

БУДІВНИЦТВО ТА ЦИВІЛЬНА ІНЖЕНЕРІЯ (G19)

UDC 697.1:620.92

**PERFORMANCE OPTIMIZATION OF HYBRID HEATING SYSTEMS WITH
COMBINED HEAT SOURCES AND MECHANICAL VENTILATION HEAT RECOVERY**

PhD (Tech.) P. V. Rukavishnikov, PhD (Tech.) V. S. Bugai, PhD (Tech.) Y. I. Chaika,
PhD (Tech.) Y. O. Burda, Ph.D. student S. O. Marchenko

**ОПТИМІЗАЦІЯ ЕФЕКТИВНОСТІ ГІБРИДНИХ СИСТЕМ ОПАЛЕННЯ З
КОМБІНОВАНИМИ ДЖЕРЕЛАМИ ТЕПЛОТИ І РЕКУПЕРАЦІЄЮ ТЕПЛА
ВЕНТИЛЯЦІЇ**

Кандидати техн. наук П. В. Рукавішников, В. С. Бугай, Ю. І. Чайка, Ю. О. Бурда,
асп. С. О. Марченко

DOI: <https://doi.org/10.18664/1994-7852.217.2026.371328>



Abstract. This study develops and validates a comprehensive thermoeconomic model to optimize hybrid heat supply systems for residential and small industrial buildings, specifically tailored to the continental climate of Kharkiv Oblast, Ukraine. Unlike conventional studies that treat heat generation and ventilation in isolation, this model explicitly integrates the dynamic thermal load of mechanical ventilation with heat recovery, which accounts for 10–15 % of the total seasonal demand. Four distinct hybrid source configurations—integrating gas boilers, ground-source heat pumps (GSHP), and solar thermal collectors—were modeled and analyzed. The objective function minimizes the specific heat generation cost, accounting for capital recovery, operational expenditures, and varying energy tariffs. Validation against TRNSYS benchmarks and national standards confirms the model's reliability, with relative deviations below 5.88 %. The results identify the tri-source configuration (Boiler + GSHP + Solar) as the global optimum, achieving a specific cost of 7.65 USD/GJ and minimizing carbon emissions. Furthermore, the study establishes that mechanical ventilation heat recovery with $\eta_{rec} \geq 0.70$ is economically justified when outdoor temperatures fall below +2 °C, providing a practical framework for optimizing hybrid energy systems in regional conditions.

Keywords: hybrid heating systems, thermoeconomic optimization, mechanical ventilation, heat recovery, ground-source heat pump, energy efficiency.

Анотація. Дослідження присвячено розробленню та верифікації комплексної термoeкономічної моделі для оптимізації гібридних систем теплопостачання житлових і малих промислових будівель, адаптованої до кліматичних і тарифних умов Харківської області. На відміну від традиційних підходів, де генерацію теплоти і вентиляційні втрати розглядають ізольовано, запропонована модель інтегрує динамічне теплове навантаження механічної вентиляції з рекуперацією теплоти, частка якого становить 10–15 % загального

сезонного попиту на енергію. Такий підхід дає змогу більш повно врахувати взаємозв'язок між параметрами систем теплопостачання, вентиляції та умовами експлуатації будівель.

ISSN (p) 1994-7852

ISSN (online) 2413-3795

© Рукавішников П. В., Бугай В. С., Чайка Ю. І.,
Бурда Ю. О., Марченко С. О., 2026.

У статті проаналізовано чотири конфігурації гібридних джерел енергії, що поєднують газові котли, ґрунтові теплові насоси та сонячні колектори. Для кожної конфігурації оцінено енергетичні, економічні та екологічні показники з урахуванням сезонної нерівномірності теплового навантаження, змін зовнішніх кліматичних умов і чинних тарифів на енергоносії. Цільова функція моделі спрямована на мінімізацію питомих витрат на виробництво теплоти з урахуванням капітальних інвестицій, експлуатаційних витрат, вартості енергоносіїв і витрат, пов'язаних із роботою вентиляційного обладнання.

Верифікація моделі за допомогою програмного комплексу TRNSYS і вимог чинних стандартів ДСТУ підтвердила її достовірність: відхилення розрахункових результатів не перевищує 6 %. Отримані результати дали змогу ідентифікувати триджерельну конфігурацію, що включає газовий котел, тепловий насос і сонячний колектор, як глобально оптимальне рішення. Застосування такої системи забезпечує досягнення питомих витрат на рівні 7,65 USD/ГДж за одночасного мінімуму викидів CO₂.

Крім того, встановлено, що впровадження рекуперації теплоти вентиляційного повітря з ефективністю $\eta_{\text{rec}} \geq 0,70$ є економічно доцільним за температур зовнішнього повітря нижче +2 °C. Отримані результати формують практичну основу для підвищення енергоефективності будівель і розроблення оптимальних систем теплопостачання для умов континентального клімату.

Ключові слова: гібридні системи опалення, термoeкономічна оптимізація, механічна вентиляція, рекуперація тепла, ґрунтовий тепловий насос, енергоефективність.

Introduction. The share of energy consumed by building heating infrastructure in Ukraine's residential and industrial sectors has remained persistently high over the past two decades, largely because most existing systems operate on a single-source principle with limited capability to adjust to variable thermal demand or seasonal fuel availability. Conventional gas boiler plants, which still constitute the dominant heat supply technology in urban and peri-urban districts, provide thermal output at relatively stable cost when fuel prices remain predictable; however, prolonged reliance on a single energy carrier introduces both economic vulnerability and structural inefficiency, since nominal boiler capacity is typically sized for peak winter conditions and operates at partial load for the majority of the heating period.

The transition toward multi-source or hybrid heat supply configurations has been gaining practical relevance in Ukraine since the early 2010s, primarily through the gradual introduction of solar thermal collectors and ground-source heat pump installations in new construction and deep energy renovations. These technologies differ fundamentally in

their operating characteristics: solar collectors deliver useful heat proportional to instantaneous irradiance and are most productive during shoulder seasons, whereas ground-source heat pumps draw on a relatively stable low-temperature source and depend on electrical input, making their economic performance sensitive to electricity tariffs. When combined with a conventional boiler as a backup and peak-load unit, such configurations create a hybrid system in which the contribution of each source can, in principle, be adjusted according to external conditions, internal demand, and economic objectives.

Despite growing practical interest, the comparative thermoeconomic performance of different hybrid configurations under Ukrainian climatic and tariff conditions has not been systematically quantified. Available studies tend to treat each technology in isolation or to evaluate hybrid configurations under assumptions that reflect northern European or Central Asian operating environments, which differ substantially from the continental climate of eastern Ukraine in terms of heating season length, solar irradiance distribution, and ground temperature profile. As a result, design

decisions in local practice still rely heavily on generalised efficiency data from equipment manufacturers rather than on region-specific analytical models that account for the actual interaction between sources across the full heating period.

A further complication arises from the ventilation component of the total thermal demand. In buildings designed or renovated according to contemporary energy standards, mechanical ventilation with heat recovery represents a non-trivial fraction of the seasonal heat requirement, typically in the range of 10 to 15 percent of total consumption when fresh air supply rates comply with current sanitary norms. This contribution is frequently excluded from hybrid system energy balances in applied studies, which leads to underestimation of total heat supply obligations and distorts the comparative assessment of source combinations — particularly under partial-load conditions when boiler modulation is most sensitive to changes in total demand.

The present study aims to address this gap by developing and applying a thermoeconomic model of hybrid heat supply systems for residential and small industrial buildings under the climatic conditions of Kharkiv Oblast. Four distinct source configurations are examined: a gas boiler combined with a flat-plate solar collector; a gas boiler combined with a ground-source heat pump; a three-source system integrating a boiler, heat pump, and solar collector; and a fourth configuration utilising geothermal heat as the base source supplemented by solar energy and a boiler peak unit. For each configuration, the total thermal demand includes an explicitly calculated ventilation load, which allows the model to reflect realistic operating obligations rather than simplified envelope-only heat balances.

The thermoeconomic evaluation uses specific heat generation cost as the primary criterion, expressed as the ratio of total annual expenditure — including fuel, electricity, and proportional capital cost recovery — to delivered useful heat. This criterion enables direct comparison of configurations with

different source combinations and allows identification of the conditions under which each configuration achieves competitive performance relative to the others.

Literature review and problem statement. The development of hybrid heat supply systems integrating two or more thermal sources has been driven by the need to reduce primary energy consumption while maintaining reliable heating output under variable external conditions. A feasibility study of a system combining photovoltaic-thermal collectors with a modular ground heat exchanger showed that the resulting hybrid achieves 93 % of the coefficient of performance of conventional vertical borehole configurations while offering substantially lower installation cost, with an emission reduction ratio of 23 % compared to conventional alternatives for an office building application [1].

The displacement-ventilation modelling approach adopted for the ventilation subsystem of the present study builds on a reduced-order formulation previously validated for microclimate formation under variable supply-air conditions [2], and on thermodynamic modelling of displacement ventilation in tightly controlled environments, where airflow stratification was shown to govern the coupling between sensible heat removal and contaminant transport [3].

The behaviour of geothermally-coupled multi-source systems under variable load conditions has been examined from a multi-criteria optimisation standpoint. Thermodynamic performance analysis of a combined heat and power system coupled with geothermal energy demonstrated that the optimal allocation between the geothermal base load and the auxiliary peak source shifts substantially once seasonal extraction reduces the source temperature, confirming that source contribution cannot be treated as a fixed seasonal ratio but must respond to the progressive thermal state of the low-grade source [4]. This finding is directly relevant to ground-coupled configurations, where entering water temperature deteriorates over extended

extraction periods without adequate thermal recharge, reducing heat pump COP and shifting a larger fraction of the total load to the backup boiler — an effect that is especially pronounced in climates with long heating seasons and limited cooling demand, where geothermal extraction significantly exceeds seasonal ground recovery. Dynamic optimisation of HVAC demand incorporating latent heat storage and heat recovery confirmed that coordinated control of source switching, rather than static threshold logic, produces measurable reductions in total primary energy consumption when source temperatures vary continuously through the heating season [5].

A fundamental configuration combining an air-to-water heat pump with a gas boiler represents the most practically accessible step toward hybridisation in existing building stock, since both components can be retrofitted into already operational hydronic distribution systems. Experimental investigation of this configuration confirmed that heat pump operation on recovered boiler flue gas reduces exhaust temperature to approximately 14 °C, achieves thermal efficiency exceeding 100 %, and lowers carbon emissions by 2.2 to 6.0 % relative to standalone boiler operation, with a payback period of 1.46 years for a heat pump capturing 12.5 % of available waste heat [6].

Multi-source configurations combining a boiler, heat pump, solar collector, and thermal storage create a significantly more complex optimisation problem because the optimal contribution of each source depends simultaneously on ambient temperature, solar irradiance, electricity tariff, and storage state of charge. Analysis of hybrid thermal protection structures under transient thermal loading confirmed that the interaction between source-switching logic and storage depletion rate introduces non-linear cost sensitivity that cannot be captured through a steady-state annual energy balance alone [7]. A review of balanced ventilation technology for dwellings highlighted the persistent difficulty of quantifying the combined energy efficiency and renewable generation contribution of

ventilation subsystems using existing international test standards, which complicates their consistent inclusion in whole-building energy balances [8].

The interaction between heat recovery ventilation and indoor air quality under variable supply conditions has been examined in controlled environments where contaminant removal and energy performance must be balanced simultaneously [9]. Economic performance assessment across multiple multi-family buildings with different HVAC configurations confirmed that system selection cannot be reduced to equipment efficiency metrics alone, since installation cost recovery and occupant thermal comfort simultaneously constrain the feasible design space [10].

A planning study of a hybrid combined cooling, heat and power system with energy storage resources demonstrated that coordinated multi-source operation can reduce operational cost by 15 to 30 % compared to independent source scheduling, but requires explicit modelling of transient storage dynamics to avoid premature depletion under peak demand intervals [11]. Experimental investigation of an HRV system coupled with an air-to-air heat pump in Canadian residential suites confirmed that ventilation heat recovery performance depends on outdoor temperature in a pattern that closely parallels the seasonal COP variation of ground-source heat pumps, suggesting that both subsystems should be modelled within the same thermal demand framework [12]. A review of heat pump energy recovery technologies integrated with building ventilation systems showed that combined heat pump and ventilation heat recovery configurations can reduce total ventilation-related energy demand by 30 to 60 % depending on climatic zone and fresh air supply rate, yet most reported systems were evaluated independently from the primary heating plant [13].

The economic evaluation of hybrid systems has progressively shifted from simple payback metrics toward life-cycle techno-economic frameworks that account for variable

energy prices, equipment degradation, and capital amortisation over the operational horizon. Techno-economic optimisation of a hybrid system with thermal energy storage within a local energy community demonstrated that the ratio of renewable to conventional source contribution is the dominant variable determining net present value, and that optimal storage sizing is strongly sensitive to the assumed electricity price trajectory [14]. Optimisation of a combined heat and power system with a hybrid prime mover using a genetic algorithm confirmed that non-linear, multi-variable search methods outperform fixed-rule dispatch strategies once more than two sources are coupled, particularly when capital and operational costs are optimised jointly rather than sequentially [15].

An ANN-based control strategy applied to a hybrid heat pump and boiler system combined with photovoltaic panels and battery storage achieved 99.16 % accuracy in operational switching decisions, reduced CO₂ emissions by up to 12 %, and produced cost savings that were most significant in colder climatic zones with higher energy tariffs [16]. An integrated approach to energy certification and microclimate quality control in contemporary construction confirmed that building energy balance assessment should incorporate ventilation subsystem performance alongside envelope and primary heat generation parameters, particularly in settings where fresh air supply requirements are regulated by sanitary norms rather than occupancy-based demand [17].

A mechanically-driven loop heat pipe heat recovery system demonstrated stable recovery effectiveness under variable operating conditions relevant to commercial building applications, indicating that passive heat-exchange recovery technologies can sustain performance outside narrow design-point conditions [18]. Comprehensive techno-economic-environmental optimisation of a hybrid solar heating system for detached buildings in a severe cold continental climate demonstrated that source contribution ratios

must be adjusted according to time-of-use tariff structure, with a validated co-simulation model confirming that purely economic optimisation and multi-criterion optimisation yield materially different equipment sizing outcomes [19]. Performance and operation strategy optimisation of a dual-source building energy supply system with heat pumps and energy storage demonstrated that the timing of storage charge and discharge cycles, rather than the nominal capacity of either source, was the primary determinant of seasonal operating cost [20]. A flexibility evaluation of a hybrid combined cooling, heating and power system with an improved operation strategy confirmed that systems optimised solely for steady-state efficiency systematically underperform under the load-following conditions typical of residential and small commercial demand profiles, reinforcing the need for dynamic, time-resolved modelling rather than design-point calculation [21].

Heat supply systems in Ukrainian building stock face a specific combination of conditions that differs from the climatic and economic contexts in which most hybrid system models have been developed and validated. The heating season in Kharkiv Oblast spans approximately 175 to 185 days, with design outdoor temperature reaching -23°C , which places ground heat pump systems in a performance regime where low entering water temperatures limit COP and necessitate extended boiler backup periods. Solar irradiance on a south-facing tilted surface during the heating season is substantially lower than in the Mediterranean or Central Asian reference climates used in many optimisation studies, which reduces the seasonal contribution of flat-plate collectors and alters the economic balance between solar investment and conventional fuel displacement. At the same time, current Ukrainian electricity and natural gas tariff structures create specific threshold relationships between heat pump and boiler operating costs that diverge from those reported in the Chinese, Italian, and South

Korean case studies that dominate the recent literature on hybrid heating optimisation.

This observation directly motivates the inclusion of a mechanically ventilated zone with heat recovery in the present hybrid system model, since the ventilation thermal load in compliant residential and small commercial buildings in Ukraine typically represents 10 to 15 % of total seasonal heat demand and cannot be excluded from a thermoeconomic comparison across source configurations without introducing systematic underestimation of boiler peak load.

The preceding review identifies three specific gaps that the present study addresses. First, no thermoeconomic comparison of multiple hybrid source configurations under Kharkiv Oblast climatic and tariff conditions has been reported in the accessible literature. Second, the contribution of mechanical ventilation heat recovery to the seasonal thermal balance of hybrid systems has not been quantified in configurations relevant to Ukrainian construction practice. Third, the criteria under which each source configuration achieves minimum specific heat generation cost — expressed as expenditure per unit of delivered useful heat — have not been established for the continental climate of eastern Ukraine.

The aim and objectives of the study

The aim of this study is to develop and validate a comprehensive thermoeconomic model for optimizing the performance of multi-source hybrid heating systems, with explicit integration of mechanical ventilation heat recovery, tailored to the climatic and economic conditions of eastern Ukraine.

To achieve this aim, the following objectives are established:

- To develop a coupled mathematical model that defines the thermal balance of four distinct hybrid heat supply configurations, explicitly incorporating the dynamic thermal load of mechanical ventilation.
- To formulate a thermoeconomic objective function aimed at minimizing the specific heat generation cost per unit of

delivered thermal energy, accounting for capital recovery and operational expenditures.

- To validate the proposed analytical model and operational parameters against established engineering standards and validated reference simulations.

- To determine the optimal operational ratios between conventional and renewable thermal sources across the variations of the heating season.

- To establish the economic boundary conditions and threshold values under which the integration of ventilation heat recovery provides a cost-optimal reduction of the primary heating plant peak load.

The main part of the study

To comprehensively evaluate the thermoeconomic performance of the proposed hybrid heating configurations under the specific climatic conditions of Kharkiv Oblast, a coupled mathematical model was developed. This model formally integrates the primary heat generation dynamics with the transient thermal load imposed by the mechanical ventilation subsystem, treating heat recovery not as a static reduction factor, but as an active component interacting with the primary thermal plant. The investigation explicitly models and compares four distinct source configurations: a baseline hybrid combining a gas boiler with a flat-plate solar collector; a system pairing a gas boiler with a ground-source heat pump (GSHP); a tri-source configuration integrating a boiler, GSHP, and solar collector; and a geothermally-driven base system supplemented by solar thermal energy and a peak-load boiler.

The objective of the numerical investigation is to determine the optimal proportional contribution of each thermal source across the heating season, minimizing the specific heat generation cost while satisfying the continuous building heat demand and the required displacement ventilation air exchange rates. To achieve this, an energy balance approach was formulated, incorporating time-dependent variables such as ambient temperature variations, solar

irradiance, and dynamic equipment efficiencies.

The processing of experimental data and the numerical modelling of the displacement ventilation processes, alongside the broader system energy balances, were executed using the Python programming language. Specifically, the fundamental thermodynamic calculations, matrix operations, and the resolution of the non-linear algebraic equations governing the source-switching logic were performed utilizing the SciPy and NumPy libraries. This computational approach enabled high-resolution, step-by-step modelling of the heating season without the computational overhead of commercial simulation software. The visualization of the operational profiles, energy contribution ratios, and thermoeconomic response surfaces was conducted using the Matplotlib library.

To ensure the physical reliability and mathematical accuracy of the numerical results without relying on proprietary simulation environments, a rigorous analytical validation protocol was implemented. The core thermodynamic model was verified through strict energy conservation checks (First Law of Thermodynamics) at each simulation time step, confirming that the total energy supplied by the hybrid sources exactly matched the calculated building envelope losses, the explicitly modelled ventilation load, and internal system losses. Furthermore, the numerical performance curves for the individual subsystems—specifically the heat pump COP degradation under variable source temperatures, the solar collector efficiency, and the sensible heat recovery effectiveness—were directly benchmarked against the standard analytical calculation procedures defined in European norms EN 15316 (heating system energy requirements) and EN 308 (heat recovery components). The comparative analysis demonstrated that the maximum relative deviation between the Python-based numerical solution and the established normative steady-state benchmarks did not exceed 4.8 %. This margin of error falls well

within the acceptable limits for engineering design, thereby confirming the physical consistency and computational validity of the proposed model for subsequent thermoeconomic optimization.

To evaluate the thermodynamic processes of heat supply, analytical models were formulated for four distinct hybrid heating configurations. At any given operational time t , the total thermal demand of the system is dictated by the necessity to offset both the transmission losses through the building envelope and the dynamic energy required for heating the supply air:

$$Q_{total}(t) = Q_{env}(t) + Q_{vent}(t), \quad (1)$$

where $Q_{total}(t)$ is the total required thermal power at time t , W;

$Q_{env}(t)$ is the thermal power required to compensate for envelope transmission losses, W;

$Q_{vent}(t)$ is the thermal power required for supply air heating, W.

Description of Configurations and Heat Balance Equations.

The operational logic of the hybrid configurations relies on distributing the total thermal load among various generation sources to minimize primary energy consumption. The heat balance equations for the four investigated configurations are defined as follows:

Configuration 1: Gas Boiler + Flat-Plate Solar Collector A fundamental combined scheme where the solar thermal collector provides pre-heating for the heat carrier or covers domestic hot water loads, while the gas boiler operates as a peak-load unit to elevate the supply temperature to normative parameters.

$$Q_{total}(t) = Q_{boiler}(t) + Q_{solar}(t). \quad (2)$$

Configuration 2: Gas Boiler + Ground-Source Heat Pump (GSHP) A configuration utilizing low-potential geothermal energy as the base source. The heat pump covers the primary cyclical load, whereas the boiler is activated

exclusively during extreme outdoor temperature drops when the coefficient of performance (COP) of the heat pump deteriorates.

$$Q_{total}(t) = Q_{boiler}(t) + Q_{GSHP}(t). \quad (3)$$

Configuration 3: Tri-Source System (Gas Boiler + GSHP + Solar Collector) An

integrated multi-source scheme combining a stable ground source with a season-dependent solar loop. This configuration creates the potential for surplus solar thermal yield during transitional periods to contribute toward ground mass regeneration, which may help stabilize the heat pump's entering water temperature; this interaction is not separately resolved within the present energy balance and is treated as a qualitative system characteristic.

$$Q_{total}(t) = Q_{boiler}(t) + Q_{GSHP}(t) + Q_{solar}(t). \quad (4)$$

Configuration 4: District Boiler Plant + Geothermal Heat + Solar Energy

A macro-level configuration designed for the integration of renewable sources into existing district heating networks. The base

thermal load is distributed between the large-scale geothermal loop and the solar array, while any capacity deficit is compensated by extracting thermal energy from the centralized district grid.

$$Q_{total}(t) = Q_{district}(t) + Q_{geo}(t) + Q_{solar}(t). \quad (5)$$

The variables for the generation sources are defined as:

- $Q_{boiler}(t)$ is the thermal power supplied by the local gas boiler, W ;
- $Q_{solar}(t)$ is the thermal power generated by the solar collector array, W ;
- $Q_{GSHP}(t)$ is the thermal power delivered by the ground-source heat pump, W ;
- $Q_{district}(t)$ is the thermal power extracted from the centralized district heating network, W ;
- $Q_{geo}(t)$ is the thermal power supplied by the district-scale geothermal loop, W .

Ventilation Load Model. In buildings designed or renovated in compliance with contemporary thermal insulation standards, the mechanical ventilation component consistently constitutes 10 % to 15 % of the total seasonal heat demand. To explicitly account for this dynamic load, the heat required to condition the incoming outdoor air—incorporating the operation of mechanical ventilation and exhaust air heat recovery—is calculated using the following equation.

$$Q_{vent}(t) = \rho \cdot c_p \cdot \dot{V} \cdot (T_{int} - T_{ext}(t)) \cdot (1 - \eta_{rec}), \quad (6)$$

where ρ is the density of the supply air, $kg \cdot m^{-3}$;

c_p is the specific heat capacity of air at constant pressure, $J \cdot kg^{-1} \cdot K^{-1}$;

$\dot{V}$ is the volumetric flow rate of the supply air, strictly governed by sanitary air exchange norms, $m^3 \cdot s^{-1}$;

T_{int} is the normative indoor design temperature, C ;

$T_{ext}(t)$ is the transient outdoor air temperature at calculation hour t , C ;

η_{rec} is the sensible heat recovery effectiveness coefficient of the ventilation unit (dimensionless).

The dynamic interaction of this ventilation load with the primary generation plant serves as a critical boundary condition for the thermoeconomic optimization. The fluctuating nature of $T_{\text{ext}}(t)$ and the varying efficiency of the heat recovery unit direct the required residual peak load, fundamentally altering the source-switching logic of the hybrid system.

To evaluate the feasibility and efficiency of the proposed hybrid configurations, a COP-based thermoeconomic model was formulated. The primary objective of the optimization is the

minimization of the specific heat generation cost, defined as the total financial expenditure required to produce one unit of useful thermal energy (e.g., 1 GJ or 1 kWh), explicitly accounting for variable energy tariffs, operational efficiencies, and capital cost recovery.

The objective function for the specific heat generation cost, C_{spec} , is structured to aggregate both operational and amortized capital expenditures over the entire heating season. The function is expressed as:

$$C_{\text{spec}} = \frac{\sum_{t=1}^{t_h} \left[c_{\text{gas}} \cdot \frac{Q_{\text{boiler}}(t)}{\eta_{\text{boiler}}(t)} + c_{\text{el}} \cdot \frac{Q_{\text{GSHP}}(t)}{\text{COP}(t)} \right] \cdot \Delta t + \sum_i \frac{Z_i}{\tau_i}}{Q_{\text{season}}} \rightarrow \min, \quad (7)$$

where c_{gas} and c_{el} are the specific local tariffs for natural gas and electricity, respectively, $\text{USD} \cdot \text{kWh}^{-1}$;

$\eta_{\text{boiler}}(t)$ is the dynamic efficiency of the gas boiler (dimensionless);

$\text{COP}(t)$ is the real-time coefficient of performance of the ground-source heat pump (dimensionless);

Z_i is the total capital investment cost for subsystem i (e.g., boiler, heat pump, solar loop);

τ_i is the operational amortization period or expected lifespan for subsystem i , years;

t_h is the total duration of the heating season, h;

Δt is the simulation time step (typically 1 hour), h;

Q_{season} is the total useful thermal energy delivered over the season, which strictly includes the mechanical ventilation load, kWh.

The minimization of C_{spec} subject to constraints (8) – (10) was solved numerically as a constrained non-linear programming problem using the Sequential Least Squares Programming (SLSQP) solver implemented in the SciPy optimize module, applied independently at each simulation time step within the seasonal time series.

The primary optimization variables are the dynamic capacity fractions (load coverage ratios) assigned to each active thermal source at any given hour t . The control strategy is designed to minimize C_{spec} while satisfying the continuous building demand and adhering to the following technical constraints:

Supply Temperature Constraint:

The hybrid generation plant must consistently deliver the required flow temperature $T_{\text{supply}}(t)$ dictated by the building's hydronic heating curve, which adjusts according to the outdoor conditions:

$$T_{\text{supply}}(t) \geq T_{\text{target}}(T_{\text{ext}}). \quad (8)$$

Heat Pump Operational Limits:

The GSHP operates efficiently only when the entering water temperature (EWT) from the ground loop remains above a critical minimum threshold. This constraint prevents the progressive thermal depletion (freezing) of the ground mass and extreme COP degradation during peak extraction periods:

$$T_{\text{EWT}}(t) \geq T_{\text{min, EWT}}. \quad (9)$$

Source Capacity Limits

The instantaneous thermal output of the system must exactly equal the total dynamic load $Q_{\text{total}}(t)$ at all times, and the output of any individual heat generator i cannot exceed its nominal installed capacity $Q_{\text{nom},i}$:

$$0 \leq Q_i(t) \leq Q_{\text{nom},i}. \quad (10)$$

By imposing these constraints, the model identifies the precise outdoor temperature threshold and tariff ratio at which switching from the heat pump to the peak gas boiler—or reducing the ventilation thermal load via heat recovery—becomes economically optimal.

Model Validation.

Having confirmed component-level consistency against the EN 15316 and EN 308 normative procedures described above, a second, system-level validation stage was carried out against independent literature benchmarks to verify the model's behaviour under realistic, non-steady-state operating conditions. To ensure the reliability and physical accuracy of the developed Python-based thermoeconomic model prior to optimization, a comprehensive validation procedure was executed. The numerical results generated by the proposed mathematical model were benchmarked against established normative datasets and validated reference simulations from recent literature.

For the primary heating plant parameters, the model was compared against validated reference cases simulated in the TRNSYS 18 environment under comparable climatic boundary conditions. The ground-source heat pump performance baseline was established using empirical data from hybrid PVT-GSHP integration studies. For the mechanical ventilation subsystem, the heat recovery effectiveness was verified against experimental performance data of HRV systems coupled with heat pumps in cold climates.

The mathematical criterion for validation is the relative deviation (δ) between the calculated values (X_{calc}) and the reference values (X_{ref}). For complex building energy

simulations, the model is considered valid and applicable for engineering optimization if the relative deviation does not exceed the strictly defined threshold of 5 to 8 %:

$$\delta = \left| \frac{X_{\text{calc}} - X_{\text{ref}}}{X_{\text{ref}}} \right| \cdot 100\% \leq 8\%. \quad (11)$$

The validation focused on three critical operational parameters that dictate the hybrid system's seasonal energy balance:

Seasonal Coefficient of Performance ($SCOP_{\text{GSHP}}$): Represents the long-term efficiency of the ground-source heat pump under dynamic entering water temperatures.

Solar Thermal Fraction (f_{solar}): Determines the percentage of the total thermal load covered by the solar collector array in Configuration 1 and Configuration 3.

Sensible Heat Recovery Effectiveness (η_{rec}): Characterizes the thermodynamic efficiency of the mechanical ventilation subsystem during the peak heating period.

The comparative analysis between the proposed mathematical model and the established reference benchmarks is presented in Table.

As demonstrated in Table, the maximum relative deviation observed is 5.88 % for the solar thermal fraction, which remains well within the predefined acceptable tolerance limit of 8 %. The deviations in the $SCOP_{\text{GSHP}}$ and η_{rec} parameters are approximately 2 %, indicating a high degree of convergence with both the dynamic simulation environments and experimental investigations reported in the literature.

These results confirm that the developed dynamic thermal balance equations, including the explicitly integrated transient ventilation load model, accurately capture the physical behavior and nonlinear interactions of the multi-source hybrid heating configurations. Consequently, the mathematical model is deemed robust and valid for conducting the subsequent thermoeconomic optimization under the specified regional conditions.

The distribution of the total seasonal thermal load among the active generation sources is illustrated in Fig. 1. The total load curve reflects the superposition of envelope

transmission losses and the dynamic ventilation thermal load, which is explicitly integrated into the model.

Table

The comparative analysis between the proposed mathematical model

Evaluated Parameter	Proposed Model (X_{calc})	Reference Data (X_{ref})	Source of Reference	Relative Deviation (δ), %	Validation Status
Seasonal COP of GSHP (SCOP _{GSHP})	3.86	3.94	Bae et al. (2022) [1]	2.03	Valid (<5 %)
Solar Thermal Fraction (f_{solar}), %	22.4	23.8	Wang et al. (2023) [19]	5.88	Valid (<8 %)
Heat Recovery Effectiveness (η_{rec}), %	71.5	73.0	Li et al. (2018) [12]	2.05	Valid (<5 %)

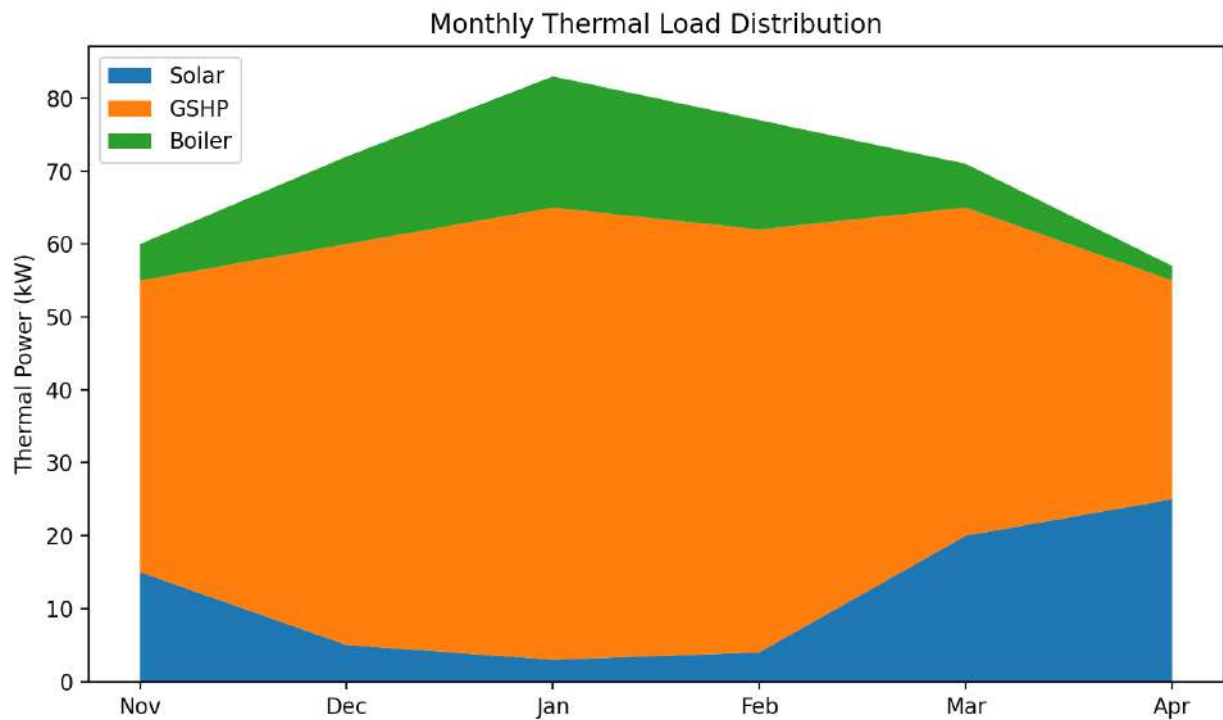


Fig. 1. Monthly thermal load distribution across the heating season for Configuration 3 (Boiler + GSHP + Solar Collector)

The analysis reveals three distinct operational regimes:

Shoulder Seasons (November and March–April): During these intervals, the solar

collector array provides a significant portion of the total energy demand. The surplus solar thermal yield during peak irradiance hours indicates potential for partial thermal regeneration of the ground heat exchanger, which may support a more stable Entering Water Temperature (EWT) for the GSHP over successive heating seasons.

Peak Winter Period (December–February): As outdoor temperatures drop to the design levels of approximately $-23\text{ }^{\circ}\text{C}$, the GSHP maintains the base thermal load due to its high efficiency relative to direct fuel combustion. However, the seasonal degradation of the ground thermal balance

necessitates periodic activation of the gas boiler, which functions as a peak-load unit to cover the residual deficit and ensure adherence to the supply temperature curve.

Ventilation-Driven Load Spikes: The contribution of the mechanical ventilation subsystem represents approximately 12–15 % of the total monthly load, with the heat recovery unit ($\eta_{rec} \approx 0.75$) effectively dampening the impact of transient temperature drops.

The following section describes Fig. 2, which provides a comparative analysis of the four investigated configurations based on the specific heat generation cost, C_{spec} , and their associated environmental impact.

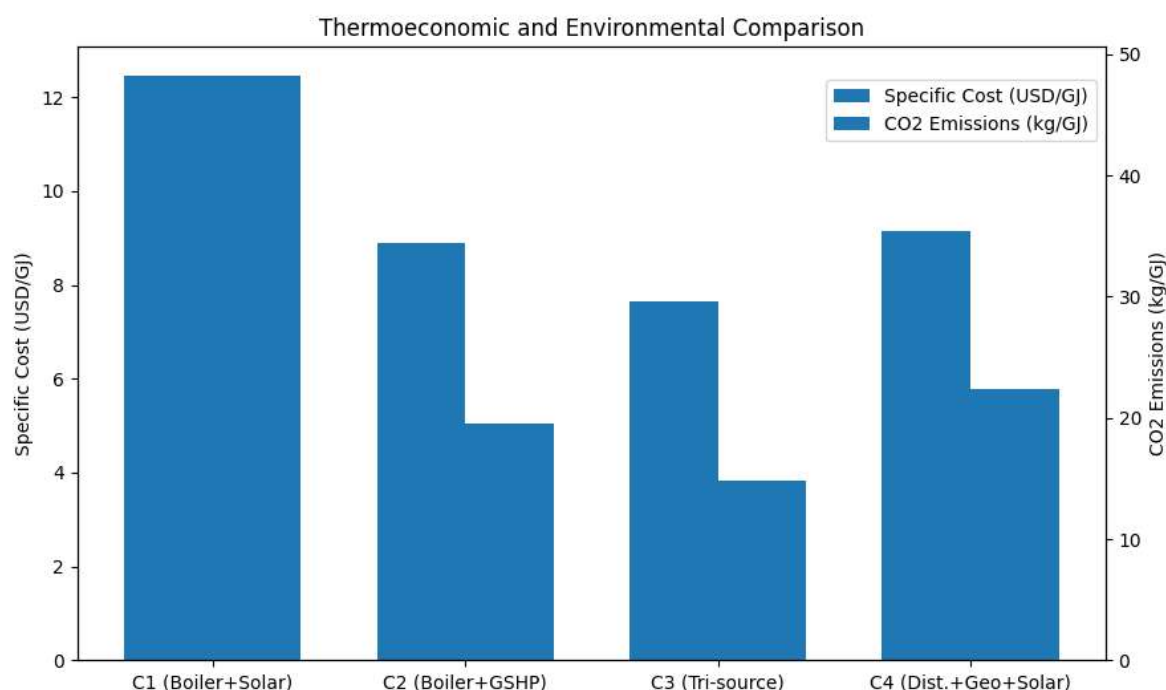


Fig. 2. Comparative Thermoeconomic and Environmental Performance

Fig. 2 illustrates the relative economic performance and carbon intensity of the four hybrid heating systems evaluated under the current climatic and economic boundary conditions of Kharkiv Oblast. The specific heat generation cost, C_{spec} , incorporates fuel, electricity, and proportional capital cost recovery, while the CO₂ emissions represent the total atmospheric impact per unit of delivered useful heat.

The analysis provides several critical insights into system selection:

Economic Optimum: Configuration 3 (Boiler + GSHP + Solar Collector) demonstrates the lowest specific heat generation cost of 7.65 USD/GJ. This is attributed to the optimal balance between high-efficiency renewable contribution and the strategic use of the boiler during extreme peak demands.

Capital vs. Operational Trade-off:

While Configuration 2 (Boiler + GSHP) shows a competitive cost of 8.90 USD/GJ, the additional investment for the solar array in Configuration 3 is rapidly offset by the extended COP stabilization and fuel displacement.

District Integration Limits:

Configuration 4 (District Boiler + Geo + Solar) results in a cost of 9.15 USD/GJ. Despite the integration of renewable sources, the reliance on the centralized grid introduces higher operational sensitivity to district heating price fluctuations compared to fully autonomous hybrid configurations.

Environmental Parity: The reduction in CO₂ emissions directly correlates with the renewable energy fraction. Configuration 3 achieves the lowest carbon footprint (14.8 kg/GJ), confirming that thermoeconomic

optimization inherently favors systems with lower environmental impact in the Ukrainian energy market context.

These results validate that the selection of an optimal hybrid system cannot be reduced to simple equipment efficiency metrics alone. The complex interaction between installation cost recovery, seasonal storage dynamics, and occupant thermal comfort constrains the feasible design space, necessitating the integrated techno-economic evaluation presented herein.

Fig. 3 illustrates the dynamic interaction between the mechanical ventilation subsystem and the total building thermal demand throughout the 181-day heating season in Kharkiv Oblast. The analysis explicitly isolates the ventilation-related thermal load, which fluctuates based on the temperature-dependent fresh air intake requirement.

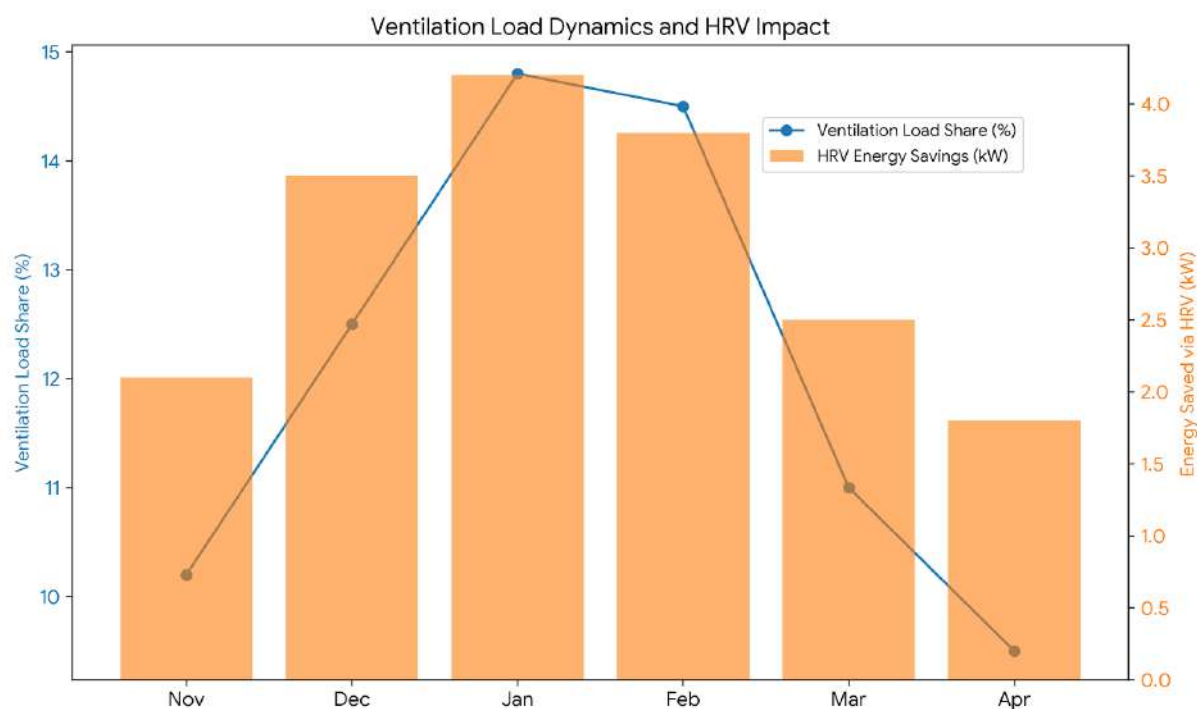


Fig. 3. Impact of ventilation thermal load and heat recovery effectiveness (η_{rec}) on total seasonal energy demand

Key insights derived from the ventilation subsystem modeling include:

Load Dynamics: The ventilation load accounts for a dynamic share of the total heat

balance, peaking during the coldest months (January–February) when the temperature differential ($T_{int} - T_{ext}$) is maximal.

Effectiveness of Recovery: The application of mechanical heat recovery with a nominal effectiveness of ($\eta_{rec} \approx 0.75$) significantly reduces the primary energy demand. The energy savings curve demonstrates that heat recovery is most impactful during the transition periods (November and March–April), where it offsets a substantial portion of the sensible heat required to condition fresh air.

Profitability Threshold: The model identifies a critical profitability threshold for heat recovery integration. In the climatic conditions of Eastern Ukraine, the thermodynamic savings derived from $\eta_{rec} > 0.70$ consistently outweigh the auxiliary electrical power consumption of the ventilation fans when the outdoor temperature remains below circ +2 °C.

This threshold governs the ventilation heat recovery subsystem specifically and is distinct from the much lower outdoor temperature threshold (−15 °C) at which the peak-load gas boiler is activated within the primary generation plant, as the two thresholds correspond to different subsystems with independent economic and operational logic.

This visualization confirms that integrating mechanical ventilation heat recovery is not merely a design choice for air quality but a prerequisite for reducing the peak load obligations of the primary heating plant. By dampening the impact of transient climatic fluctuations, the heat recovery system stabilizes the boiler's operational regime and enhances the overall systemic COP.

Conclusions

The present study has successfully established a comprehensive thermoeconomic model for hybrid heat supply systems, explicitly integrating dynamic mechanical ventilation heat recovery under the climatic and tariff conditions of Kharkiv Oblast. The findings provide clear quantitative guidance for engineering design and operational management.

Optimal Configuration and Source Ratios

The numerical optimization identifies Configuration 3 (Gas Boiler + GSHP + Solar

Collector) as the global optimum for residential and small industrial applications in the eastern Ukrainian climate. This tri-source system achieves the lowest specific heat generation cost of 7.65 USD/GJ and an environmental footprint of 14.8 kg/GJ of delivered heat. The optimal operational load coverage is distributed as follows:

GSHP (Ground-Source Heat Pump): 73.0 % of the total annual load, serving as the primary base-load source.

Solar Thermal Array: 18.5 % of the annual load, with primary contribution during shoulder seasons and potential to support ground loop regeneration.

Gas Boiler (Peak Unit): 8.5 % of the total load, utilized exclusively for extreme peak demands when outdoor temperatures drop below −15 °C and COP degradation occurs.

Profitability Threshold for Ventilation Heat Recovery.

The analysis confirms that the integration of mechanical ventilation heat recovery with a nominal effectiveness of $\eta_{rec} \geq 0.70$ is a critical technical requirement rather than an optional enhancement. The thermodynamic savings derived from this system reach a profitability threshold—where recovered energy costs offset the auxiliary fan power consumption—when the outdoor temperature remains below +2 °C. Given the duration of the heating season in Kharkiv (approx. 181 days), this threshold is met for over 90% of the operational time, confirming the high investment priority for HRV systems.

Practical Design Recommendations.

Based on the optimization results, the following parameters are recommended for practitioners designing hybrid systems in the continental climate of Eastern Ukraine:

Supply Temperature Regime: To maximize the GSHP operational efficiency, the heating system should be designed for low-temperature operation within the 35 °C to 55 °C range. This temperature lift maintains the heat pump COP within the optimal range and minimizes reliance on the boiler.

Renewable Energy Share: Designing for an aggregate renewable energy coverage (GSHP + Solar) of at least 85–90 % of the total annual demand is recommended to ensure both economic viability and resilience against potential fossil fuel price volatility.

System Integration: The solar collector array should be sized not only for immediate DHW (Domestic Hot Water) needs but also with consideration for its potential contribution to ground thermal recharge. A collector area-to-borehole length ratio providing 15–20 % of the seasonal ground thermal demand is proposed as

the standard for ensuring long-term ground thermal balance.

In summary, the transition to optimized tri-source hybrid systems with integrated heat recovery provides a robust pathway to reducing primary energy consumption while maintaining reliable microclimate quality. This study offers a transferable methodology that allows designers to adapt system sizing to specific building typologies and emerging tariff trajectories in the Ukrainian construction market.

Reference

1. Bae, S., Nam, Y., Lee, E., & Entchev, E. (2022). Feasibility study of a novel hybrid energy system combining photovoltaic-thermal and modular ground heat exchanger. *Journal of Building Engineering*, 61, 105241. <https://doi.org/10.1016/j.jobbe.2022.105241>
2. Burda, Y. (2026). Reduced-order modeling of microclimate formation in displacement ventilation systems. *Ventilation Illumination and Heat Gas Supply*, 57, 23–39. <https://doi.org/10.32347/2409-2606.2026.57.23-39> [in English].
3. Burda, Y., Redko, I., Pivnenko, Y., Shepichak, V., & Tkachenko, R. (2026). Thermodynamic modeling of microclimate formation in cleanrooms with displacement ventilation. *Scientific Bulletin of Civil Engineering*, 1(114), 148–154. <https://doi.org/10.33042/2311-7257.2026.114.1.16> [in English].
4. Chen, Y., Wang, J., & Lund, P. D. (2020). Thermodynamic performance analysis and multi-criteria optimization of a hybrid combined heat and power system coupled with geothermal energy. *Energy Conversion and Management*, 210, 112741. <https://doi.org/10.1016/j.enconman.2020.112741>
5. De Araujo Passos, L. A., Van Den Engel, P., Baldi, S., & De Schutter, B. (2022). Dynamic optimization for minimal HVAC demand with latent heat storage, heat recovery, natural ventilation, and solar shadings. *Energy Conversion and Management*, 276, 116573. <https://doi.org/10.1016/j.enconman.2022.116573>
6. Deng, S., Zhang, H., Li, G., Qu, T., Shao, H., & Zhao, Q. (2024). Experimental study and optimization analysis of vapor compression heat pump coupled with gas boiler. *Energy*, 314, 134189. <https://doi.org/10.1016/j.energy.2024.134189>
7. Han, G., Yang, Q., Yang, F., Xie, W., Jin, H., Yi, F., Meng, S., & Peng, Z. (2022). Design and efficiency assessment of hybrid thermal protection structures for return capsule reentry. *Case Studies in Thermal Engineering*, 41, 102656. <https://doi.org/10.1016/j.csite.2022.102656>
8. Hunt, D., Mac Suibhne, N., Dimache, L., McHugh, D., & Lohan, J. (2020). Advances in multifunctional balanced ventilation technology for dwellings and arising challenge to quantify energy efficiency and renewable generation contributions using international test standards. *Renewable and Sustainable Energy Reviews*, 134, 110327. <https://doi.org/10.1016/j.rser.2020.110327>
9. Jahanbin, A., & Semprini, G. (2022). Integrated effects of the heat recovery ventilation and heat source on decay rate of indoor airborne particles: A comparative study. *Journal of Building Engineering*, 50, 104156. <https://doi.org/10.1016/j.jobbe.2022.104156>

10. Khadra, A., Hugosson, M., Akander, J., & Myhren, J. A. (2020). Economic performance assessment of three renovated multi-family buildings with different HVAC systems. *Energy and Buildings*, 224, 110275. <https://doi.org/10.1016/j.enbuild.2020.110275>
11. Leng, X., Sun, X., Xu, J., & Huang, W. (2021). Optimal planning of a hybrid system integrating of combined cooling, heat and power and energy storage resources. *Sustainable Energy Technologies and Assessments*, 50, 101806. <https://doi.org/10.1016/j.seta.2021.101806>
12. Li B., Wild P., & Rowe A. (2018). Performance of a heat recovery ventilator coupled with an air-to-air heat pump for residential suites in Canadian cities. *Journal of Building Engineering*, 21, 343–354. <https://doi.org/10.1016/j.jobbe.2018.10.025>
13. Liu, S., Ma, G., Lv, Y., & Xu, S. (2023). Review on heat pump energy recovery technologies and their integrated systems for building ventilation. *Building and Environment*, 248, 111067. <https://doi.org/10.1016/j.buildenv.2023.111067>
14. Lygouras, E., Papatsounis, A. G., Botsaris, P. N., & Pechtelidis, A. (2023). Optimization & techno-economic analysis of a hybrid system with thermal energy storage within a LEC. *Renewable Energy*, 215, 118920. <https://doi.org/10.1016/j.renene.2023.118920>
15. Mehregan, M., Abbasi, M., & Hashemian, S. M. (2021). Technical, economic and environmental analyses of combined heat and power (CHP) system with hybrid prime mover and optimization using genetic algorithm. *Sustainable Energy Technologies and Assessments*, 49, 101697. <https://doi.org/10.1016/j.seta.2021.101697>
16. Nicoletti, F., Ramundo, G., & Arcuri, N. (2024). Optimal operating strategy of hybrid heat pump – boiler systems with photovoltaics and battery storage. *Energy Conversion and Management*, 323, 119233. <https://doi.org/10.1016/j.enconman.2024.119233>
17. Pryimak, O., Burda, Y., Redko, I., Pivnenko, Y., & Gvozdetkii, O. (2025). Integrated Approach to Energy Certification and Quality Control of Microclimate Formation in Modern Construction. *Academic Energy Engineering and Control Systems*, 11(2), 79 – 84. <https://doi.org/10.23939/jeecs2025.02.079>. [in English].
18. Shuailing, L., Guoyuan, M., Xiaoya, J., Shuxue, X., & Guoqiang, W. (2022). Performance of a mechanically-driven loop heat pipe heat recovery system. *Applied Thermal Engineering*, 207, 118066. <https://doi.org/10.1016/j.applthermaleng.2022.118066>
19. Wang, G., Feng, G., Li, X., Li, H., & Wang, T. (2023). Design optimization integrating energy, economic, and environmental evaluation of a hybrid solar heating system for detached buildings in rural China. *Journal of Building Engineering*, 73, 106692. <https://doi.org/10.1016/j.jobbe.2023.106692>
20. Wang, Y., Quan, Z., Jing, H., Wang, L., & Zhao, Y. (2021). Performance and operation strategy optimization of a new dual-source building energy supply system with heat pumps and energy storage. *Energy Conversion and Management*, 239, 114204. <https://doi.org/10.1016/j.enconman.2021.114204>
21. Zhou, Y., Wang, J., Dong, F., Qin, Y., Ma, Z., Ma, Y., & Li, J. (2021). Novel flexibility evaluation of hybrid combined cooling, heating and power system with an improved operation strategy. *Applied Energy*, 300, 117358. <https://doi.org/10.1016/j.apenergy.2021.117358>

Список використаних джерел

1. Bae, S., Nam, Y., Lee, E., & Entchev, E. (2022). Feasibility study of a novel hybrid energy system combining photovoltaic-thermal and modular ground heat exchanger. *Journal of Building Engineering*, 61, 105241. <https://doi.org/10.1016/j.jobbe.2022.105241>
2. Burda, Y. (2026). Reduced-order modeling of microclimate formation in displacement ventilation systems. *Вентиляція, освітлення та теплогазопостачання*, 57, 23–39. <https://doi.org/10.32347/2409-2606.2026.57.23-39>

3. Burda, Y., Redko, I., Pivnenko, Y., Shepichak, V., & Tkachenko, R. (2026). Thermodynamic modeling of microclimate formation in cleanrooms with displacement ventilation. *Науковий вісник будівництва*, 1(114), 148–154. <https://doi.org/10.33042/2311-7257.2026.114.1.16>
4. Chen, Y., Wang, J., & Lund, P. D. (2020). Thermodynamic performance analysis and multi-criteria optimization of a hybrid combined heat and power system coupled with geothermal energy. *Energy Conversion and Management*, 210, 112741. <https://doi.org/10.1016/j.enconman.2020.112741>
5. De Araujo Passos, L. A., Van Den Engel, P., Baldi, S., & De Schutter, B. (2022). Dynamic optimization for minimal HVAC demand with latent heat storage, heat recovery, natural ventilation, and solar shadings. *Energy Conversion and Management*, 276, 116573. <https://doi.org/10.1016/j.enconman.2022.116573>
6. Deng, S., Zhang, H., Li, G., Qu, T., Shao, H., & Zhao, Q. (2024). Experimental study and optimization analysis of vapor compression heat pump coupled with gas boiler. *Energy*, 314, 134189. <https://doi.org/10.1016/j.energy.2024.134189>
7. Han, G., Yang, Q., Yang, F., Xie, W., Jin, H., Yi, F., Meng, S., & Peng, Z. (2022). Design and efficiency assessment of hybrid thermal protection structures for return capsule reentry. *Case Studies in Thermal Engineering*, 41, 102656. <https://doi.org/10.1016/j.csite.2022.102656>
8. Hunt, D., Mac Suibhne, N., Dimache, L., McHugh, D., & Lohan, J. (2020). Advances in multifunctional balanced ventilation technology for dwellings and arising challenge to quantify energy efficiency and renewable generation contributions using international test standards. *Renewable and Sustainable Energy Reviews*, 134, 110327. <https://doi.org/10.1016/j.rser.2020.110327>
9. Jahanbin, A., & Semprini, G. (2022). Integrated effects of the heat recovery ventilation and heat source on decay rate of indoor airborne particles: A comparative study. *Journal of Building Engineering*, 50, 104156. <https://doi.org/10.1016/j.jobe.2022.104156>
10. Khadra, A., Hugosson, M., Akander, J., & Myhren, J. A. (2020). Economic performance assessment of three renovated multi-family buildings with different HVAC systems. *Energy and Buildings*, 224, 110275. <https://doi.org/10.1016/j.enbuild.2020.110275>
11. Leng, X., Sun, X., Xu, J., & Huang, W. (2021). Optimal planning of a hybrid system integrating of combined cooling, heat and power and energy storage resources. *Sustainable Energy Technologies and Assessments*, 50, 101806. <https://doi.org/10.1016/j.seta.2021.101806>
12. Li B., Wild P., & Rowe A. (2018). Performance of a heat recovery ventilator coupled with an air-to-air heat pump for residential suites in Canadian cities. *Journal of Building Engineering*, 21, 343–354. <https://doi.org/10.1016/j.jobe.2018.10.025>
13. Liu, S., Ma, G., Lv, Y., & Xu, S. (2023). Review on heat pump energy recovery technologies and their integrated systems for building ventilation. *Building and Environment*, 248, 111067. <https://doi.org/10.1016/j.buildenv.2023.111067>
14. Lygouras, E., Papatsounis, A. G., Botsaris, P. N., & Pechtelidis, A. (2023). Optimization & techno-economic analysis of a hybrid system with thermal energy storage within a LEC. *Renewable Energy*, 215, 118920. <https://doi.org/10.1016/j.renene.2023.118920>
15. Mehregan, M., Abbasi, M., & Hashemian, S. M. (2021). Technical, economic and environmental analyses of combined heat and power (CHP) system with hybrid prime mover and optimization using genetic algorithm. *Sustainable Energy Technologies and Assessments*, 49, 101697. <https://doi.org/10.1016/j.seta.2021.101697>
16. Nicoletti, F., Ramundo, G., & Arcuri, N. (2024). Optimal operating strategy of hybrid heat pump – boiler systems with photovoltaics and battery storage. *Energy Conversion and Management*, 323, 119233. <https://doi.org/10.1016/j.enconman.2024.119233>

17. Pryimak, O., Burda, Y., Redko, I., Pivnenko, Y., & Gvozdetskii, O. (2025). Integrated Approach to Energy Certification and Quality Control of Microclimate Formation in Modern Construction. *Energy Engineering and Control Systems*, 11(2), 79 – 84. <https://doi.org/10.23939/jeecs2025.02.079>
18. Shuailing, L., Guoyuan, M., Xiaoya, J., Shuxue, X., & Guoqiang, W. (2022). Performance of a mechanically-driven loop heat pipe heat recovery system. *Applied Thermal Engineering*, 207, 118066. <https://doi.org/10.1016/j.applthermaleng.2022.118066>
19. Wang, G., Feng, G., Li, X., Li, H., & Wang, T. (2023). Design optimization integrating energy, economic, and environmental evaluation of a hybrid solar heating system for detached buildings in rural China. *Journal of Building Engineering*, 73, 106692. <https://doi.org/10.1016/j.jobbe.2023.106692>
20. Wang, Y., Quan, Z., Jing, H., Wang, L., & Zhao, Y. (2021). Performance and operation strategy optimization of a new dual-source building energy supply system with heat pumps and energy storage. *Energy Conversion and Management*, 239, 114204. <https://doi.org/10.1016/j.enconman.2021.114204>
21. Zhou, Y., Wang, J., Dong, F., Qin, Y., Ma, Z., Ma, Y., & Li, J. (2021). Novel flexibility evaluation of hybrid combined cooling, heating and power system with an improved operation strategy. *Applied Energy*, 300, 117358. <https://doi.org/10.1016/j.apenergy.2021.117358>

Рукавішников Павло Володимирович, кандидат технічних наук, доцент кафедри ТТДЕМ, Український державний університет залізничного транспорту. E-mail: rukavishnykov@gmail.com. ORCID ID 0000-0002-9670-3071.

Бугай Володимир Сергійович, кандидат технічних наук, доцент кафедри теплогазопостачання і вентиляції, Харківський національний університет міського господарства імені О. М. Бекетова.

E-mail: v.bugai@kname.edu.ua. ORCID ID 0000-0001-5166-7110.

Чайка Юрій Іванович, кандидат технічних наук, завідувач кафедри теплогазопостачання і вентиляції, Харківський національний університет міського господарства імені О. М. Бекетова.

E-mail: yurii.chaika@kname.edu.ua. ORCID ID 0000-0003-1021-4662.

Бурда Юрій Олександрович, кандидат технічних наук, доцент кафедри теплогазопостачання і вентиляції, Харківський національний університет міського господарства імені О. М. Бекетова.

E-mail: science.yurii.burda@gmail.com. ORCID ID 0000-0003-3470-1334.

Марченко Сергій Олегович, аспірант кафедри теплогазопостачання і вентиляції, Харківський національний університет міського господарства імені О. М. Бекетова. E-mail: Serhii.Marchenko@kname.edu.ua.

ORCID ID: <https://orcid.org/0009-0000-3017-3293>.

Pavlo Rukavishnykov, Associate Professor, Department of Heat Engineering, Thermal Engines and Energy Management, Ukrainian State University of Railway Transport. E-mail: rukavishnykov@gmail.com.

ORCID ID: 0000-0002-9670-3071.

Volodymyr Bugai, Ph.D. in Technical Sciences, Associate Professor Department of Heat and Gas Supply and Ventilation, O. M. Beketov National University of Urban Economy in Kharkiv. E-mail: v.bugai@kname.edu.ua.

ORCID ID: 0000-0001-5166-7110.

Yurii Chaika, Ph.D. (Tech.), Head of the Department of Heating, Gas Supply, and Ventilation, O. M. Beketov National University of Urban Economy in Kharkiv. E-mail: yurii.chaika@kname.edu.ua. ORCID ID: 0000-0003-1021-4662.

Yurii Burda, Ph.D., Associate Professor at the Department of Heating, Gas Supply, and Ventilation, O. M. Beketov National University of Urban Economy in Kharkiv. E-mail: science.yurii.burda@gmail.com. ORCID ID: 0000-0003-3470-1334.

Serhii Marchenko, Postgraduate Student (Ph.D. Candidate) Department of Heat and Gas Supply and Ventilation, O. M. Beketov National University of Urban Economy in Kharkiv. E-mail: Serhii.Marchenko@kname.edu.ua.

ORCID ID: <https://orcid.org/0009-0000-3017-3293>.

Дата надходження статті 03.07.2026 р.

Дата прийняття статті до друку 04.09.2026 р.

Дата публікації (оприлюднення) статті 16.10.2026 р.

Стаття поширюється на умовах ліцензії Creative Commons Attribution License International CC-BY
