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ENERGY, ECOLOGICAL AND ECONOMIC EFFICIENCY OF STEAM COMPRESSOR HEAT PUMP PLANTS AS COMPARED WITH ALTERNATIVE SOURCES OF HEAT SUPPLY

Energy, ecological and economic efficiency of steam compressor heat pump plants (HPP) with various sources of low temperature heat for heat supply systems in comparison with alternative sources of heat supply has been analyzed. Values of annual saving of equivalent fuel are determined, reduction of CO_2 emissions, cost saving on fuel-energy resources and on emissions for 1 MW HPP with various types of drive, using the heat of different low temperature sources are evaluated.

Key words: *energy efficiency, saving of equivalent fuel, ecological efficiency, economic efficiency, heat pump plant.*

Introduction

During last decades problems of energy efficiency increase of energy generation numerous studies in branch editions in the world and in Ukraine were published [1-2]. Nowadays it is very important for Ukraine to take into consideration main problems, concerning the development of fuel and energy complex: critical state of energy resources base, outdated equipment and technologies of organic fuel mining, processing and burning, low level of energy efficiency and ecological safety of energy production, shortage of domestic fuel and energy resources, high cost of imported energy resources, grows of ecological requirements. Realizing their objective character, a number of urgent measures, realization of which enables to solve the problem of provision of high level of energy efficiency and ecological safety of energy production and energy usage are to be developed.

Further considerable increase of natural gas price in Ukraine and growth of tariffs for heat energy stipulate the search of new highly efficient sources of heat supply. Usage of heat pump plants (HPP) in the systems of heat supply will provide the economy of fuel and protection of the environment as a result of reduction thermal pollution and amount of harmful emissions of combustion products.

For determination of energy efficiency of usage of initial energy of the fuel and impact of certain type of heating on the environment, the Commission on heat pumps of European Economic Community (EEC) in 1991 performed the analysis of heating systems, widely used in Europe. The results of the analysis are shown in table 1 [3]. As it is seen from the table 1, heat pumps provide high energy efficiency of initial energy and produce far less CO_2 emissions, as compared with alternative sources of energy supply.

In recent years a number of research, aimed at study the efficiency of heat pump plants usage in thermal circuits of energy supply sources were performed. In [4] the authors carried out the research, aimed at the increase of energy efficiency of heat supply sources by means of usage of HPP, taking into account the impact of circuit solutions and operation modes. Evaluation of HPP efficiency was performed in accordance with such criteria: fuel saving as compared with existing scheme, fuel and electric energy annual expenses, capital investment, thermal unit cost, term of recoupment, annual matching of expenses and profit. In [5] schemes of HPP usage at industrial electric power plants are considered. In research [6] the efficiency of HPP with electric drive and drive from gas-fired unit and waste-heat boiler is analyzed.

Table 1

Indices of heating systems (according to EEC data) [3]

Heating system	Energy efficiency of initial energy, %	CO_2 emission, kg/kW
Electrical heating	35	0.55
Liquid fuel boiler, hot water heating	80	0.29
Gas-fired boiler, hot water heating	90	0.21
Heat pump with electric drive	110	0.22…0.14
Absorption heat pump	130	0.17
Heat pump with gas-engine drive	150	0.12

Authors [7] performed comparative studies of three energy supply systems regarding the coast of heat (on the base of gas-fired boiler, heat pump and cogeneration unit with heat pump) on condition of electric energy and gas prices change for different groups of consumers. In [8] evaluation of the efficiency of four 3 MW heat supply sources, based on electric boiler, fuel-fired boiler (gas, liquid fuel) and heat pump plant was carried out. Authors [9] performed evaluation of energy efficiency of heat pump plant of small power as compared with conventional sources of heat supply, based on electric or gas-fired boilers. In [10] energy and ecological efficiency of heat pump plants with various sources of low temperature heat for enterprises of food-processing industry was evaluated, rational temperature operation modes of HPP were determined and substantiated.

In [3–10] authors **did not** perform evaluation of energy, ecological and economic efficiency of steam compressor HPP with various types of drive in heat supply systems, as compared with alternative sources of heat supply.

The aim of research is determination of energy and ecological advantages and economic preconditions of usage of steam compressor heat pumps with different sources of heat for operation in heat supply systems; evaluation of energy, ecological and economic efficiency of HPP as compared with alternative sources of heat supply.

Main part Основна частина

In [10] rational temperature operation modes of steam compressor HPP, at which the economy of equivalent fuel for various sources of low temperature heat is obtained, are determined.

On the basis of these results, the study of the efficiency of HPP with thermal capacity 1 MW with various types of compressor drive, at various sources of low temperature heat on condition of annual operation of HPP and variable temperature modes operation during the year was performed

Study was performed, applying the method of mathematical modeling of HPP operation using program in Excel environment. Energy, ecological and economic efficiency of steam compressor HPP was compared with the efficiency of alternative sources of heat supply (gas-fired boiler house and boiler house, operating in liquid fuel). The efficiency of HPP with electric drive, compressor drive from gas-piston engine (GPE) and drive from diesel engine was investigated. The schemes of the above-mentioned HPP are presented in [4].

The sources of low temperature heat for HPP were: surface and ground waters, water of circulating water supply system, geothermal waters, air, industrial heat emissions, sewage waters and heat of the soil. Characteristic of the souses of low temperature heat is given in [11].

Energy efficiency of HPP was evaluated by the index of equivalent fuel saving. Consumption of equivalent fuel by boiler house (for alternative sources of heat supply), HPP with GPE drive and diesel engine drive was evaluated. For HPP with electric drive, the consumption of equivalent fuel while electric energy generation at electric power stations was evaluated.

Saving of equivalent and working fuel as a result of HPP introduction is considerably determined by optimally chosen HPP operation modes. The results of investigation of HPP energy efficiency, on condition of variable operation modes, are presented in [12]. Studies of HPP economic efficiency was performed for existing values of energy resources cost in Ukraine. Values of fuel and energy resources cost, for which the study was performed, are showed in table 2.

Table 2

Cost of fuel and energy resources

Value of fuel and energy resources cost	Sphere of HPP introduction
	Institution and organizations, financed from state and local budgets, industrial consumers and other transactor units (management subjects) (price at 01.05.14) [13]
Price of electrical energy, Hrs./(kW·h)	1.239
Price of natural gas, Hrs./thous. m^3	6266.98

As it was already mentioned, besides energy advantages, application of heat pumps leads to decrease of environmental contamination and reduction of harmful emissions in the atmosphere. For evaluation of ecological efficiency of HPP, the index of the amount of CO_2 emissions reduction is used (see table 1), because it is connected with economic efficiency of HPP. Attraction of financial resources, obtained at a result of selling quotas for CO_2 emissions, in accordance with the Kyoto Protocol, allows to increase economic efficiency of HPP introduction and reduce the term of their recoupment. In investigation takes into account that additional financial resources, obtained from selling quotas for CO_2 emissions represent 20 $/t of emissions.

Reduction of CO_2 emissions while using 1 MW HPP as compared with the operation of hot-water boiler of the same capacity, operating on natural gas is evaluated. Emissions of CO_2 while gas combustion in boilers (for alternative sources of heat supply), while combustion of working fuel in GPE and diesel engine (for compressor drive of HPP) and CO_2 emissions during electric energy generation at electric power plants (for HPP with electric drive) were taken into account. For evaluation of the amount of CO_2 emissions statistical data from the research [3] (see table 1) were used.

Economic efficiency, obtained due to HPP introduction, is determined as the different of operation expenses of substituted hot-water boiler house and HPP. Operation expenses while hot-water boiler house or HPP functioning includes: expenses for fuel, electric energy, water, depreciation of equipment and current maintenance, earnings and other expenses. The most important component in the structure of operation expenses and heat energy cost are fuel expenses (for boiler houses and HPP with GPE drive or diesel engine drive) and electric energy (for HPP with electric drive). Considerable impact on energy and, as a result, economic efficiency of HPP produce HPP operation modes and temperature level of the chosen source of low temperature heat.

Investigations, regarding economic efficiency were carried out according to consolidated indices. For different variants of HPP financial resources saving on fuel-energy resources and CO_2 emissions was evaluated. For different sources of heat in HPP, expenses for construction of heat extraction systems from low temperature source were not taken into account.

The suggested criteria allow to evaluate energy, ecological and economic efficiency of HPP operation during a year.

Fig. 1 shows values of annual saving of equivalent fuel (in %) for 1 MW HPP with different types of compressor drives, using the heat of various low temperature sources. As it is seen from Fig. 1, for HPP with electric drive the saving of equivalent fuel is 18.51…54.53%; for HPP with GPE drive

– 48.11…74.07%; for HPP with the drive from diesel engine – 42.63…70.71%. The greatest values of equivalent fuel saving correspond to such sources of heat for HPP as: circulating water, geothermal waters and industrial heat emissions, that is stipulated by their high temperature level.

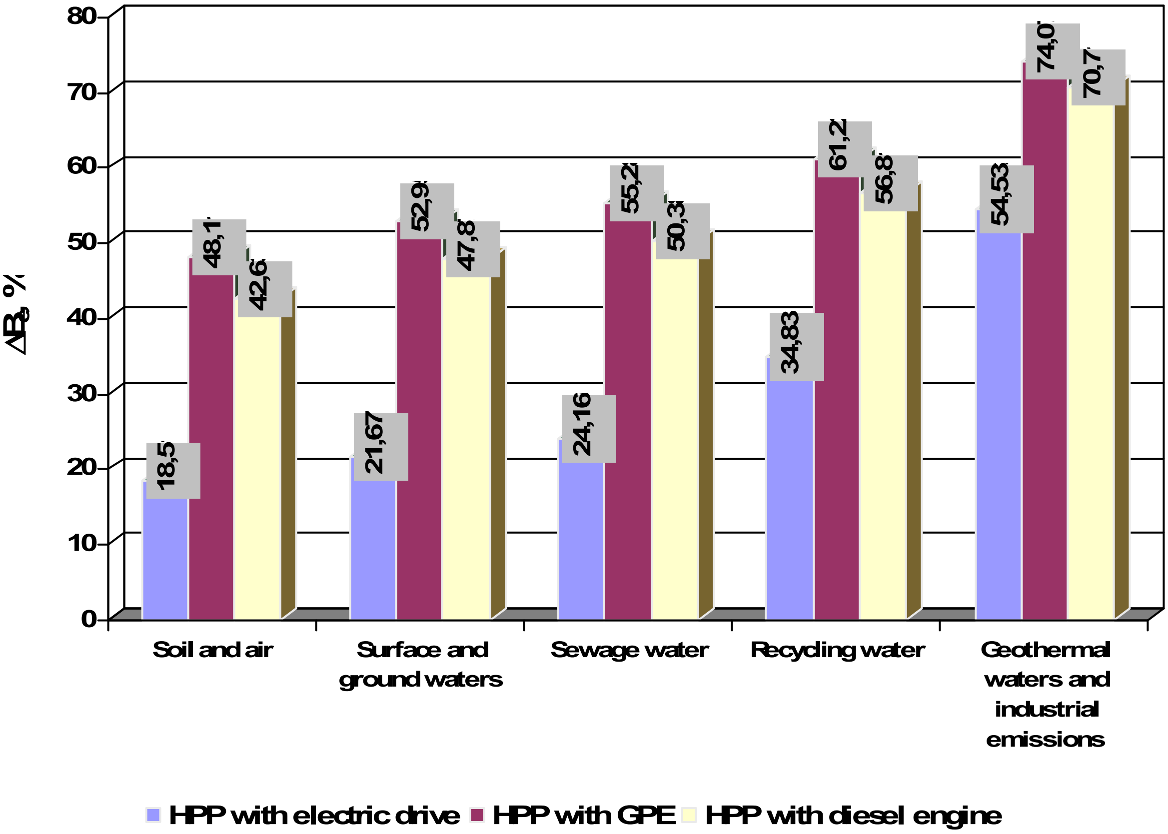

Fig. 1. Values of annual economy of equivalent fuel (in %) for HPP with various types of drive, using heat from different low temperature sources

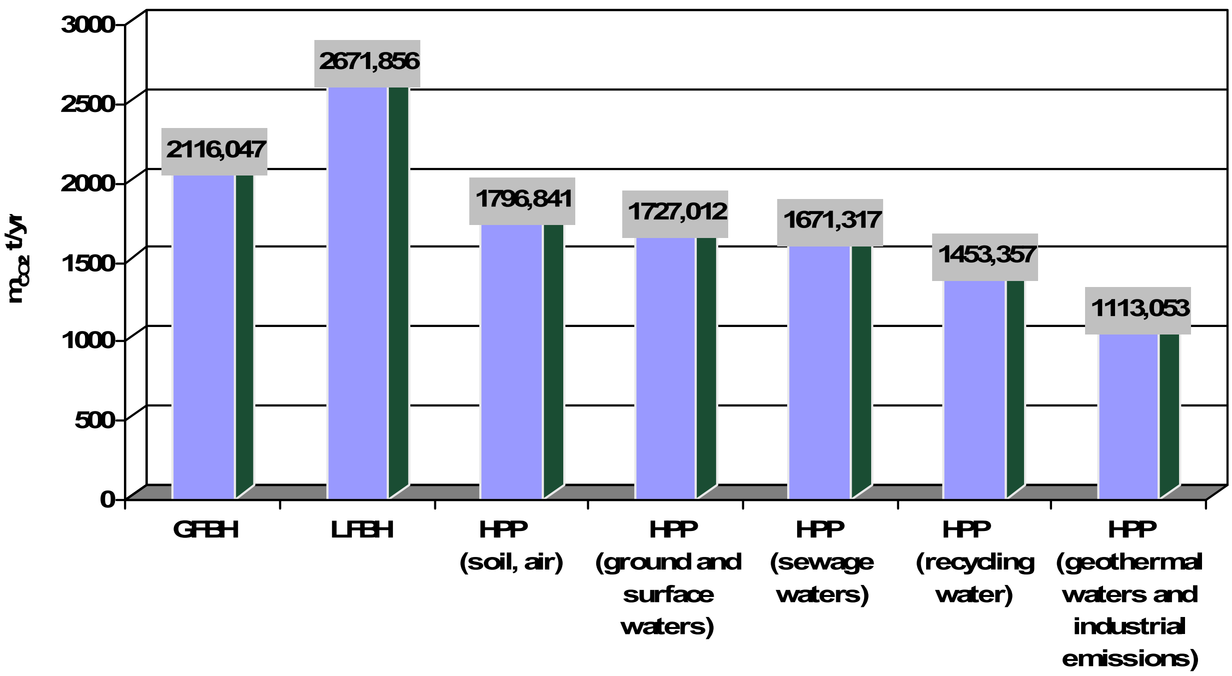

Fig. 2. Values of annual amount of CO_2 emissions produced by boiler houses, operating on gaseous and liquid fuel and 1 MW HPP with electric drive, operating on various sources of low temperature heat

Fig. 2 contains the values of annual amount of CO_2 emissions, while usage of 1 MW HPP with electric drive at different sources of low temperature heat. For comparison the values of annual amount of CO_2 emissions of boiler house of the same power, operating on gaseous fuel (GFBH) and liquid fuel (LFBH) are showed here. Emissions of CO_2 while fuel combustion in boilers and CO_2 emissions in the process of electric energy generation at electric power stations were taken into account. As it is seen from Fig. 2, while usage of HPP with electric drive considerable reduction of the amount of CO_2 emissions as compared with boiler houses is recorded.

Fig. 3 shows the values of annual amount of CO_2 emissions, using 1 MW HPP with GPE drive at different sources of low temperature heat. For comparison, the values of annual amount of CO_2 emissions of boiler house of the same power, operating on gaseous fuel (GFBH) and liquid fuel (LFBH) are shown here. As it is seen from Fig. 3, while using of HPP with GPE drive considerable reduction of the annual CO_2 emissions is recorded, than for HPP with electric drive (see Fig. 2).

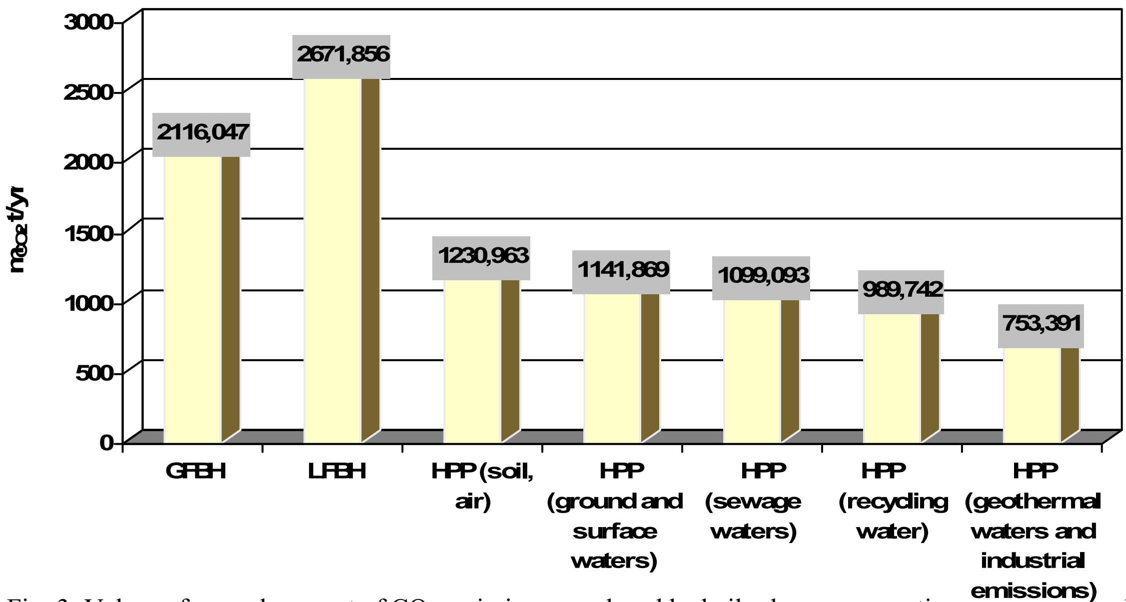

Fig. 3. Values of annual amount of CO_2 emissions, produced by boiler houses, operating on gaseous and liquid fuel and 1 MW HPP, with the drive from GPE, operating on various sources of low temperature heat

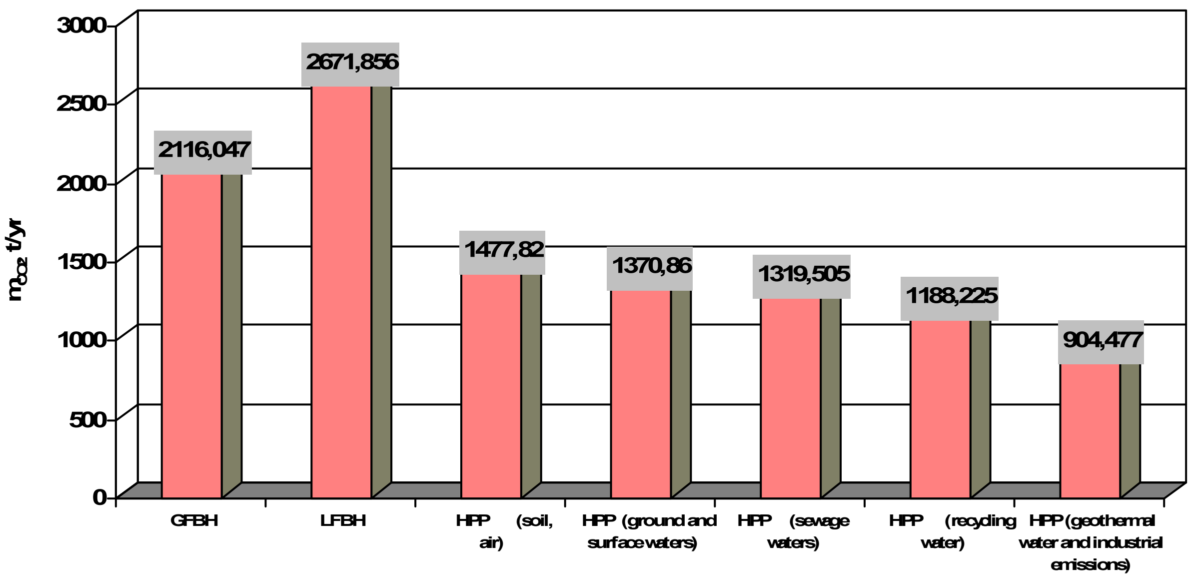

Fig. 4. Values of annual amount of CO_2 emissions, produced by boiler houses, operating on gaseous and liquid fuel and 1 MW HPP, with the diesel drive, operating on various sources of low temperature heat

Fig. 4 contains the values of annual amount of CO_2 emissions while using 1 MW HPP with diesel engine drive at various sources of low temperature heat. As in previous cases, values of annual amount of CO_2 emissions of the boiler house of the same power, operating on gaseous and liquid fuel are shown for comparison. As it is seen in Fig. 4, in case of HPP with diesel engine drive usage, annual amount of CO_2 emissions is grater than for HPP with GPE drive, but less than for HPP with electric drive. As it is seen from Fig. 2 – 4 HPP produces less impact on the environment than boiler houses.

Fig. 5 shows values of annual reduction of CO_2 emissions amount, using 1 MW HPP with different types of compressor drive, at various sources of low temperature heat. The greatest values of annual reduction of CO_2 emissions amount correspond to the following sources of heat for HPP: circulating water, geothermal waters and industrial heat emissions. It is stipulated by high temperature level of the above-mentioned sources of low temperature heat and, as a result, high energy efficiency of HPP in these sources of low temperature heat are used.

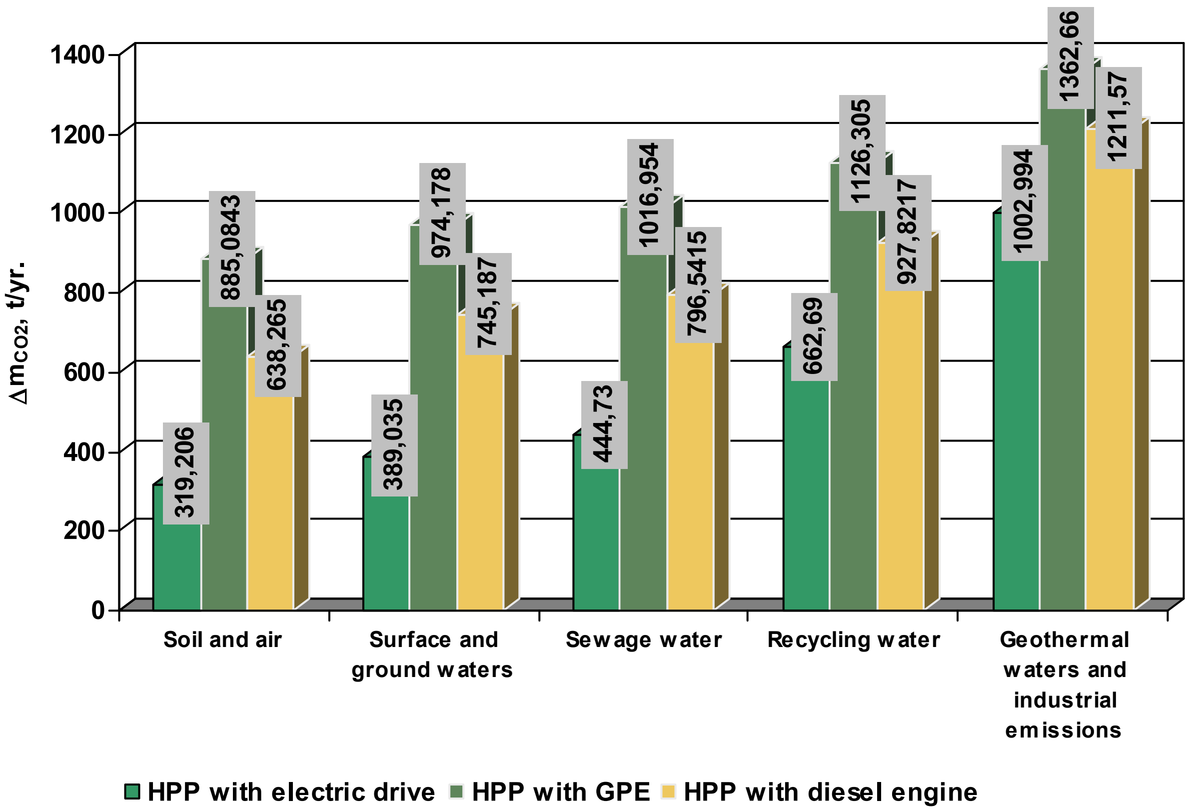

Fig. 5. Values of annual reduction of CO_2 emissions, using 1 MW HPP with various types of compressor drive, at different sources of low temperature heat

Fig. 6 contains the values of annual reduction of CO_2 emissions amount (in %) for the cases when HPP with different types of drive, at various sources of low temperature heat, as compared with the operation of gas-fired boiler house. It is seen from Fig. 6, that for HPP with different types of drive, for all investigated sources of low temperature heat the reduction of CO_2 emissions amount is provided.

Fig. 7 shows the values of annual saving of ΔE_e funds on CO_2 emissions, using 1 MW HPP with different types of drive, at various sources of low temperature heat, as compared with gas-fired boiler house. Depending on the chosen variant of HPP application, annual saving of financial resources on CO_2 emissions will be from 76.609 to 327.037 thous. hrs./yr.

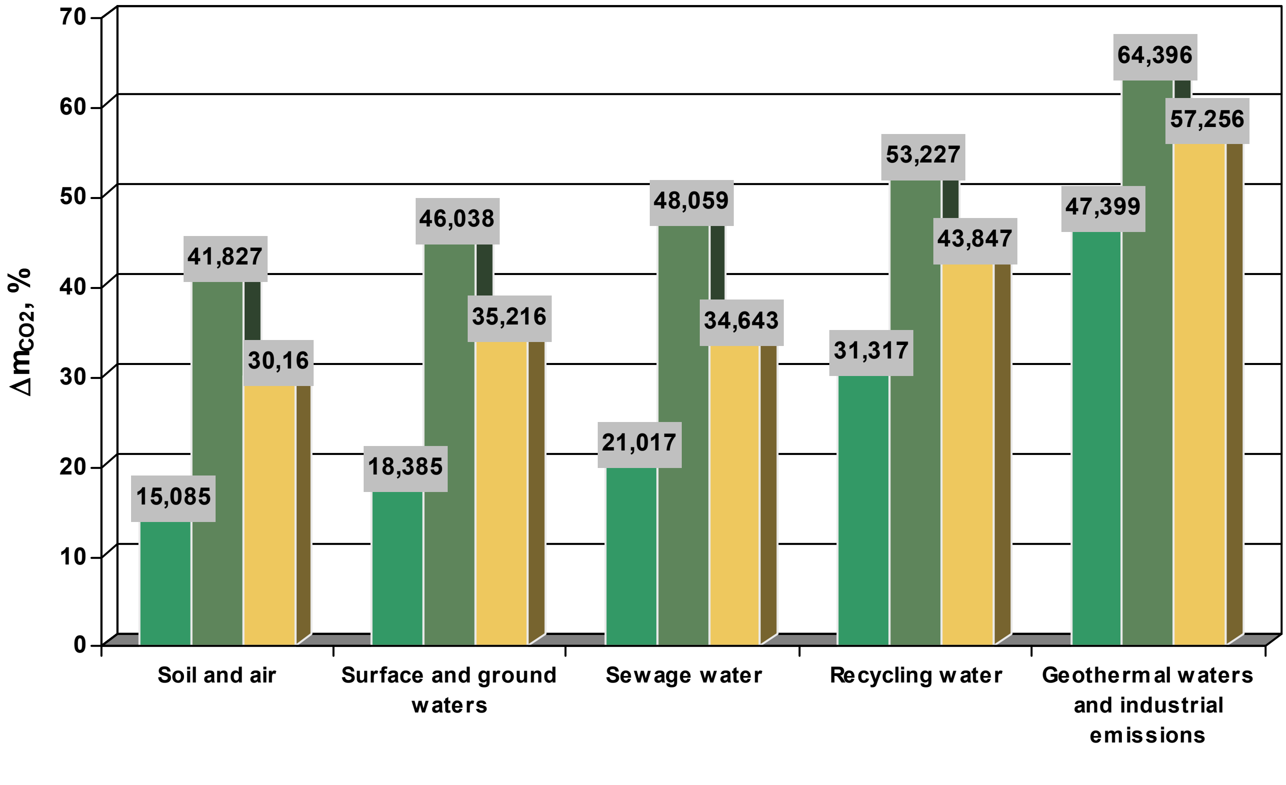

Fig. 6. Values of annual reduction of CO_2 emissions (in %) for the cases of HPP usage with various types of drive at different sources of low temperature heat, as compared with gas-fired boiler house

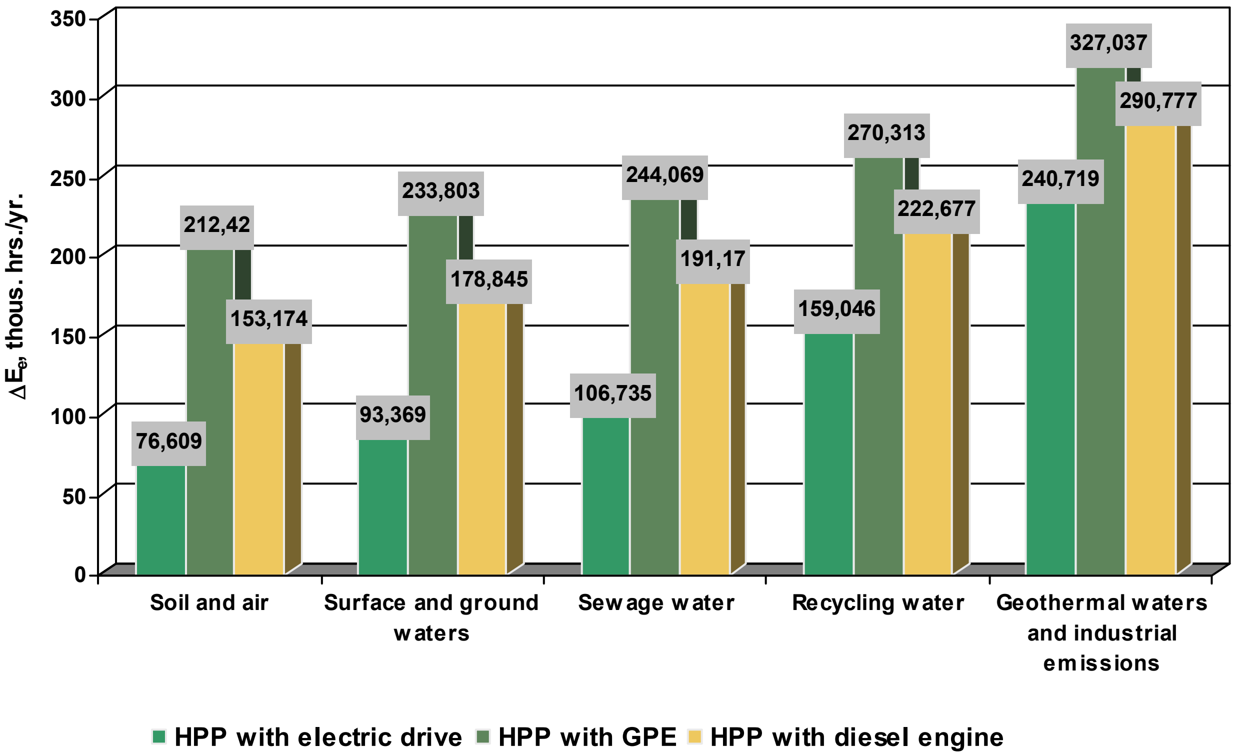

Fig. 7. Values of annual cost saving on CO_2 emissions, using 1 MW HPP with various types of drive on different sources of low temperature heat, as compared with the operation of gas-fired boiler house

Fig. 8 shows the distribution of annual saving of finance on the fuel ΔE_f and emissions ΔE_e for the cases of usage of HPP with GPE drive, at different sources of low temperature heat, as compared with the operation of gas-fired boiler house. As it is seen from Fig. 8, the greatest values of annual saving of finance on fuel and emissions correspond to the following sources of heat for HPP: circulating water, geothermal waters and industrial heat emissions. It is stipulated by high temperature level of the above-mentioned sources of low temperature heat, high energy efficiency of HPP and considerable saving of fuel in case of usage of these sources of low temperatuture heat.

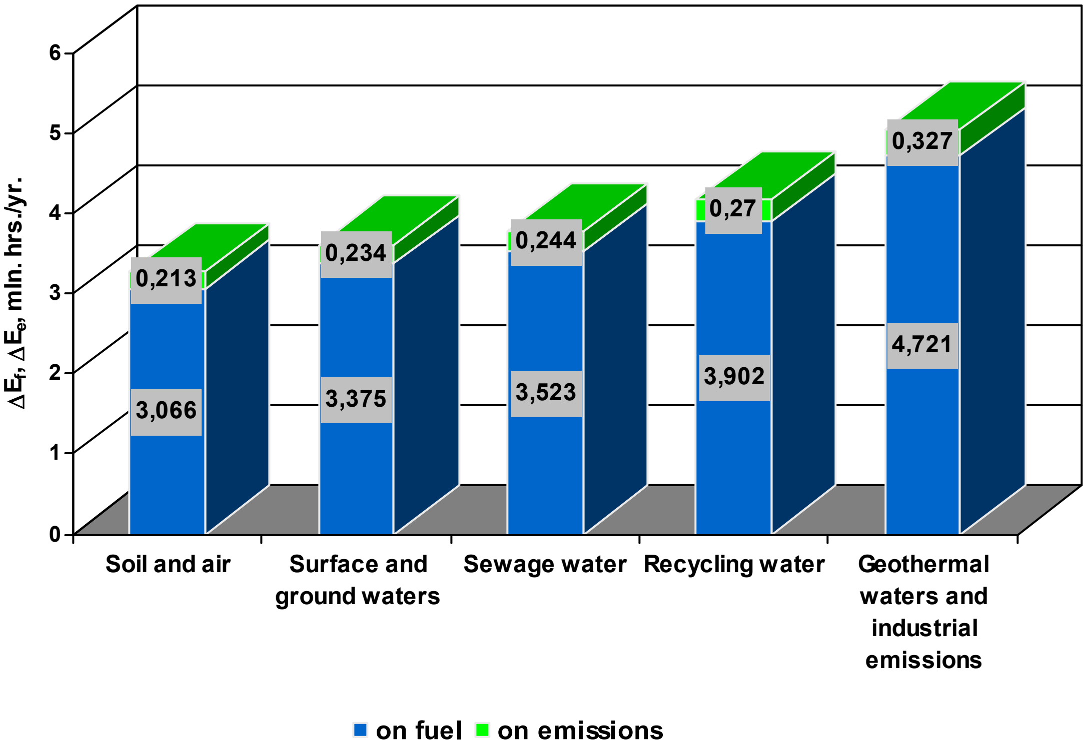

Fig. 8. Distribution of annual cost saving on fuel and emissions for the cases of HPP with GPE-drive, at different sources of low temperature heat, as compared with the operation of gas-fired boiler house

Fig. 9 shows the distribution of annual saving of finance on fuel and energy resources ΔE_f and emissions ΔE_e as a result of usage of HPP with electric drive, for various sources of low temperature heat, as compared with the operation of gas-fired boiler house.

It is seen from Fig. 8 and 9 that in case of usage of HPP with electric drive greater finance saving is obtained (on fuel and general) than for HPP with GPE drive. It is stipulated, first of all, by considerable amounts of expensive working fuel saving (natural gas) as a result of application of HPP with electric drive.

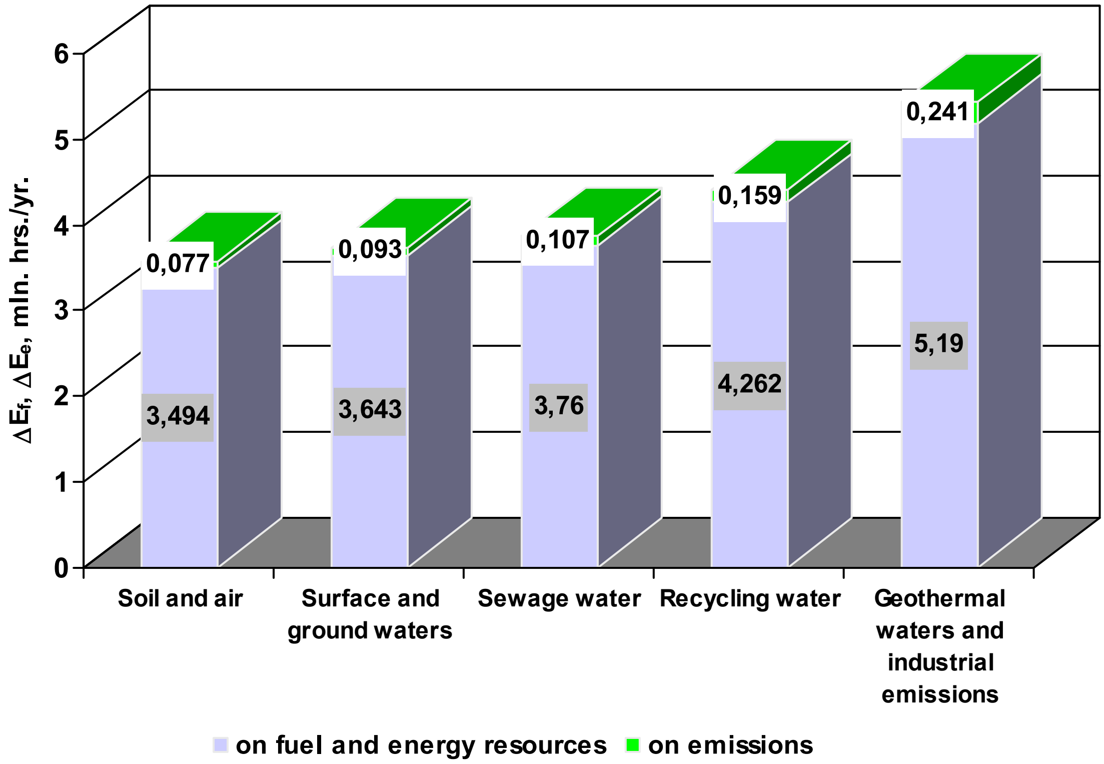

Fig. 9. Distribution of annual cost saving on fuel and emissions as a result of HPP with electric drive usage, for different sources of low temperature heat, as compared with the operation of gas-fired boiler house

Conclusions

Evaluation of energy, ecological and economic efficiency of steam compressor HPP with different types of drive in the systems of heat supply as compared with alternative sources of heat supply is carried out.

Values of annual saving of equivalent fuel for 1 MW HPP with different types of drive, using the heat of various low temperature sources are determined. Depending on the chosen sources of low temperature heat the saving of equivalent fuel is: for HPP with electric drive 18.51…54.53%; for HPP with GPE drive – 48.11…74.07%; for HPP with the drive from diesel engine – 42.63…70.71%. The greatest values of equivalent fuel saving correspond to such sources of heat for HPP as: circulating water, geothermal waters and industrial heat emissions, that is stipulated by their high temperature level.

Reduction of CO_2 emissions while using 1 MW HPP as compared with the operation of hot-water boiler of the same power, functioning on natural gas, was evaluated. It was determined, that:

– for HPP with different types of drive, for all investigated sources of low temperature heat, reduction of the amount of CO_2 emissions is provided;;

– for HPP with GPE drive considerable reduction of annual amount of CO_2 emissions than for HPP with electric drive is registered;

– if HPP with diesel engine is used, annual amount of CO_2 emissions is greater than for HPP with GPE drive, but is less, than for HPP with electric drive;

– HPP produce less impact on the environment, than boiler houses.

Economy of finance for fuel and energy resources and emissions for 1 MW HPP with different types of drive, using the heat of various low temperature sources is evaluated. When HPP with electric drive is used, greater saving of resources (on fuel and general), than for HPP with GPE drive is obtained. It is stipulated, first of all, by considerable volumes of expensive working fuel saving (natural gas) as a result of HPP with electric drive application.

The greatest values of equivalent fuel saving, annual reduction of the amount of CO_2 emissions, annual saving of finance resources on fuel and emissions correspond to such sources of heat for HPP as: circulating water, geothermal waters and industrial heat emissions. It is stipulated by high temperature level of the above-mentioned sources of low temperature heat, high energy efficiency of HPP and considerable saving of fuel in case of usage of these sources of low temperature.

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