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MODELLING THE EFFICIENCY OF THE HEAT PUMP SYSTEM WITH TANK ACCUMULATOR FOR PERMANENT AND INTERMITTENT HEATING MODES OF THE PUBLIC BUILDINGS

А. Денисова, О. Жайворон. **Моделювання ефективності теплонасосної системи з баком-акумулятором для постійного та періодичного режимів роботи системи опалення громадських будівель.** У статті розглянуто математичне моделювання ефективності комбінованих теплонасосних систем з накопиченням теплової енергії для періодичного опалення громадських будівель. Проаналізовано можливості комбінованої теплонасосної системи для роботи з традиційною системою опалення з урахуванням кліматичних умов, коли температура бівалентної точки визначає кількість енергії, що надходить від традиційного теплогенератора. Проведено чисельне моделювання процесів у системі комбінованого переривчастого опалення. Запропонована методологія аналізу може слугувати раціональним підходом до подальшого розвитку теплонасосних технологій періодичного опалення. Проведено оцінку ефективності режимів роботи системи короткочасного опалення за режимами роботи споживачів тепла. Запропонована методика сприяє підвищенню енергоефективності теплонасосних систем з баковими акумуляторами з урахуванням режимів роботи споживачів тепла. Результати моделювання включають коефіцієнт корисної дії та нагрівальну потужність. Виявлено режими роботи, коли значення коефіцієнта корисної дії були дуже високими. Аналіз результатів чисельного моделювання показує, що для теплонасосних систем з тепловим акумулятором відбувається вирівнювання кривої навантаження теплогенераторів, що призводить до рівномірної роботи джерела тепла. Конструкція технічних деталей теплового насоса була оптимізована з енергетичним балансом, який добре підходить для аналізу режимів роботи теплового насоса, інтегрованого з накопичувачем теплової енергії. Таким чином, розглядається раціональна тривалість короткочасних періодів опалення, коли тепловий насос працює з тепловим акумулятором, тривалість послідовного режиму опалення та режиму очікування з зарядкою теплового акумулятора, які позитивно впливають на енергоефективність. Згідно з результатами, додаткова новизна дозволяє оптимізувати технічні деталі та режими роботи комбінованої теплонасосної системи на частках відновлюваних джерел для постійного підвищення її енергоефективності. Математична модель, підтверджена експериментальними результатами, може бути використана для дослідження доцільності інтеграції бака-акумулятора в системи опалення теплового насоса з використанням відновлюваних джерел енергії.

Ключові слова: ефективність, тепловий насос, тепловий акумулятор, періодичний обігрів, модель енергетичного балансу

A. Denysova, O. Zhaivoron. **Modelling the efficiency of the combined heat pump system with tank accumulator for permanent and intermittent heating modes of the public buildings.** The paper considers mathematical modeling the efficiency of the combined heat pump systems with thermal energy storage for intermittent heating of the public buildings. The abilities of the combined heat pump system working with traditional heating system with the account of climate data values when the position of the bivalent point on the temperature axis affects at the amount of heat energy supplied from the reserved generator of heat are analyzed. Numerical modeling of processes in the combined intermittent heating system was carried out. The proposed methodology of the analysis may serve as a rational approach to further development the heat pump technologies of intermittent heating. Evaluation of the effectiveness of work modes the intermittent heating system from the operating modes of heat consumers are carried out. The proposed methodology contributes to energy efficiency of the heat pump systems with tank accumulators with the ac-count of operating modes of heat consumers. Simulation results include coefficient of performance and heating capacity. The periods of operation when the values of the coefficient of performance were very high were revealed. Analysis of the results of numerical modeling shows that for heat pump systems with heat accumulators, the load curve of heat generators is equalized, which leads to uniform operation of the heat source. The design of technical details of the heat pump was optimized with the energy balance which is well suited for the analysis of work modes of the heat pump integrated with thermal energy storage. The rational length of intermittent heating periods when the heat pump operates with heat accumulator, duration of successive heating mode and stand-by mode with charging the heat accumulator which have positive influence on energy efficiency are considered, consequently. According to the results, additional novel-ty aspect allows to optimize the technical details and work modes of the combined heat pump system at renewable sources shares to have continuous improvement of its energy efficiency. The mathematical model validated with experimental results can be employed for investigation the feasibility of integrating the tank accumulator into heat pump heating systems using renewable sources of energy.

Keywords: efficiency, heat pump, heat accumulator, intermittent heating, energy balance model

Introduction

The global requirement for sustainable energy provision and a political imperative for energy independence have combined to increase interest in the use of renewable energy sources to meet growing energy demands. Therefore, the heat pump systems (HPS) introduces a new path for sustainable systems with clean energy supply and an improved energy efficiency. Current power systems are still

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dominated by fossil fuel-based electricity generation and operated on supply following the changing demand. Actually, the task of increasing energy efficiency should be realized by implementation of the innovation technologies of production and consumption of energy with the lowest energy losses. The most efficient way of the energy saving is the introduction of heat pumps (HP) with tank accumulators, by virtue of their ability to utilize a renewable energy sources (RES) for heating systems [1–6].

Even so, the decisions presented in literature, which describe the peculiarities of tools for heat pump system with tank accumulator (TA) for permanent and intermittent heating modes of the public buildings are insufficient [7–11]. The foreign investigations [12–14], lack of the methods, which take into account HPS with TA and conditions of their practical application for permanent and intermittent heating modes of the public buildings at the environmental conditions of the Ukraine and South-Eastern Europe. The features of influence the heat-circuit design solutions and operating modes of HPS on the value of the replacement factor of an alternative heating system haven't been clarified till now [15, 16]. In the last decade, energy generation from HP using RES has seen a sharp rise, but the energy supply from RES is inconstant because it is weather dependent. Thus, the energy production from installations using RES partially satisfies the energy demand. However, the power generation production exceeds the demand during certain time of a day during which has seen a high intensity of energy coming from RES. This excess energy can be used through a power-to-heat technology.

Analysis of the latest research

The power-to-heat approach refers to the conversion of electricity to heat through HP, innovative boilers accumulators etc. Power-to-heat strategies can be used at the centralized or decentralized level. Heat is produced centrally either with heat generators stand-alone or in combination with heat pumps. Most of the power-to-heat technologies involve the use of an energy storage mechanism [17]. It should be noted that heat pumps are much more energy-efficient than other renewable and conventional technologies. Once installed and operated properly, one unit of electricity used by a heat pump delivers 3…5 units of heat on average over the heating season. By contrast, one unit of electricity used by an electrolyser (Fig. 1) to produce hydrogen, which is then combusted, results in 0.6…0.8 units of heat. The efficiency of a high-efficiency biomass boiler is around 0.9 units.

The efficiency of heat pumps has increased steadily over the past decades due to research, competition, minimum efficiency performance standards and energy labelling schemes. Different types of HP suit different applications and regions. Enhanced design can improve their efficiency even further. In several regions, heat pumps already have a considerable market share due to their beneficial total life-cycle cost. The market share is significant for newly-built houses because heat pumps are often the best option to meet energy performance standards set by new building regulations. Even though the overall penetration is growing, heat pumps are still a rather rare solution for replacing existing heating systems due to higher upfront costs or lack of awareness and know-how among installers and designers.

This investigation differs from earlier references presented in this article by systematic approach to analyze for issue the conditions of the efficiencies of various schemes of HP with thermal storage for intermittent heating of the academic buildings which ensure the maximum replacement rate of the thermal load. This reduces the level of fossil fuel consumption in structure of regional energy balance and ensures the substantial energy saving, ecological and economical effects.

The recommendations in works [18, 19, 20] is insufficient in our case under permanent and intermittent operational modes for justification the scheme-construction solutions in the HP system with tank accumulator, for heating the public buildings.

The coupling of heat accumulators (HA) with a HP is a rational way to improve the efficiency of the heating system. The tank accumulator can increase the share of use the renewable energy sources (RES) and favoring self-consumption of energy for HPS [21, 22]. The use of tank accumulator for the optimal operation of HPS in different operation modes is analyzed in [23]. Nevertheless, fully established criteria for optimal sizing of HP coupled to tank accumulator are not yet obtainable. For rational implementation of HP system with HA, the mathematical model of the energy system is required [24].

Goal

The purpose of this study to establish the influence of volume of the heat accumulator on the efficiency of heat pump system using simulation, with the account of intermittent heat load, inertia of heating system and climate conditions.

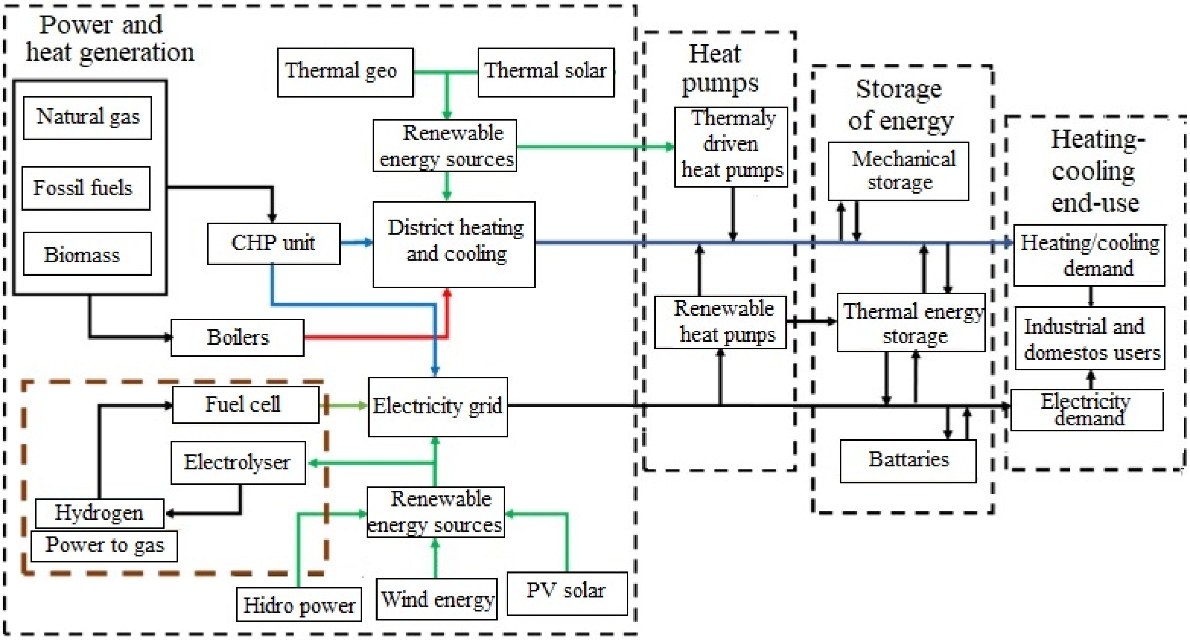

Fig. 1. Power and heat generation system at renewable sources of energy

Presenting main material

Public buildings are objects that have a considerable importance because they bring together different in the light of education and culture comparing to other types of buildings [25]. It is stated that approximately 40 % of the total energy consumed in Europe and Ukraine is constituted by the energy consumed in public and commercial buildings [26]. Since students and teachers spend most of their time in the public buildings, these objects make up a large share of the non-residential fund. The public buildings are the essential energy consumers, which are much different from public buildings due to their variable time and spatial periods of operation [27]. More over considering these cases, it is obvious that the imperative necessity of the energy consumption saving in public buildings requires further detailed study. In fact, research and studies have shown that educational buildings consume significant amounts of energy. As a matter of fact, provided that sufficient thermal comfort and indoor air quality conditions in educational buildings are limited and the buildings are designed according to special parameters, energy efficiency can be achieved [28]. As mentioned before, many studies have been published for the special parameters required for educational buildings and the factors affecting energy consumption. Correct dates for modelling such as: Q_{HP} – heating capacity, COP – the coefficient of performance, building geometry, heating equipment and climate conditions are important to determining the energy efficiency of HPS [29]. COP for a heat pump can be expressed as a curve showing energy consumed to operate the equipment versus the amount of heat energy provided to the building (Fig. 2).

The balance point at COP curve for a heat pump describes the point beyond which it is inefficient to continue operating the building's heating equipment because we get less heat energy to supply the building than the energy, we use to operate the equipment. Since COP curves show that we cannot continue to use a heat pump efficiently, a backup heating system is required if heat pumps are installed in cold climate regions. The balance point corresponds to outdoor temperature above –5 $^{\circ}$C. Below balance point heat pump can’t keep up.

The analysis presented in this work is based on the numerical modelling of HP with tank accumulator of heat for increasing the lifetime of the unit which depends on the number of on-off cycles. A further advantage of avoiding intermittencies is represented by the possibility of obtaining improved thermal comfort inside the building.

The analysis of HPS with HA behavior over the heating season October 2021 – May 2022 has been done. The thermal energy consumption (Q_{H}) and monthly average ambient temperature ($T_{a,\mathrm{av}}$) are shown in Fig. 3 using data base of RETScreen [30] for heating season in Odessa, Ukraine.

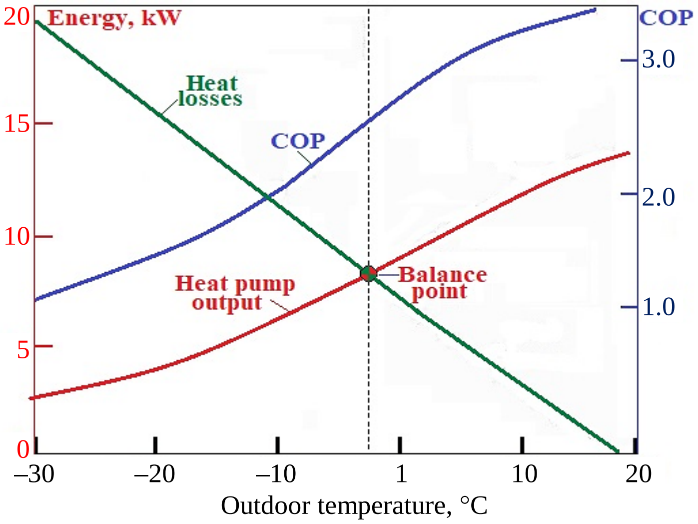

Fig. 2. COP and balance point

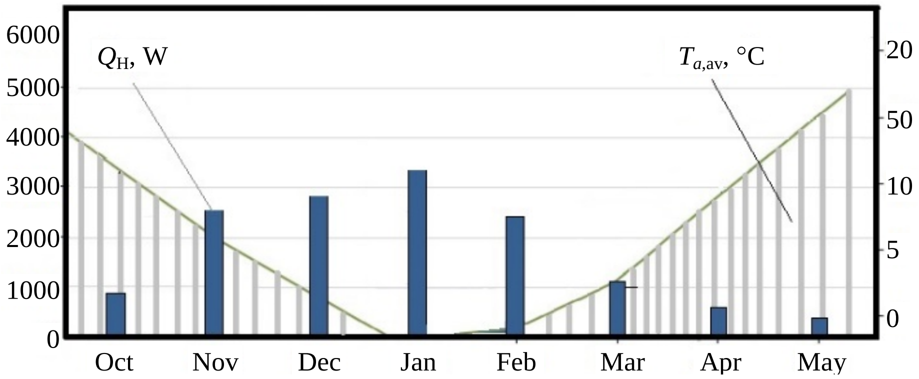

Fig. 3. The thermal energy Q_H and ambient temperature ($T_{a,av}$) over the heating season

During experiments it was measured the monthly average inlet temperature (t_{in}), the inlet (t_{in}) and return temperatures (t_{out}), the ambient temperature (t_a) and the electric power consumption (Q_{el}). This data allowed to analyze the monthly energy efficiency of the HPS with the tank accumulator and energy consumption of the heat pump in operation and stand-by mode. However, there are a number of circumstances that significantly affect the effectiveness of intermittent heating in the public buildings (educational, administrative and industrial): absence of energy sources for forcing mode of room heating; high inertia of the central heating system; lack of thermal modernization. The first factor especially affects the efficiency of intermittent heating and leads to climatic restrictions on the use of variable heating modes in public buildings.

Results relative for heat pump systems with tank accumulators at permanent and intermittent operational modes of heating public buildings show that the presence of tank accumulator increases energy efficiency of the heat pump system in virtue of smoother its operation mode.

The preliminary guideline for sizing the volume of tank accumulator in relation to the heat pump capacity are 70 liters for 1 kilowatt for permanent mode of heating is suggested in works [3, 19]. But this a rough recommendation for intermittent operation mode of HPS.

Thus, the purpose of this study to establish the influence of volume of the heat accumulator on the efficiency of heat pump system using simulation, with the account of intermittent heat load, inertia of heating system and climate conditions.

Description of research and data analysis. Public buildings are objects that have a considerable importance because they bring together different in the light of education and culture comparing to other types of buildings [25]. It is stated that approximately 40 % of the total energy consumed in Europe and Ukraine is constituted by the energy consumed in public and commercial buildings [26]. Since students and teachers spend most of their time in the public buildings, these objects make up a large share of the non-residential fund. The public buildings are the essential energy consumers, which are much different from public buildings due to their variable time and spatial periods of operation [27]. More over considering these cases, it is obvious that the imperative necessity of the energy consumption saving in public buildings requires further detailed study. In fact, research and studies have shown that educational buildings consume significant amounts of energy.

Using of HP technology is a promising way for increasing energy efficiency, only if the unit is properly sized and operated. The HP system performance can be highly reduced under many circumstances, such as high temperature lift, defrost operation, partial loads, and frequent on-off cycles. Some of these conditions occur when the HP must match variable heating demands in response to the building thermal dynamics or during mid-season or in quite temperate climatic conditions. Besides the conventional coefficient of performance (COP), additional indexes can be defined to appropriately compare different operational modes of the same HP systems:

– the nominal full-load performance $\mathrm{COP_{NOM}}$ provided by the heat pump manufacturer at the reference sources of temperature, according to technical standards. For example, the reference temperature values for air-to-water heat pumps are 7 °C for outdoor air and 35 °C for supply water temperature [20];

– the full-load performances $\mathrm{COP_{FL}}$ provided by the by the heat pump manufacturer at the different external and supply temperatures provided by the technical standards. *FL* indicates a quantity evaluated at maximum compressor speed at full-load performances [21];

– the operative part-load performance $\mathrm{COP_{HP}}$ simulated through a validated HP model. This index accounts for both external and supply temperatures, together with the effects of the capacity control;

– the overall HP system performance $\mathrm{COP_S}$, calculated as the ratio between the heat provided to the building by the system Q'_{HEAT} and the electrical energy input $N'_{\mathrm{HEAT,\,in}}$ used by the heat pump. This value considers not only the HP performance but also the thermal losses of energy in all elements of system.

A common heat pump performance evaluation methodology consists of interpolating the index of exergy efficiency $\eta_{\mathrm{FL}}^{\mathrm{Ex}}$ depending on actual operative temperatures:

$$\eta_{\mathrm{FL}}^{\mathrm{Ex}} = \mathrm{COP_{FL}} \frac{T_{\mathrm{out,HP,FL}} - T_{a,\mathrm{in,HP,FL}}}{T_{\mathrm{out,HP,FL}} + 273}, \tag{1}$$

where $\eta_{\mathrm{FL}}^{\mathrm{Ex}}$ – index of exergy efficiency of the heat pump which based on the manufacturers experimental $\mathrm{COP_{FL}}$ values, considering the reference supply and outdoor temperature $T_{\mathrm{out,HP,FL}}$ and $T_{a,\mathrm{in,HP,FL}}$.

These indexes refer to the instantaneous thermal or electrical power exchanged by the heat pump or overall HP system. However, it is also interesting to analyze their average value over month, year or seasonal period τ.

The most common time-integral coefficients of performance are:

– seasonal coefficient of performance COP defined as the ratio between the thermal energy output and electrical energy input of the HP unit $\mathrm{COP_{HP}}$ or the overall HP system $\mathrm{COP_S}$ over the period τ:

$$\mathrm{COP_{HP}} = \frac{\int_\tau Q'_{\mathrm{HP}} d\tau}{\int_\tau N'_{\mathrm{HEAT,\,in}} d\tau} = \frac{\int_\tau m'_{\mathrm{HP}} c_f (T_{\mathrm{HP,out}} - T_{\mathrm{HP,in}}) d\tau}{\int_\tau N'_{\mathrm{HEAT,\,in}} d\tau} = \frac{Q_{\mathrm{HP}}}{W_{\mathrm{HP,in}}}, \tag{2}$$

$$\mathrm{COP_S} = \frac{\int_\tau Q'_{\mathrm{HEAT}} d\tau}{\int_\tau N'_{\mathrm{HEAT,\,in}} d\tau} = \frac{Q_{\mathrm{HEAT}}}{N_{\mathrm{HP,in}}}; \tag{3}$$

– ratio of capacity is the parameter R_C which associated with the real mode of operation of HP installation or overall system. It can be evaluated according to the delivered heat Q_{HP} and the maximum available energy output at the nominal full-load power at the given external and supply temperatures over the considered time including off periods:

$$R_C = \frac{Q_{\mathrm{HP}}}{\int_{\tau} Q'_{\mathrm{FL}}(T_{\mathrm{out,HP}};T_{a,\mathrm{in,\,HP}})d\tau}. \tag{4}$$

According to the technical standards, it is possible to evaluate a corrective factor f_{R_C} as a function of R_C, assuming values 0…1. Finally, the coefficient of performance $\mathrm{COP}_{\mathrm{HP}}$ of the HP, and the corresponding energy input $N_{\mathrm{HP,\,in}}$ can be evaluated as:

$$\mathrm{COP}(T_{\mathrm{out,HP}};T_{a,\mathrm{in,\,HP}};R_C) = \frac{T_{\mathrm{out,HP}}+273}{T_{\mathrm{out,HP}}-T_{a,\mathrm{in,\,HP}}}\eta_{\mathrm{FL}}^{\mathrm{Ex}} f_{R_C}, \tag{5}$$

$$N_{\mathrm{HP,in}} = \frac{Q_{\mathrm{HP}}}{COP(T_{\mathrm{out,HP}};T_{a,\mathrm{in,\,HP}};R_C)}. \tag{6}$$

The COP values as defined in Equation (5) can be generally applied on an hourly, daily and monthly time step, when proper f_{R_C} expressions are available [21].

Modelling of processes in integrated system with heat pump and thermal energy storage

Dynamic Simulation Model of the Building and Heat Emission System. The experimental requires an accurate energy model of the building. The conceptual layout of the HP system available in the laboratory “Energy saving technologies” of National Polytechnic University of Odessa, is shown in Fig. 4, including all the installed devices, measurements, controls, and corresponding energy fluxes. Fig. 4 shows the main heat fluxes affecting the energy balance of a generic building or thermal zone that has been included in the building dynamic energy model, where: heat transfer through opaque surfaces, ventilation losses, heat gains related to solar radiation, occupants and electrical appliances. The quantities of energy stored in building external and internal walls and their effects in the thermal exchange of the building are included in the dynamic energy model. In this model [28] where used a classical thermal network approach, widely used for research levels.

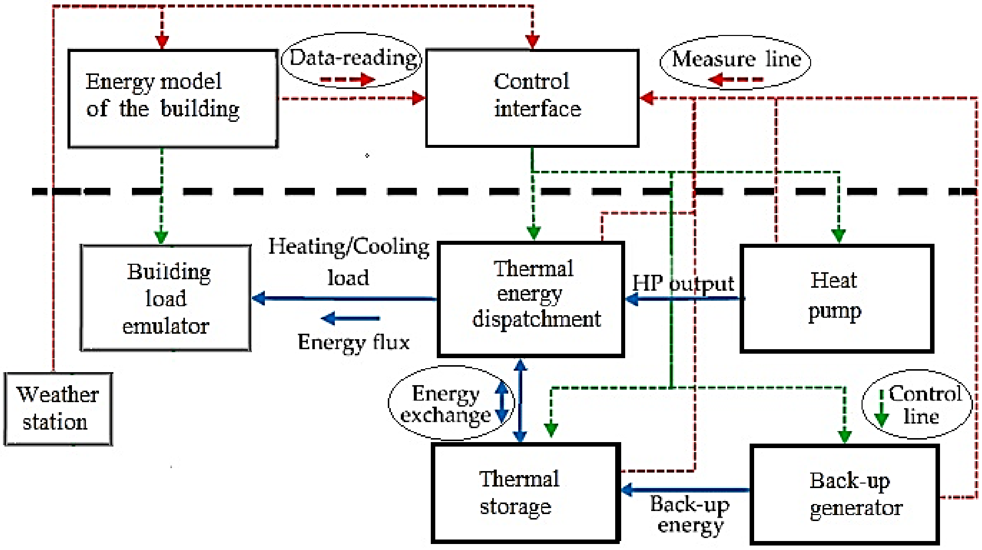

Fig. 4. Components and logical scheme emulator and hardware apparatus of the public building

The building dynamic model corresponds to a linear $N \times N$ set of equations that can be quickly solved at each timestep, where N is the number of thermal nodes considered in the model, including the one of indoor air. The evolution of nodes’ temperature is a function of such climate data as outdoor air temperature, solar irradiance, sky temperature, heat gains, namely: people, electrical appliances, lighting), and heat exchanged by the system terminals. The heat gain delivered by the emission system can be evaluated through a few additional linear equations to be added to the overall set representing the building, where fan coils (FC) are the heat units.

The heat transfer performance is modeled through the classical methods of heat exchangers theory:

$$\begin{cases} Q'_{\text{FC}} = m'_f c_f \ (T_{f,\text{in}} - T_{f,\text{out}}); \\ Q'_{\text{FC}} = m'_{a,\text{vel}} c_a \ (T_{a,\text{out}} - T_{a,\text{in}}); \\ Q'_{FC} = (\text{UA})_{\text{vel}} \overline{\Delta T}_{f,a}. \end{cases} \tag{7}$$

Equation (7) allows the evaluation of $Q'_{\text{FC}}, T_{a,\text{out}}, T_{f,\text{out}}$ as a function of the inlet air temperature $T_{a,\text{in}}$, inlet fluid temperature $T_{f,\text{in}}$, air flow rate $m'_{a,\text{vel}}$, water flow rate m'_f and overall heat transfer coefficient $(\text{UA})_{\text{tot, vel}}$ evaluated from manufacturer's datasheet. The subscripted indicates that different values of the coefficient are used according to the fan speed (generally, high, medium, and low). The heating performance of the fan coils and the corresponding heat gain for the indoor air node are evaluated at each timestep. If $\overline{\Delta T}_{f,a}$ is approximated with the difference between water and air temperatures, according linear equation (7), it can be added and solved in conjunction with the overall model of the building. Otherwise, classical numerical techniques for non-linear equations can be used. The heat emission system is modelled as two additional thermal nodes, $T_{f,\text{in}}$ and $T_{f,\text{out}}$ in the overall building thermal network. $T_{f,\text{in}}$ is set equal to the measured temperature of the fluid at the inlet section of the building emulator; $T_{f,\text{out}}$ is an unknown of the problem to be calculated at each timestep. Its value is then applied as the set point for the three-way mixing vale in the building emulator**.** The case study is a classroom in the laboratory "Energy saving technologies" of National Polytechnic University of Odessa, Ukraine (Fig. 5).

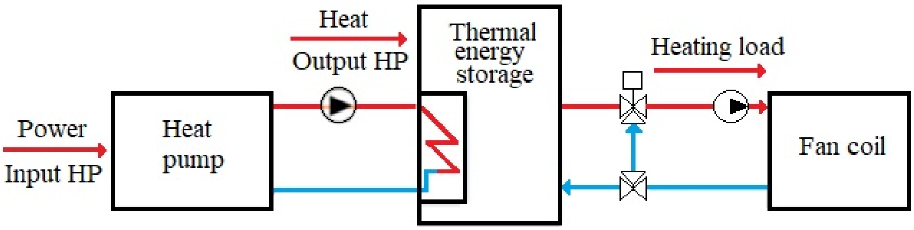

Fig. 5. Layout and components of hardware

Air change rate has been set as equal to 0.5 volumes per hour. Occupants, lighting, and electrical appliances are included in the building energy balance as heat gains.

The hourly profiles are shown in Fig. 6.

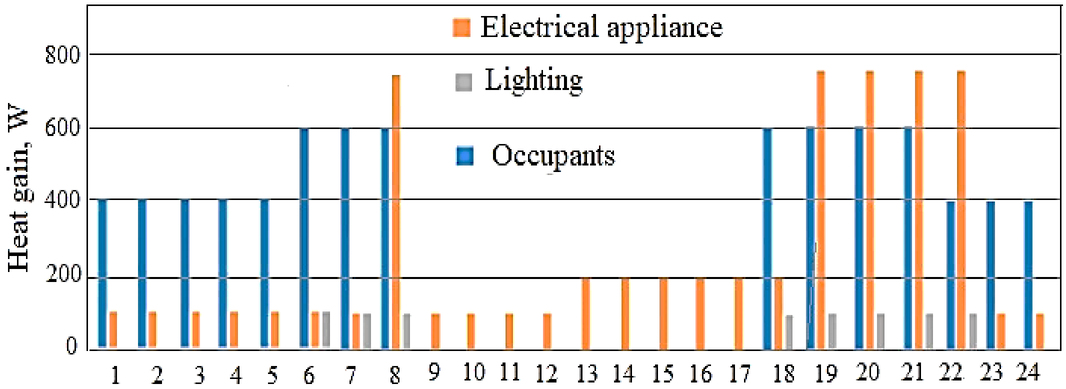

Fig. 6. Daily profiles of internal heat gains for the classroom

For example, this design thermal load of the case study (>5.8 kW) is coherent with the thermal capacity of the heat pump. Considering the number of rooms, the assumed five equal *FC* located within the thermal zone. The nominal data depending on fan coil speed are provided by manufacturer's datasheet in Table 1.

Table 1

Fan coils parameters

	Maximum FC speed	Medium FC speed	Minimum FC speed
Thermal power, kW	1	0.74	0.53
Water low rate, L/h	170	125	90
Air low rate, m^3/h	174	119	83

During experiments the main objective was the measurement during the heating period of the seasonal performances of the HP and of the whole system in real operational conditions, thus subjected to various modulation cycles because of weather and heat gains evolution, building thermal inertia, water loop and HP generator dynamic characteristics. Different operational modes were tested. As previously mentioned, a single-zone thermostat controlled the on-off signal to the HP with an indoor setpoint of 20±1 °C. Three operational modes (OM) of the FC were tested in order to evaluate their effect on the system performance:

– OM#1 corresponds to a setpoint value of the supply temperature equal to 40 ◦C and medium fan coil speed;

– OM#2 uses the same supply temperature but the fan coil speed was reduced to minimum;

– OM#3 has a supply temperature set equal to 35 ◦C and min fan coil speed.

The two performance indexes in equation (2) and (3) allow a separate analysis of the heat generator and of the overall building system.

COP_S only refers to the useful heat delivered to the building thermal zone. Thus, it can be used to evaluate the relevance of the thermal losses associated to the distribution pipework and to the control of the emulated heating system.

Integrated System Modelling under permanent mode of work of the heat pump system with heat storage

To simulate the effects of a tank accumulator, a validated model of the examined HPS was employed to evaluate its performance under the same climate and energy demand profile for winter periods (15 December – 15 February) during which the system is controlled at standard values of water temperature and speed of fan coil. Coefficient of performance of HP is evaluated as a function of water temperature, $T_{\text{out,HP}}$, outdoor temperature, $T_{a,\text{in,HP}}$, and capacity ratio R_C.

The experimental data showed that OM#3 at min speed; $T_{f,\text{out}} = 35$ °C shows an improved behavior of the system. HP operation is characterized by long 8.5 hours on-periods at night. The average HP thermal output during on-periods decreases from 4.0 kW in OM#1 to 1.5 kW in OM#3, which is a more similar value to the fan coil thermal output 1.2 kW.

Under OM#3 the system reaches a steady state condition and a thermal balance with the building heating demand. The losses of the heating loop 0.14 kW) were reduced to 0.55 kW under OM#1 and 0.6 kW for OM#2 due to the absence of the continuous alternation of additional heating-up requirements and deactivation losses.

Under OM#3, the compressor has enough time to start modulating its speed with a compressor frequency 30 Hz. These work conditions decrease the inefficiencies due to on–off cycles; consequently, seasonal COP_{HP} increases to 3.2 and seasonal COP_{sys} increases to 3.35 at the average outdoor temperature 10 ^oC, water supply temperature 32 °C, and capacity ratio 0.125.

How the system operates under the three OM during the whole test period are presented in figures (Figs. 7, 8).

When OM#1 applies at medium speed and $T_{f,\text{out}} = 40$ °C), the profiles are characterized by continuous on-off cycles of about 40 min. The average duration of each on period is 20 min, is not sufficient to achieve a steady state condition of the water loop, thus the supply and return temperatures do not reach the setpoint values and continuously fluctuate. However, the FC thermal output during this transient period is enough to heat up the indoor air until the switching off conditions 21 °C; the heat pump was thus deactivated without any modulation of the compressor speed.

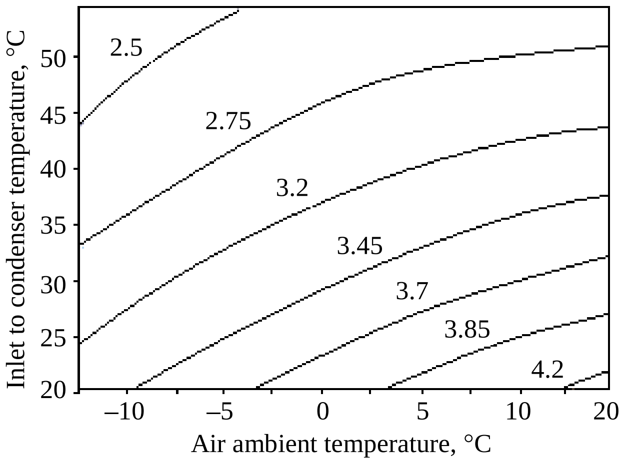

Fig. 7. Plots for COP as a function of the ambient air temperature and the condenser inlet temperature

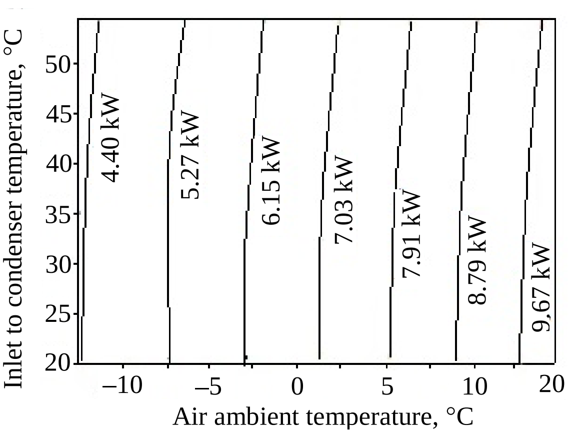

Fig. 8. Plots for COP as a function of the temperature an inlet to condenser

Integrated System Modelling under intermittent mode of work of heat pump system with the heat storage

For the numerical simulation of the heat supply object, the educational building National Polytechnic University of Odessa has been selected, which has 4 floors, total area and volume of the premises – 1500 m^2 and 4800 m^3, respectively [34]. An analysis of the results of numerical simulation of the operating modes of the heat pump system using heat tank (Fig. 9) shows a significant advantage of the heat storage potential is represented by the sum of the areas 1_{I} and 1_{II}), which is explained by the possibility of charging the heat storage during the non-operation period of the system: transition and standby modes. At the same time, the thermal energy storage potential exceeds the thermal needs necessary for the heating mode (the power deficit that the thermal energy storage covers is represented by area 2), where T=200 h is the characteristic of the inertia of the building (time constant).

In this case, the intermittent heat pump system with heat accumulator will operate with a minimum capacity of the heat generator (Fig. 10). The minimum allowable thermal energy of the heat generator is equal to $Q_{\text{min}} = 53$ kW, and the required volume of the tank accumulator is V_{HT}=19 m^3 (Fig. 10, point A).

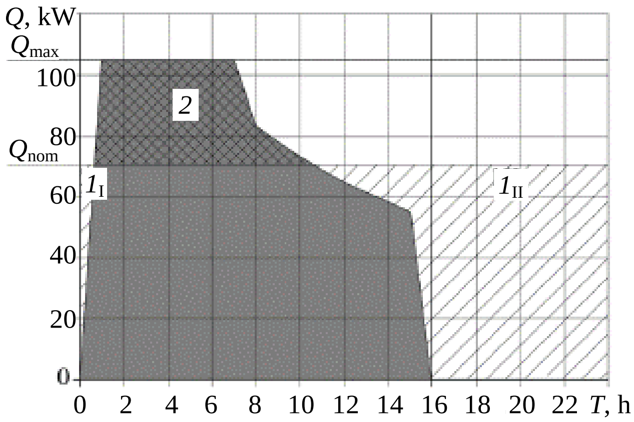

Fig. 9. Intermittent heating load of the HP system taking into account the heat tank at ambient air temperature –18 °C: *1* – potential of the heat generator (under the non-operation period) for the accumulation of heat;
2 – heat shortage

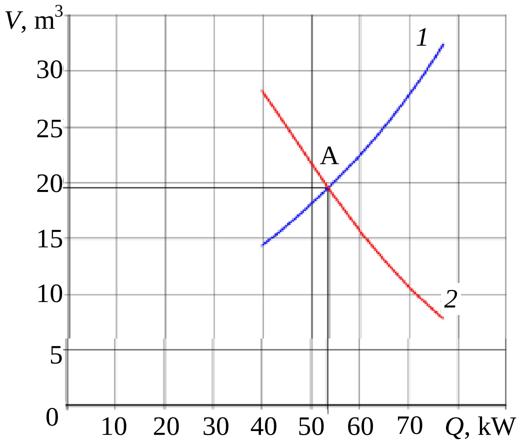

Fig. 10. The dependence of the heat tank (*V*) volume on the power of the heat generator of the intermittent heating system (*Q*) ambient air temperature –18 °C: *1* – potential of the heat generator (during the non-operation period) for the accumulation of heat; *2* – power shortage is covered by heat tank

The coefficient of reduction of thermal power is called the coefficient of thermal power reduction/ This value shows the degree of decrease in the thermal power of heat generators due to the use of the thermal potential of the heat accumulator:

$$k = Q/Q_{\max}, \tag{8}$$

where $Q_{\max}$ – the maximum power of the heat generator to ensure the heating mode during intermit tent heat supply, kW; Q – the current thermal power of the heat generator, kW.

To analyze the energy-saving capabilities of the heat tank of the system, a coefficient of efficiency of using the heat tank volume:

$$w = V_{\mathrm{HT}}/V_{\max}, \tag{9}$$

where V_{HT} – volume, with the minimum allowable heat capacity of the system, m^3; $V_{\max}$ – the maximum heat tank volume available for use, which works with maximum thermal energy, m^3.

The coefficient of efficiency of using the heat tank (w) volume – the ratio of the heat tank volume (capable of replacing excess thermal power in the heating mode) and the maximum heat tank volume (available when using the system with maximum thermal power).

The accumulating substitution parameter of thermal load $\delta = V_{\mathrm{HT}}/(Q_{\mathrm{nom}} - Q_{\min}) = 1.18$ m^3/kW when $Q_{\mathrm{nom}} = 70$ kW; $Q_{\min} = 53$ kW and $V_{\mathrm{HT}} = 19$ m^3 [34].

The substitution parameter δ shows what volume of heat tank must be selected for the heat pump system at intermittent work mode in order to ensure the maximum replacement of the fraction of the thermal power of the system that operates in the intermittent heating mode.

Results

Analyzing the obtained results of numerical modeling, the features of permanent and intermittent modes of the heat pump system using heat accumulators are determined.

For permanent operation mode the experimental data showed that behavior of the system was improved at min speed and $T_{f,\mathrm{out}} = 35$ °C. HP operation at night is characterized by long 8.5 hours during on-periods. The average HP thermal output during on-periods decreases from 4.0 kW to 1.4 kW. In this operation mode the system reaches a steady state condition and a thermal balance with the building heating demand. The losses of the heating loop were reduced due to the absence of the continuous alternation of additional heating-up requirements and deactivation losses. These work conditions decrease the inefficiencies due to on-off cycles; consequently, seasonal COP increases. In this case, the inclusion of a thermal energy storage was also simulated, and the influence of the tank accumulator volume on the HP system energy performance was analyzed, finding an optimal sizing at about 50 liters per one kilowatt of HP capacity with tank accumulator.

For intermittent operation mode results relative for heat pump systems with tank accumulators for educational buildings revealed that the presence of the heat accumulator ensures the smoothest operation mode of HPS and increases its energy efficiency. Thus, it is possible to conclude that the heat energy storage use is a way to significantly reduce the maximum power of heat generators due to the rational use of the heat tank energy potential. The next step in increasing the efficiency of using heat supply sources is to determine the minimum allowable power of heat generators. This value can be established by quantitative comparison of both influential parameters, namely, the heat tank thermal potential, which is charged during the non-operation period, and the excess heat, which ensures the heating mode.

Generalization and analysis of the results of numerical simulation allows to establish:

– the range of a possible decrease in the power of the heat generator due to its joint operation with the heat accumulator in the heating mode;

– justify the feasibility of using one degree or another of thermal modernization of the building (conditions for the use of combined thermal insulation, both external and internal);

– the additional potential to reduce the power of heat generators (~14 %) and heat tank volume (~5 %) through the use of combined thermal insulation determines the level of thermal modernization. The use of shielding of internal walls in combined thermal insulation (reducing the total heat consumption for heating massive internal walls) allows to reduce the heating period and, accordingly, to reduce the power of the heat generator and the volume of the heat accumulator. The solution of this problem will increase the feasibility of using a combined heat supply system using heat accumulators, the cost of which is reduced due to the rational redistribution of power between heat generators and heat tank.

Conclusions

In conclusion, for all the three operational modes, the experimental data showed a considerable reduction 35 % of the coefficients of performance with respect to the ones based on manufacturer's datasheet and technical standards. Moreover, in any operation modes, the actual performances of the heat pump were about 3.0. The latter value is lower than the expectations considering the mild climate of Odessa. With reference to the Ukrainian educational buildings we found that the break-even seasonal performance required for an electrically driven heat pump to be economically advantageous with respect to a gas boiler is in the range 2.23…2.5, depending on actual prices of natural gas, electricity, and boiler efficiency. The duration of the modes, the moments of switching from mode to mode, and also the case of refusal from standby operation modes. To determine the possibility of replacing the thermal power of the heat generator.

The factors affecting the efficiency of the permanent and intermittent heat pump system with tank accumulator are identified. The accumulating substitution parameter allows to choose optimal conditions of use the storage of heat in HPS.

The obtained results allow to solve the problem of the effective functioning of the intermittent heat supply system with a maximum fraction of the replacement of the thermal power of the heat tank and heat generator. The application of the methodology for choosing the rational operation conditions of the heat supply system for intermittent work mode taking into account the accumulating substitution parameter of thermal load, allows achieving a reduction in the maximum power of heat generators by 50 %.

Література

1. Industrial waste heat utilization for low temperature district heating / Hao Fang, Jianjun Xia, Kan Zhu, Yingbo Su, Yi Jiang. *Energy Policy*. 2013. vol. 62. P. 236–246. DOI: 10.1016/j.enpol.2013.06.104.
2. Qian H., Wang Y. Modeling the interactions between the performance of ground source heat pumps and soil temperature variations. *Energy for Sustainable Development*. 2014. vol. 23. P. 115–121. DOI: doi.org/10.1016/j.esd.2014.08.004.
3. Yang W., Sun L., Chen Y. Experimental investigations of the performance of a solar-ground source heat pump system operated in heating modes. *Energy and Buildings*. 2015. vol. 89. P. 97–111. DOI: doi.org/10.1016/j.enbuild.2015.08.006.
4. Sarbu I., Sebarchievici C. General review of ground-source heat pump systems for heating and cooling of buildings. *Energy and Buildings.* 2014. vol. 70. P. 441–454. DOI: doi.org/10.1016/j.enbuild.2013.11.068.
5. Warmenpumpen Testzentrum. Test Results of Air to Water Heat Pumps based on EN 14511. 2011. URL: http://www.ntb.ch/fileadmin/Institute/IES/pdf/PruefResLW110620_Eng.pdf.
6. Stuart J.S., Bale V.R., Marc A.R. Geothermal heat pump systems: Status review and comparison with other heating options. *Applied Energy*. 2013. vol. 101. P. 341–348. DOI: doi.org/10.1016/j.apenergy.2012.01.048.
7. Bayer P., Saner D., Belay S., Rybach L., Blum P. Greenhouse gas emission savings of ground source heat pump systems in Europe: A review. *Renewable Sustainable Energy Reviews*. 2012. vol.16. P. 1256–1267. DOI: doi.org/10.1016/j.rser.2011.09.027.
8. Ruiz-Calvo F., Cervera-Vázquez J., Montagud C., Corberán J.M. Reference data sets for validating and analyzing GSHP system based on an eleven-year operation period. *Geothermics*. 2016. vol. 64. P. 538–550.
9. Alberto Liuzzo-Scorpo, Bo Nordell, Signhild Gehlin. Influence of regional groundwater flow on ground temperature around heat extraction boreholes. *Geothermics.* 2015. vol. 56. P. 119–127. DOI: doi.org/10.1016/j.geothermics.2015.04.002.
10. Hu P.F., Hu Q.S., Lin Y.L., Yang W., Xing L. Energy and exergy analysis of a ground source heat pump system for a public building in Wuhan, China under different control strategies. *Energy and Buildings*. 2017. vol. 152. P. 301–312. DOI: doi.org/10.1016/j.enbuild.2017.07.058.
11. . Rad F.M., Fung A.S., Leong W.H. Feasibility of combined solar thermal and ground source heat pump systems in cold climate, Canada. *Energy and Buildings*. 2013. vol. 61. P. 224–232. DOI: doi.org/10.1016/j.enbuild.2013.02.036.
12. Nguyen H.V., Law Y.L.E., Alavy M., Walsh P.R., Leong W.H., Dworkin S.B. An analysis of the factor- affecting hybrid ground-source heat pump installation potential in North America. *Applied Energy*. 2014. vol. 125. P. 28–38. DOI: doi.org/10.1016/j.apenergy.2014.03.044.

13. Zhijian Liu,Wei Xu, Cheng Qian, Xi Chen, Guangya Jin. Investigation on the feasibility and performance of ground source heat pump (GSHP) in three cities in cold climate zone, China. *Renewable Energy*. 2015. vol. 84. pp. 89–96. DOI: doi.org/10.1016/j.renene.2015.06.019.
14. Wenxin Li, Xiangdong Li, Yong Wan, Jiyuan Tu. An integrated predictive model of the long-term performance of ground source heat pump (GSHP) systems. *Energy and Buildings*. 2018. vol. 159. P. 309–318. DOI: doi.org/10.1016/j.enbuild.2017.11.012.
15. Massimo Cimmino. Fluid and borehole wall temperature profiles in vertical geothermal boreholes with multiple U-tubes. *Renewable Energy*. 2016. vol. 96, part A. P. 137–147. DOI: doi.org/10.1016/j.renene.2016.04.067.
16. Nikola Kuzmic, Ying Lam E. Law, Seth B. Dworkin. Numerical heat transfer comparison study of hybrid and non-hybrid ground source heat pump systems. *Applied Energy*. 2016. vol. 165. P. 919–929. DOI: 10.1016/j.apenergy.2015.12.122.
17. Kojo Atta Aikins, Jong Min Choi. Current status of the performance of GSHP (ground source heat pump) units in the Republic of Korea. *Energy*. 2012. vol. 47. P. 77–82. DOI: doi.org/10.1016/j.energy.2012.05.048.
18. Liu, X.R. Analysis of heat balance and regional characteristics of ground-coupled heat pump systems. *Heating, Ventilation and Air Condition*. 2008. vol. 38. P. 57–59. DOI: doi.org/10.3969/j.issn.1002-8501.2008.09.014.
19. CO_2-abatement cost of residential heat pumps with Active Demand Response : demand- and supply-side effects / D. Patteeuw, G. Reynders, K. Bruninx, C. Protopapadaki, E. Delarue, D. William, D. Saelens, and L. Helsen. *Applied Energy*. 2015. 156. 490501. DOI: 10.1016/j.apenergy.2015.07.038.
20. Mathiesen B.V., Lund H., Karlsson K. 100% Renewable energy systems, climate mitigation and economic growth. *Appl. Energy*. 2011. 88. 488–501.
21. Franco A., Salza, P. Strategies for optimal penetration of intermittent renewables in complex energy systems based on techno-operational objectives. *Renew. Energy.* 2011. 36. 743–753.
22. Lund P.D., Lindgren J., Mikkola J., Salpakari J. Review of energy system flexibility measures to enable high levels of variable renewable electricity. *Renew. Sustain. Energy Rev*. 2015. 45. 785–807.
23. Reynders G., Lopes R.A., Marszal-Pomianowska A., Aelenei D., Martins J., Saelens D. Energy flexible buildings: An evaluation of definitions and quantification methodologies applied to thermal storage. *Energy Build.* 2018. 166. 372–390.
24. Samuels J.A., Grobbelaar S.S., Booysen M.J. Light-years apart: Energy usage by schools across the South African affluence divide. *Energy Res Soc Sci.* 2020. 70. 101692.
25. Geraldi M.S., Ghisi E. Mapping the energy usage in Brazilian public schools. *Energy Build.* 2020. 224. 110209.
26. Martinopoulos G., Kikidou V., Bozis D. Energy assessment of building physics principles in secondary education buildings. *Energies.* 2018. 11(11). 2929.
27. Kikidou V. Energy assessment of building physics principles in secondary education buildings. 2017. URL: https://repository.ihu.edu.gr/xmlui/handle/11544/29176.
28. Air Conditioners, Liquid Chilling Packages and Heat Pumps, with Electrically Driven Compressors, for Space Heating and Cooling. EN 14825. Testing and Rating at Part. Load Conditions and Calculation of Seasonal Performance. European Committee for Standardization (CEN). Brussels, Belgium, 2018. DOI: https://doi.org/10.1016/j.enbuild.2018.02.040.
29. Blarke M. B. Towards an intermittency-friendly energy system: Comparing electric boilers and heat pumps in distributed cogeneration. *Applied Energy*. 2012. 91(1). 349–365. DOI: 10.1016/j.apenergy.2011.09.038.
30. Clean Energy Management Software platform RETScreen. URL: https://www.reeep.org/projects/retscreen-expert-decision-intelligence-software-platform.
31. Conti P., Bartoli C., Franco A., Testi D. Experimental analysis of an air heat pump for heating service using a hardware-in-the loop system. *Energies.* 2020. 13. 4498. DOI: 10.3390/en13174498.
32. Schito E., Conti P., Urbanucci L., Testi D. Multi-objective optimization of HVAC control in museum environment for artwork preservation, visitors’ thermal comfort and energy efficiency. *Build. Environ*. 2020. 180. 107018.
33. Saltelli A., Ratto M., Andres T., Campolongo F., Cariboni J., Gatelli D., Saisana M., Tarantola S. Global Sensitivity Analysis. The Prime, Editor Willey. GB, 2008, 305 p. URL: http://www.andreasaltelli.eu/file/repository/A_Saltelli_Marco_Ratto_Terry_Andres_Francesca_CampolongoJessica_Cariboni_Debora_Gatelli_Michaela_Saisana_Stefano_Tarantola_Global_Sensitivity_Analysis_The_Primer_Wiley_Interscience_2008_.pdf.
34. Klymchuk O., Denysova A., Balasanian G., Ivanova L., Bodiul O. Enhancing efficiency of using energy resources in heat supply systems of buildings with variable operation mode. *Eureka. Physics and Engineering*. 2020. (3). 59–68. DOI: https://doi.org/10.21303/2461-4262.2020.001252.

References

1. Hao Fang, Jianjun Xia, Kan Zhu, Yingbo Su, & Yi Jiang. (2013). Industrial waste heat utilization for low temperature district heating. *Energy Policy*, 62, 236–246. DOI: 10.1016/j.enpol.2013.06.104.
2. Qian, H., & Wang, Y. (2014). Modeling the interactions between the performance of ground source heat pumps and soil temperature variations. *Energy for Sustainable Development*, 23, 115–121. DOI: doi.org/10.1016/j.esd.2014.08.004.
3. Yang, W., Sun, L., & Chen, Y. (2015). Experimental investigations of the performance of a solar-ground source heat pump system operated in heating modes. *Energy and Buildings*, 89, 97–111. DOI: doi.org/10.1016/j.enbuild.2015.08.006.
4. Sarbu, I., & Sebarchievici, C. (2014). General review of ground-source heat pump systems for heating and cooling of buildings. *Energy and Buildings*, 70, 441–454. DOI: doi.org/10.1016/j.enbuild.2013.11.068.
5. Warmenpumpen Testzentrum. (2011). Test Results of Air to Water Heat Pumps based on EN 14511. Retrieved from: http://www.ntb.ch/fileadmin/Institute/IES/pdf/PruefResLW110620_Eng.pdf.
6. Stuart, J.S., Bale, V.R., & Marc, A.R. (2013). Geothermal heat pump systems: Status review and comparison with other heating options. *Applied Energy*, 101, 341–348. DOI: doi.org/10.1016/j.apenergy.2012.01.048.
7. Bayer, P., Saner, D., Belay, S., Rybach, L., & Blum, P. (2012). Greenhouse gas emission savings of ground source heat pump systems in Europe: A review. *Renewable Sustainable Energy Reviews*, 16, 1256–1267. DOI: doi.org/10.1016/j.rser.2011.09.027.
8. Ruiz-Calvo, F., Cervera-Vázquez, J., Montagud, C., & Corberán, J.M. (2016). Reference data sets for validating and analyzing GSHP system based on an eleven-year operation period. *Geothermics*, 64, 538–550.
9. Alberto Liuzzo-Scorpo, Bo Nordell, & Signhild Gehlin. (2015). Influence of regional groundwater flow on ground temperature around heat extraction boreholes. *Geothermics*, 56, 119–127. DOI: doi.org/ 10.1016/j.geothermics.2015.04.002.
10. Hu, P.F., Hu, Q.S., Lin, Y.L., Yang, W., & Xing, L. (2017). Energy and exergy analysis of a ground source heat pump system for a public building in Wuhan, China under different control strategies. *Energy and Buildings*, 152, 301–312. DOI: doi.org/10.1016/j.enbuild.2017.07.058.
11. Rad, F.M., Fung, A.S., & Leong, W.H. (2013). Feasibility of combined solar thermal and ground source heat pump systems in cold climate, Canada. *Energy and Buildings*, 61, 224–232. DOI: doi.org/10.1016/j.enbuild.2013.02.036.
12. . Nguyen, H.V., Law, Y.L.E., Alavy, M., Walsh, P.R., Leong, W.H., & Dworkin, S.B. (2014). An analysis of the factor- affecting hybrid ground-source heat pump installation potential in North America. *Applied Energy*, 125, 28–38. DOI: doi.org/10.1016/j.apenergy.2014.03.044.
13. Zhijian Liu, Wei Xu, Cheng Qian, Xi Chen, & Guangya Jin. (2015). Investigation on the feasibility and performance of ground source heat pump (GSHP) in three cities in cold climate zone, China. *Renewable Energy*, 84,. 89–96. DOI: doi.org/10.1016/j.renene.2015.06.019.
14. Wenxin Li, Xiangdong Li, Yong Wan, & Jiyuan Tu. (2018). An integrated predictive model of the long-term performance of ground source heat pump (GSHP) systems. *Energy and Buildings*, 159, 309–318. DOI: doi.org/10.1016/j.enbuild.2017.11.012.
15. Massimo Cimmino. (2016). Fluid and borehole wall temperature profiles in vertical geothermal boreholes with multiple U-tubes. *Renewable Energy*, 96, A, 137–147. DOI: doi.org/10.1016/j.renene.2016.04.067.
16. Nikola Kuzmic, Ying Lam E. Law, & Seth B. Dworkin. (2016). Numerical heat transfer comparison study of hybrid and non-hybrid ground source heat pump systems. *Applied Energy*, 165, 919–929. DOI: 10.1016/j.apenergy.2015.12.122.
17. Kojo Atta Aikins, & Jong Min Choi. (2012). Current status of the performance of GSHP (ground source heat pump) units in the Republic of Korea. *Energy*, 47, 77–82. DOI: doi.org/10.1016/j.energy.2012.05.048.
18. Liu, X.R. (2008). Analysis of heat balance and regional characteristics of ground-coupled heat pump systems. *Heating, Ventilation and Air Condition*, 38, 57–59. DOI: doi.org/10.3969/j.issn.1002-8501.2008.09.014.
19. Patteeuw, D., Reynders, G., Bruninx, K., Protopapadaki, C., Delarue, E., William, D., Saelens, D., & Helsen, L. (2015). CO_2-abatement cost of residential heat pumps with Active Demand Response : demand- and supply-side effects. *Applied Energy, 156*, 490–501. DOI: 10.1016/j.apenergy.2015.07.038.
20. Mathiesen, B.V., Lund, H., & Karlsson, K. (2011). 100% Renewable energy systems, climate mitigation and economic growth. *Appl. Energy,* 88, 488–501.
21. Franco, A., & Salza, P. (2011). Strategies for optimal penetration of intermittent renewables in complex energy systems based on techno-operational objectives. *Renew. Energy, 36*, 743–753.

22. Lund, P.D., Lindgren, J., Mikkola, J., & Salpakari, J. (2015). Review of energy system flexibility measures to enable high levels of variable renewable electricity. *Renew. Sustain. Energy Rev*, 785–807.
23. Reynders, G., Lopes, R.A., Marszal-Pomianowska, A., Aelenei, D., Martins, J., & Saelens, D. (2018). Energy flexible buildings: An evaluation of definitions and quantification methodologies applied to thermal storage. *Energy Build,* 166, 372–390.
24. Samuels, J.A., Grobbelaar, S.S., & Booysen, M.J. (2020). Light-years apart: Energy usage by schools across the South African affluence divide. *Energy Res Soc Sci.,* 70, 101692.
25. Geraldi, M.S., & Ghisi, E. (2020). Mapping the energy usage in Brazilian public schools. *Energy Build,* 224, 110209.
26. Martinopoulos, G., Kikidou, V., & Bozis, D. (2018). Energy assessment of building physics principles in secondary education buildings. *Energies,* 11(11), 2929.
27. Kikidou, V. (2017). *Energy assessment of building physics principles in secondary education buildings.* URL: https://repository.ihu.edu.gr/xmlui/handle/11544/29176.
28. Air Conditioners, Liquid Chilling Packages and Heat Pumps, with Electrically Driven Compressors, for Space Heating and Cooling. EN 14825. Testing and Rating at Part. Load Conditions and Calculation of Seasonal Performance. European Committee for Standardization (CEN). Brussels, Belgium, 2018. DOI: https://doi.org/10.1016/j.enbuild.2018.02.040.
29. Blarke, M. B. (2012). Towards an intermittency-friendly energy system: Comparing electric boilers and heat pumps in distributed cogeneration. *Applied Energy,* 91(1), 349–365. DOI: 10.1016/j.apenergy.2011.09.038.
30. Clean Energy Management Software platform RETScreen. URL: https://www.reeep.org/projects/retscreen-expert-decision-intelligence-software-platform.
31. Conti, P., Bartoli, C., Franco, A., & Testi, D. (2020). Experimental analysis of an air heat pump for heating service using a hardware-in-the loop system. *Energies,* 13, 4498. DOI: 10.3390/en13174498.
32. Schito, E., Conti, P., Urbanucci, L., & Testi, D. (2020). Multi-objective optimization of HVAC control in museum environment for artwork preservation, visitors' thermal comfort and energy efficiency. *Build. Environ*, 180, 107018.
33. Saltelli, A., Ratto, M., Andres, T., Campolongo, F., Cariboni, J., Gatelli, D., Saisana, M., & Tarantola, S. (2008). *Global Sensitivity Analysis*. The Prime, Editor Willey. GB. URL: http://www.andreasaltelli.eu/file/repository/A_Saltelli_Marco_Ratto_Terry_Andres_Francesca_CampolongoJessica_Cariboni_Debora_Gatelli_Michaela_Saisana_Stefano_Tarantola_Global_Sensitivity_Analysis_The_Primer_Wiley_Interscience_2008_.pdf.
34. . Klymchuk, O., Denysova, A., Balasanian, G., Ivanova, L., & Bodiul, O. (2020). Enhancing efficiency of using energy resources in heat supply systems of buildings with variable operation mode. *Eureka. Physics and Engineering*, (3), 59–68. DOI: https://doi.org/10.21303/2461-4262.2020.001252.

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