 \text{ m}$$

Taking 100 m of pipe as one loop, this yields 600/100 = 6.1, rounded to 6 loops of underground coil for this 400 m² field.

A smaller worked example in the source design notes considers raising 250 litres of water from 5 °C to 45 °C, for which a 1-ton system with 2 loops of underground coil is sufficient; this is a separate, smaller-capacity instance from the 400 m² / 6-loop field above and the two results should not be read as sizing the same installation. Both values are retained here as originally specified, and the appropriate one should be selected according to the actual site heat load.

2.3.2 Case B – Air-to-water heat pump power sizing

Design assumptions: heat load demand 3500 W; heating space 90-130 sq. ft; hot-water demand 75 litres; hot-water delivery temperature 45 °C; incoming cold-water temperature 5 °C.

The energy required to heat the 75-litre DHW draw is obtained from the sensible-heat relation $Q_o = \text{mass} \times \text{specific heat capacity} \times \text{temperature rise}$:

$$Q_o = 75 \text{ kg} \times 4186 \text{ J/kg} \cdot ^\circ\text{C} \times 40 ^\circ\text{C} = 12,558,000 \text{ J}$$

Converting from joules to watt-hours (1 Wh = 3600 J):

$$12,558,000 \text{ J} / 3600 = 3488.33 \text{ Wh} \approx 3.5 \text{ kWh}$$

Conclusion: a 75-litre draw of water can be heated from 5 °C to 45 °C within one hour by a heat pump delivering approximately 3.5 kW, which sets the minimum electrical/thermal duty the PV and battery system must be able to support during a heating cycle.

2.4 Installation Considerations

Installation planning differs mainly at the heat-source interface. For the horizontal GSHP, siting decisions must account for location and climate zone (a central-US condition is assumed here), heat pump capacity, trench length, trench-to-trench gap, trench depth, slinky coil

length and diameter, compressor capacity, and the glycol charge of the loop fluid; trenching is carried out to below the frost line and the coiled HDPE pipe is laid before backfilling, as shown in Fig-3 and Fig-4. For the air-to-water unit, installation instead centres on siting the outdoor air-source unit for adequate airflow, connecting the indoor hydronic distribution equipment, and mounting the PV array and, where used, the battery bank and hybrid inverter.



Fig-3: Horizontal ground-loop trenching and pipe-coil installation



Fig-4: Completed horizontal loop-field trenches prior to backfill

Table-1: Component requirements by system variant

Functional group	Horizontal GSHP components	Air-to-water HP components
Heat pump unit	Compressor unit, refrigerant heat exchanger	Compressor unit, refrigerant heat exchanger
Indoor unit	DHW tank, circulator pump, expansion vessel, radiators / underfloor heating	DHW tank, circulator pump, expansion vessel, radiators / underfloor heating
Control system	Pressure sensor, thermostat, energy management system, smart meter	Pressure sensor, thermostat, energy management system, smart meter

Functional group	Horizontal GSHP components	Air-to-water HP components
PV / storage system	PV panels, mountings	PV panels, mountings, battery bank, hybrid inverter
Heat-source-side equipment	HDPE ground-loop pipes, manifolds	Outdoor air-source evaporator coil and fan unit

2.5 Case Study

Three configurations are compared in this section: a horizontal GSHP paired with standard PV panels, the same horizontal GSHP paired with PVT collectors, and an air-to-water heat pump paired with a battery-backed

PV system. Across the GSHP cases, PVT collectors are found to deliver a higher thermal yield than standard PV, but the higher per-panel cost of PVT makes standard PV the more cost-effective choice for most projects; the air-to-water case, by contrast, trades the land requirement of the loop field for the added cost of battery storage.

Table-2: Comparative case-study summary – demand, size and installed cost

Configuration	Component	Demand / capacity	Quantity / size	Cost (₹)	Cost (£)
Case 1: PV + Horizontal GSHP	PV panel (400 W)	35 kW (12 hr)	22 panels	14,000–17,000 /panel	140–170 /panel
	GSHP (horizontal)	10 kWh (350 L DHW)	600 m pipe (6 loops)	37,00,000–38,00,000	35,000–36,000
Case 2: PVT + Horizontal GSHP	PVT collector – electrical	35 kW (12 hr)	25 panels	74,000–84,000 /panel	700–800 /panel
	PVT collector – thermal (DHW)	10 kWh (350 L DHW)	14 panels	74,000–84,000 /panel	700–800 /panel
Case 3: PV + Air-to-water HP	PV panel (400 W)	—	12 panels	14,000–17,000 /panel	—
	Battery bank	150 Ah / 250 Ah	7×150 Ah, 4×250 Ah	12,000–16,000 (150Ah); 19,000–23,000 (250Ah)	—
	Hybrid inverter	5 kW	1	1,00,000–1,50,000	—

Table-3: PV versus PVT collector attribute comparison

Attribute	PV-based	PVT-based
Electrical efficiency	20–23%	17–19%
Thermal efficiency	—	50–76%
Coefficient of performance (COP)	—	4.5–5
Cost (per panel)	₹14,000–₹17,000	₹74,000–₹84,000
Size variants	250 W – 700 W	200 W – 800 W
Weight	20–25 kg (approx.)	20–30 kg
Life span	25–30 years	20–25 years



Fig-5: Horizontal GSHP CAD model with rooftop PV array

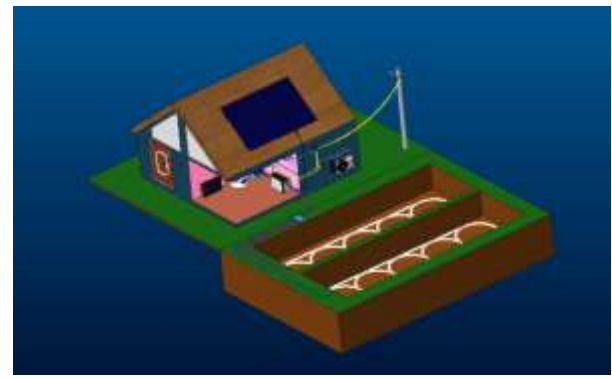


Fig-6: PV-integrated air-to-water heat pump CAD model

2.6 Savings Analysis

For a 5-ton heat pump, the estimated electrical demand without renewable coupling is 60 kW; integrating the unit with the horizontal GSHP reduces this to 35 kW, giving a saving of 25 kW per day. Expressed monthly at a 30-day billing cycle, the saving is:

$$\text{Monthly saving} = 25 \text{ kW} \times 30 \times (\text{cost per unit})$$

Applying representative residential electricity tariffs – ₹10 per unit in India, £0.25 per unit in the UK, and 14.92 cents per unit in the US – gives the monthly cost avoidance summarised in Table-4.

Table-4: Estimated monthly savings from GSHP-PV integration (25 kW/day reduction)

Power saved	Saving – India (₹)	Saving – UK (£)	Saving – US (\$)
25 kW/day	9,000	187.5	110

For the air-to-water configuration, directing self-generated PV electricity to the heat pump likewise reduces grid draw and the associated electricity and heating cost, while the battery bank extends self-consumption into non-generating hours, improving the economics of both the PV array and the heat pump beyond what either would achieve running independently.

3. CONCLUSIONS

Coupling PV generation with a heat pump – whether ground- or air-coupled – allows the thermal and electrical halves of a building's energy demand to be met largely from on-site renewable resources, cutting grid dependence, operating cost and carbon emissions relative to either technology used alone. The comparison in this paper indicates that standard PV integration with a horizontal GSHP gives the best balance of installed cost and long-term saving for sites where loop-field land is available, since the two subsystems can each be sized and operated near their individual optimum without the added capital cost of PVT collectors. PVT integration remains justified where thermal yield per unit roof area is the binding constraint, despite its higher cost and generally shorter service life relative to PV. Where land for a horizontal loop field cannot be accommodated, an air-to-water heat pump paired with battery-backed PV offers a practical alternative, trading the excavation requirement

for additional storage cost. In all three configurations, self-consumption of PV electricity by the heat pump reduces the load placed on the distribution grid, improves the economic return on the PV investment, and moves the building closer to zero-energy operation.

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FUTURE SCOPE

Energy storage and smart energy management:

Adding electrical battery storage and thermal storage (hot-water tanks or phase-change material) buffers the mismatch between PV generation and heating demand; smart control and automation, coupled with demand-response participation and continuous performance monitoring, can align heat-pump operation with real-time PV output to maximise self-consumption and flag efficiency losses early.

Hybridisation with other renewable sources:

Diversifying the electrical supply with wind, biomass, tidal or hydrogen-derived electricity improves resilience where solar resource is seasonal or intermittent, and sector coupling with electric vehicles and wider smart-home energy management can extend the same self-consumption logic across transport and building loads.

Heat pump performance and material advancements:

Variable-speed compressors allow output to track real-time heating and cooling needs rather than cycling on/off, improving part-load efficiency; continued development of low global-warming-potential refrigerants and improved heat exchangers can raise coefficient of performance, particularly in cold-climate operation, and hybrid multi-source heat pumps that draw on air, ground and water as conditions allow can further stabilise seasonal performance.

Grid interaction and demand-side flexibility:

Bidirectional heat pump operation – shifting between heating and cooling duty and dynamically time-shifting operation to periods of high PV output or low grid demand – can improve grid stability while reducing the occupant's exposure to peak tariffs.