SMART GRID СИСТЕМИ ТА ТЕХНОЛОГІЇ
SMART GRID SYSTEM AND TECHNOLOGY

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THE FUNCTIONING MODEL OF INTEGRATED ENERGY SUPPLY SYSTEM WITH CO-GENERATION UNITS OPERATION, TAKING INTO ACCOUNT PROSPECTS OF BIOENERGY DEVELOPMENT IN UKRAINE

In conditions of renewable energy sources development and implementation of modern technologies in the energy sector, energy from biomass in the structure of power supply systems is an actual topic. The development of bioenergy is an important part of ensuring the energy security of many countries, as it enables to reduce fossil fuel consumption, dependence on imported energy sources and ensure sustainable local energy supply. The article presents the functioning model of integrated energy supply system (energy hub) with co-generation units operation, taking into account prospects of bioenergy development in Ukraine. This paper studies the optimal operation problem of an energy hub with multiple energy sources to serve electricity and heat loads in the presence prices. The main task was solved to make full use of its own energy sources to meet the needs of consumers in energy carriers with the most effective financial performance. The availability of electric and thermal energy storage devices will allow more efficient usage of available energy resources and equipment. Usage of a cogeneration plant in the structure of the energy hub gives the opportunity to provide energy resources and the possibility of generated electricity trading. A multicriteria approach to the planning and optimization of the operation of such energy hub is proposed. According to the simulation results using the example of an energy hub, it is shown that this method is suitable for planning hourly energy consumption with a compromise in terms of the minimum cost of these energy resources and CO2 emissions.

Keywords**:** integrated power distribution systems, distributed generation, active consumer, cogeneration technology, energy hub, CHP based microgrid, biomass, biogas.

1. Introduction

Current energy policy of developed countries is based on understanding an exhaustion of traditional fuel and energy resources, the need to preserve the environment and prevent global climate change. That is why in the world so much attention is devoted to issues of energy saving, energy efficiency and the use of renewable energy sources (RES). Ukraine does not stand aside too; renewable energy development issue is a priority today.

The development of unconventional and renewable energy sources should be considered as an important factor in improving energy security. The large-scale use of the potential of such energy sources in Ukraine is not only a national priority, but also has significant international significance as an important factor in countering global climate change, and improves the overall state of energy security in Europe. That is why increasing the level of use of alternative (non-conventional and renewable) energy and fuel sources is one of the main areas of implementation of the state policy of energy saving in Ukraine.

According to the Energy Balance of Ukraine from 2014 to 2017, the share of energy produced from renewable energy sources in gross final energy consumption, calculated according to the rules of Directive 2009 /28 /EU, increased from 3.9 % to 6,7 %.

A significant increase in the share of «clean» energy in final energy consumption is noted in specific sectors:

- power industry – from 7.4 % to 8.6 %;
- heating, cooling systems – from 3.4 % to 7.6%;

Noteworthy is the fact that bioenergy is actively developing in Ukraine. In 2017, biofuels and wastes occupy the largest share in the energy recovery from renewable sources, 80 %. Thus, according to the Bioenergy Association of Ukraine [1], the total supply of primary energy from biofuels and wastes in 2017 amounted to 3,046 thousand tons of oil equivalent, which is equivalent to replacing about 3.8 billion m^3 of gas.

In addition, the data analysis conducted by the Bioenergy Association of Ukraine for the 2010–2017 period indicates that the average rate of bioenergy sector development in Ukraine is:

- 43 % per year according to «production of biofuels and wastes» indicator;
- 33 % per year by the indicator «Total supply of primary energy from biofuels and wastes».

Electricity production from biogas begins to develop dynamically in Ukraine. Thus, in the year the biogas capacity has increased from 34 MW – 2017 to 46 MW – 2018. (Figure 1). Particularly promising is the production of biogas from garbage. In Ukraine, about 10 million tons of waste are generated annually and there are almost 5.5 thousand dumps. Figure 2 shows the dynamics of growth of biomass capacity in Ukraine.

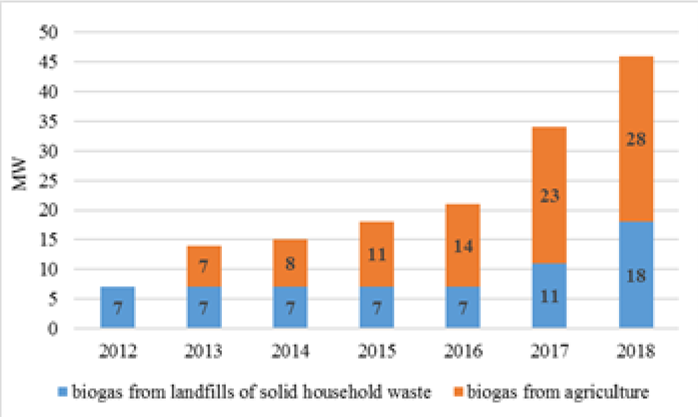

Figure 1 – Dynamics of growth of biogas capacities in Ukraine

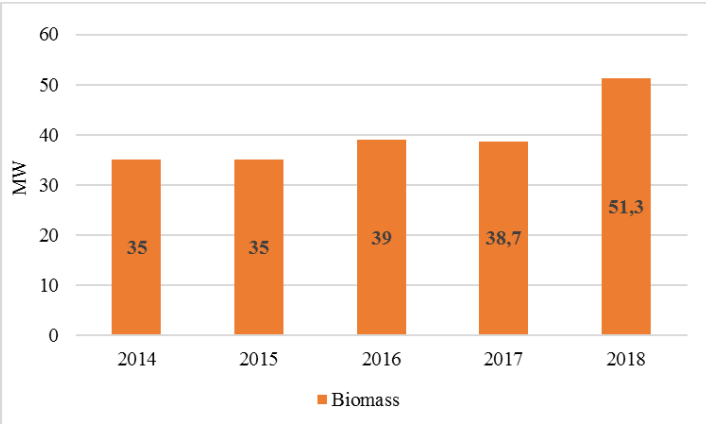

Figure 2 – Dynamics of growth of biomass capacities in Ukraine

According to the Energy Strategy of Ukraine [1–2], by 2035, Ukraine intends to reduce fossil fuels consumption and increase the share of renewable energy sources from 6.7 % (in 2017) to 25 % (in 2035) of the total primary energy supply. In Ukraine, biomass share from all renewable energy sources is 80 %, and it is expected that this share will remain the main one in future. Consequently, projects that replace fossil fuels (coal, natural gas) with biomass are popular in Ukraine now, and their number will increase in future.

Considering that combined heat and power production is a promising technology that largely solves energy saving problems and has been reflected on a legislative level in Ukraine. According to strategic goals [3–4] of the energy systems development for high-quality and safe energy supply with the predominant use of combined heat and power generation based on cogeneration technologies.

There is a need to ensure the effective functioning of unconventional and renewable energy sources and their integration with existing energy systems. The concept of an integrated power supply system is to combine elements of the energy infrastructure, in particular related to providing consumers with electricity and heat, thereby ensuring the exchange of power between previously separated systems.

The integrated power supply system provides the functions of receiving, supplying, converting and storing various types of energy. The concept of an integrated power supply system uses the concept of «energy hubs», which can be viewed as a generalization of the concept of network nodes in traditional electrical networks to a larger number of types of energy carriers, considering the possibility of their mutual transformation.

The problem of operating energy hubs is to ensure the optimal choice of the components of energy hubs and to ensure their integration into one system. Investigating the flows of various energy carriers, they perform an analysis of the interaction between sources of energy generation and end users [5–6]. In the article [7] is to solve a multi-objective model that includes reducing carbon emission and operation cost in the presence of real time demand response program (DRP).

This paper studies the optimal operation problem of an energy hub with multiple energy sources to serve stochastic electricity and heat loads in the presence of uncertain prices [8].

In order to determine the optimal levels of energy acquisition costs, the task of operational planning of the work of the various elements of the energy hub is important, which is decided on the operational time horizon. Development and implementation of approaches to optimize the functioning of such energy hubs are promising issues in the context of sustainable energy development in Ukraine, attracting new investments in non-traditional and renewable energy sources, stimulating the activity of an active consumer, ensuring regulatory quality of electricity, implementing the Smart Grid concept [9].

2. Energy hub optimal energy consumption planning

Analyzing technology development results of thermal and electric energy production from biomass, it is possible to propose a concept of an energy hub with bioenergy equipment.

2.1. A model of integrated energy supply system of agricultural enterprise functioning

Let's introduce a model of integrated energy supply system of agricultural enterprise functioning, which aim is the fullest possible use of its own energy sources. The main energy sources consumed by enterprise are electricity for equipment process operation, lighting systems, ventilation and needs of personnel, hot water for the heating system and other needs. In order to obtain these energy sources, following sources are used: electricity can be purchased from the grid, produced by wind turbines installed in an enterprise and generated on two cogeneration plants, one of which works on biogas, and the other on solid biomass. Hot water for the heating system is obtained at the cogeneration plants. Enterprise buys electricity at the market with hourly prices, it is also possible to sell generated electricity surplus at the market. A source of biogas is a biogas generator that works on stockbreeding waste. Biogas generator does not provide a possibility for significant volumes of biogas accumulation, so it is desirable to immediately burn all generated amount. Biomass is a crop residue remaining after harvest (e.g. straw) and can be stored for a long time for use in the cold season of the year.

2.1.1. Energy consumption

Electricity consumption is characterized by maximum consumption in daylight hours and low seasonality. Hot water consumption for heating correlates with the average daily temperature of the ambient air and maximum in the winter period. The purpose of agricultural enterprise energy supply system is such a mode of its functioning, when consumers needs in energy are fully met with the most effective financial indicators, that is the maximum difference between the proceeds for the sold and purchased electricity, since other energy resources are not bought by the enterprise.

2.1.2. The objective function and the limitation of the optimization model

According to the approach proposed in [10–11], we formulate the objective function and the limitation of the optimization model. The objective function will look like this

$$\sum_{k=0}^{T-1} c_{El}^{S}(k) P_{El}^{S}(k) - c_{El}^{In}(k) P_{El}^{In}(k) \to \max , \tag{1}$$

where $c_{El}^{S}(k)$, $c_{El}^{In}(k)$ – cost of electricity for the *k*-th time interval (hour), UAH / kWh;

$P_{El}^{S}(k)$, $P_{El}^{In}(k)$ – volume of sales and purchases of electricity at the *k*-th time interval (hour), kWh.

In addition to the economic criterion in determining the optimal modes of operation of the energy hub, environmental criterion can be considered. In this case, the objective function can be the minimization of CO2 emissions during the production and transportation of energy.

The objective function for the criterion for minimizing CO2 emissions will be as follows:

$$\alpha_{El} \sum_{k=0}^{T-1} \left[P_{El}^{In}(k) - P_{El}^{S}(k) \right] + \alpha_{BioGas} \sum_{k=0}^{T-1} P_{BioGas}^{CHP}(k) + \alpha_{BioMas} \sum_{k=0}^{T-1} P_{BioMas}^{CHP}(k) \to \min , \tag{2}$$

where α_{El}, α_{BioGas}, α_{BioMas} – CO2 emissions for electricity generation in centralized power supply systems, as well as emissions from gas combustion in cogeneration units, kg/kWh.

A balance of income and consumption of energy is given in a form of restrictions. Various types of energy resources transformation will be represented by the transformation metric $\boldsymbol{\Theta}$. Also, the balance equation considers the possibility of energy accumulation (in batteries and electric insulated tanks of hot water). Considering approaches proposed in [12–13], the restrictions have a form:

$$\boldsymbol{E}(k+1)=\boldsymbol{E}(k)+\boldsymbol{A}^{ch}\boldsymbol{Q}^{ch}(k)-\boldsymbol{A}^{dis}\boldsymbol{Q}^{dis}(k)-\boldsymbol{E}_L,$$

$$\boldsymbol{L}(k)=\boldsymbol{\Theta}\boldsymbol{P}^{In}(k)-\boldsymbol{Q}^{ch}(k)+\boldsymbol{Q}^{dis}(k)-\boldsymbol{P}^{S}(k),$$

$$\boldsymbol{P}(k)^{\min}\le\boldsymbol{P}^{In}(k)\le\boldsymbol{P}(k)^{\max},\quad \boldsymbol{P}(k)^{\min}\le\boldsymbol{P}^{S}(k)\le\boldsymbol{P}(k)^{\max},$$

$$0\le Q_i^{ch}(k)\le\delta_i^{ch}(k)Q_i^{\max}(k),\quad i=1,\dots,M,$$

$$0\le Q_i^{dis}(k)\le\delta_i^{dis}(k)Q_i^{\max}(k),\quad i=1,\dots,M,$$

$$\delta_i^{ch}(k)+\delta_i^{dis}(k)\le 1,\quad i=1,\dots,M,$$

$$\boldsymbol{E}(k)^{\min}\le\boldsymbol{E}(k)\le\boldsymbol{E}(k)^{\max},\quad \boldsymbol{E}_0=\boldsymbol{E}_T,$$

where $\boldsymbol{c}$ – row vector denoting energy purchasing costs for each input power flow;

$\boldsymbol{P}^{In}$ – column vector denoting input flow of energy resources;

$\boldsymbol{P}^{S}$ – column vector denoting flow of energy resources sold;

$\boldsymbol{L}$ – column vector denoting output power flow;

$\boldsymbol{\Theta}$ – converter coupling matrix, elements could be zeros, efficiencies or product of efficiencies;

$\boldsymbol{P}^{\min}$, $\boldsymbol{P}^{\max}$ – column vector denoting minimum and maximum capacity limits for power flow;

$\boldsymbol{Q}^{ch}$, $\boldsymbol{Q}^{dis}$ – column vectors denoting power exchanged with storing devices;

$\boldsymbol{A}^{ch}$, $\boldsymbol{A}^{dis}$ – diagonal matrices for the charging and discharging efficiency of each storing device;

$\boldsymbol{E}$ – vector denoting level of the energy stored in the storing device;

$\boldsymbol{E}_L$ – vector denoting energy loss per time unit in the storing device;

$\boldsymbol{E}_0$ – vector denoting the level of the energy stored in the storing devices at time k = 0;

$Q_i^{\max}$ – a storage device capacity;

δ_i^{ch}, δ_i^{dis} – binary variables for each storing device which provide condition that storage device cannot be charged and discharged at the same time.

In addition to single-criterion objective functions, we consider a multicriteria approach to determining the optimal modes of operation of an energy hub. The task will be presented in the form

$$y\to\min,\quad F_1(\boldsymbol{P})-w_1y\le F_1^*,\quad F_2(\boldsymbol{P})-w_2y\le F_2^* \tag{3}$$

where $F_1(\boldsymbol{P})$ – objective function by economic criterion:

$$F_1(\boldsymbol{P})=\sum_{k=0}^{T-1}c_{El}^{S}(k)P_{El}^{S}(k)-c_{El}^{In}(k)P_{El}^{In}(k),$$

$F_2(\boldsymbol{P})$ – objective function by environmental criterion:

$$F_2(\boldsymbol{P})=\alpha_{El}\sum_{k=0}^{T-1}\left[P_{El}^{In}(k)-P_{El}^{S}(k)\right]+\alpha_{BioGas}\sum_{k=0}^{T-1}P_{BioGas}^{CHP}(k)+\alpha_{BioMas}\sum_{k=0}^{T-1}P_{BioMas}^{CHP}(k),$$

w_1, w_2 – weighting factors expressing a measure of relative trade-offs between goals,

F_1^*, F_2^* – the value to which we strive to approximate the result of the objective functions.

2.1.3. Installations and output flows of the energy hub

Consider the energy hub shown in Figure 3. It consists of three converters, four streams of energy and storage devices. Converters: transformers 10/0,4 kV, electrical heating system and wind power plant. Energy flows: biogas, biomass, wind's energy, electric energy. Each of the three plants is characterized by its efficiency (efficiency of converting one form of energy to another).

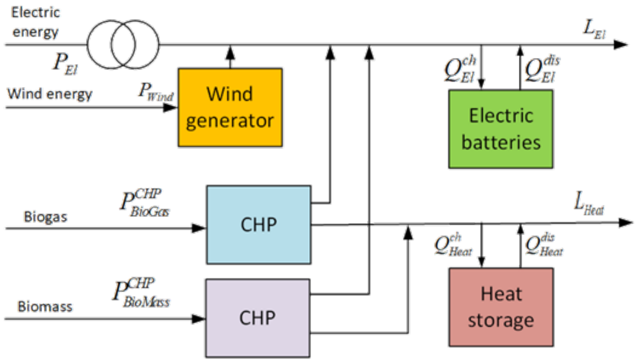

Figure 3 – Functional diagram of power hub for agricultural enterprise

Let's analyze possible sources of energy in an energy hub, as well as consumers of energy. Electricity can flow from the grid through lowering transformers 10/0,4 kV and be generated by a wind generator and cogeneration unit. Heat for a heating system may be generated from biogas and biomass. For the purposes of heat supply, energy is generated by an electrical heating system. Energy storage can occur in electric batteries. Hot water can accumulate in heat insulated tanks.

Matrix $\boldsymbol{P}$, $\boldsymbol{L}$, $\boldsymbol{\Theta}$, $\boldsymbol{Q}^{ch}$, $\boldsymbol{Q}^{dis}$, $\boldsymbol{A}^{ch}$, $\boldsymbol{A}^{dis}$ for the selected object, such as an agricultural company was developed. Using the above considerations, we got:

$$\boldsymbol{P}^{In} = \begin{bmatrix} P_{El}^{In} \\ P_{Wind} \\ P_{BioGas}^{CHP} \\ P_{BioMas}^{CHP} \end{bmatrix}, \quad \boldsymbol{P}^{S} = \begin{bmatrix} P_{El}^{S} \\ 0 \\ 0 \\ 0 \end{bmatrix}, \quad \boldsymbol{L} = \begin{bmatrix} L_{El} \\ L_{Heat} \end{bmatrix}. \tag{4}$$

Electricity is an input for transformer and electric heater P_{El}. Wind energy is an input for a windmill P_{Wind}. The biogas is an input for the cogeneration system (i.e. biogas turbine) P_{BioGas}^{CHP} and biomass is an input for cogeneration system P_{BioMas}^{CHP}. Energy consumers at the output of energy hub are domestic electricity consumers L_{El} and heating system L_{Heat}.

Installations and output flows of the energy hub are shown in Figure 1.

The transformer characterized by it's electric efficiency ϖ_{PowSys}. A wind generator transforms the wind energy into electricity with energy conversion factor ϖ_{Wind}. A cogeneration system transforms the biogas into electricity, heat for heating systems; it is characterized by biogas-electric and biogas-heating systems energy conversion factor $\varpi_{CHP.El}^{BioGas}$ and $\varpi_{CHP.Heat}^{BioGas}$ respectively. A cogeneration system transforms the biomass into electricity, heat for heating systems; it is characterized by biogas-electric and biogas-heating systems energy conversion factors $\varpi_{CHP.El}^{BioMas}$ and $\varpi_{CHP.Heat}^{BioMas}$ respectively.

Converter coupling matrix, energy conversion factors or product of efficiencies:

$$\boldsymbol{\Theta} = \begin{bmatrix} \varpi_{PowSys} & \varpi_{Wind} & \varpi_{CHP.El}^{BioGas} & \varpi_{CHP.El}^{BioMas} \\ 0 & 0 & \varpi_{CHP.Heat}^{BioGas} & \varpi_{CHP.Heat}^{BioMas} \end{bmatrix}. \tag{5}$$

The coefficients included in the transformation matrix of energy resources characterize individual power plants processes and are determined by the following formulas

$$\varpi_{CHP.El}^{BioGas} = q_{f}^{BioGas} \eta_{Gen} \eta_{El}^{BioGas} k_{T} k_{Load},$$

$$\varpi^{BioGas}_{CHP.Heat} = q^{BioGas}_{f} \eta_{Gen} \eta^{BioGas}_{El} k_T k_{Load} k_{Heat/EL},$$
$$\varpi^{BioMas}_{CHP.El} = q^{BioMas}_{f} \eta_{Gen} \eta^{BioMas}_{El} k_T k_{Load},$$
$$\varpi^{BioMas}_{CHP.Heat} = q^{BioMas}_{f} \eta_{Gen} \eta^{BioMas}_{El} k_T k_{Load} k_{Heat/EL}, \quad (6)$$
$$\varpi_{Wind} = \eta_{Gen} \eta_{Mech} \eta_{Conv} \xi,$$
$$\varpi_{PowSys} = \eta_{DistTr},$$

where q^{BioGas}_{f} – the value of a specific heat released during the complete combustion of biogas, J/m^3, which depends on the sources (basins / deposits) of its extraction, the numerical values of the heat of combustion of fuel can be obtained from the International Energy Agency (*IEA*);

η_{Gen} – the conversion efficiency of the generator (synchronous or asynchronous), it is acceptable to take close to the value of 0.87–0.9;

η^{BioGas}_{El} – the electricity conversion efficiency at full biogas burning;

k_T – the electricity efficiency at full biogas burning;

k_{Load} – the coefficient, which shows the dependence of cogeneration unit efficiency on the level of loading – more loaded cogeneration unit, higher efficiency value of the cogeneration unit;

$k_{Heat/EL}$ – the ratio of the generated thermal energy to the electric cogeneration unit;

q^{BioMas}_{f} – the value of the specific heat released during the complete combustion of biomass, J/kg, which depends on the sources (pools / deposits) of its extraction, the numerical values of the heat of combustion of fuel can be obtained from the International Energy Agency (*IEA*);

η^{BioMas}_{El} – the electricity conversion efficiency, with complete combustion of biomass;

η_{Mech} – the mechanical conversion efficiency (enhancement gearbox) is at the level of 0.93–0.95;

η_{Conv} – the conversion efficiency of the converter unit, which includes the presence of a rectifier and / or inverter, can be taken as equal to 0.81-0.93;

ξ – the coefficient of wind energy used in calculating the power developed by the wind wheel, we accept 0.3-0.35;

η_{DistTr} – the 10/0.4 kV transformer conversion factor.

Energy storage can occur in electric batteries Q^{ch}_{El}. Heat can accumulate in heat insulated tanks Q^{ch}_{Heat}. Accordingly, can be used as the accumulated electricity Q^{dis}_{El}, as well as accumulated hot water for water supply system Q^{dis}_{Heat}.

$$\boldsymbol{Q}^{ch} = \begin{bmatrix} Q^{ch}_{El} \\ Q^{ch}_{Heat} \end{bmatrix}, \quad \boldsymbol{Q}^{dis} = \begin{bmatrix} Q^{dis}_{El} \\ Q^{dis}_{Heat} \end{bmatrix}.$$

We also introduce a diagonal matrix $\boldsymbol{A}^{ch}$ for the charging efficiency of each storing device and a diagonal matrix $\boldsymbol{A}^{dis}$ for the discharging efficiencies:

$$\boldsymbol{A}^{ch} = \begin{bmatrix} \eta^{ch}_{El} & 0 \\ 0 & \eta^{ch}_{Heat} \end{bmatrix}, \quad \boldsymbol{A}^{dis} = \begin{bmatrix} \dfrac{1}{\eta^{ch}_{El}} & 0 \\ 0 & \dfrac{1}{\eta^{ch}_{Heat}} \end{bmatrix}.$$

The values included in the matrix of energy input flows represent the consumption of energy resources for one sampling time interval (usually one hour) and have the following dimensions: P_{El}^{In}, P_{Wind} – kWh, P_{BioGas}^{CHP} – m3, P_{BioMas}^{CHP} – kg.

In addition, we introduce restrictions on the daily consumption of biogas in the form of equality of generation and combustion, and set the maximum daily volume of solid biomass burning. The corresponding restrictions will come in this form

$$\sum_{k=0}^{T-1} P_{BioGas}(k) = P_{BioGas.Tot}, \quad \sum_{k=0}^{T-1} P_{BioMas}(k) < P_{BioMas.Tot}. \tag{7}$$

3. Simulation results analysis

Let's perform a numerical simulation of the considered power hub to evaluate the peculiarities of the results and model adequacy. The simulation will be performed for a duration of 24 hours with a sampling of 1 hour. Thus, the number of intervals is T = 24. Such a scenario can be considered typical, since during the operation of the power hub, statistics can be accumulated on the peculiarities of the daily schedules of the enterprise consumers load and it is quite possible to predict the next day energy demand. Forecasting of electric energy market prices can also be performed by one of the known methods [14–18].

For simulation purposes, used data on electricity market prices for one day, which are presented in Figure 4. Typical enterprise charts of electricity consumption and the power of heating system are shown in Figure 5.

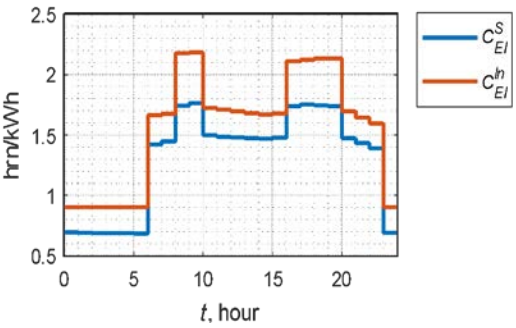

Figure 4 – Electricity market prices

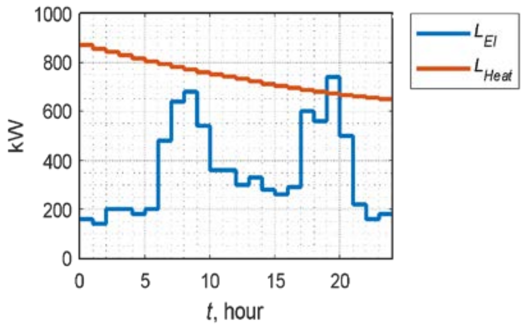

Figure 5 – Electric and heat power demand

The values of the energy conversion factors given in Table 1.

Table 1 – Values of transformation coefficients

	PowSys	Wind	CHP^{BioGas}	CHP^{BioMas}
Electric Power	0.95	0.26775	7.7328	5.13
Heat	0	0	11.5992	7.695

The maximum power values of the energy hub installations, which were user to run the simulation, is given in Table 2.

Table 2 – Maximum input power of the energy hub elements

Distribution transformer, kVA	Wind farm, kW	Biogas CHP, m^3/hour	Biomass CHP, kg/hour
2500	1000	300	3000

The capacity of electric storage batteries is assumed to be 500 kWh, and the amount of heat energy that can be stored in a heat-insulated tank is 5000 kWh.

For the case of using the environmental criterion, emissions from electricity generation can be calculated considering the national significance of the CO2 emission factor for electricity according to [19] developed in 2013–2014 by the Joint Energy and Transport Research Center (European Commission), which for Ukraine is 0.924 kg/kWh. For the case of gas combustion in cogeneration plants, the average value for this type of equipment was taken.

In order to take into account, the volumes of electricity generated by the wind turbine, one must take into account the daily volatility of the wind. It is not possible to predict the direction of wind speed on an hourly basis;

therefore, it is proposed to perform simulation modeling of wind power plants based on statistical data measured for this object.

Simulation of the optimization problem was performed using MATLAB's Optimization Toolbox package. The results using only economic criterion are shown in Figures 6–12.

On Figure 8 positive values of P_{El} correspond to the purchase of electricity in the market (P_{El}^{In}) negative – the sale of electricity (P_{El}^{S}).

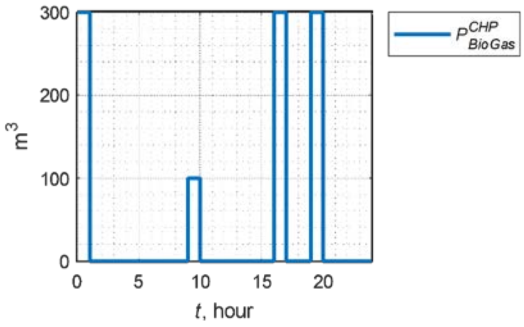

Figure 7 – Biogas CHP productivity

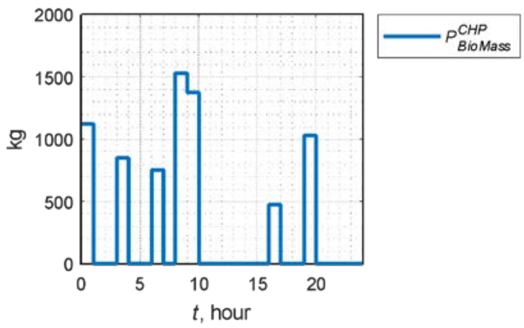

Figure 8 – Biomass CHP productivity

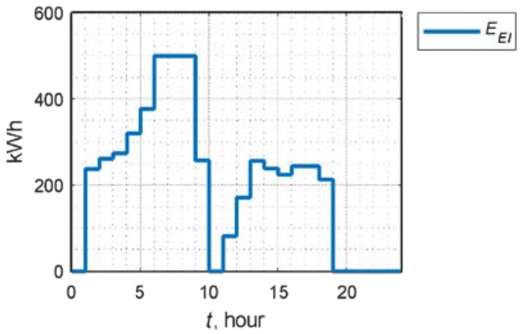

Figure 9 – Energy stored in electric accumulator

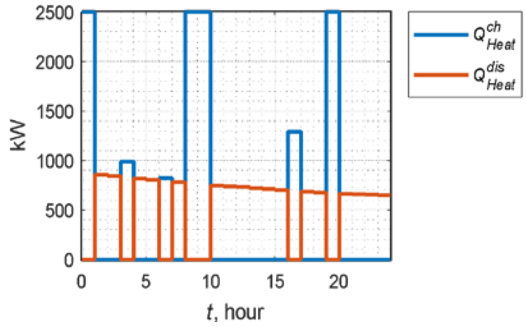

Figure 11 – Power exchange with heat storage

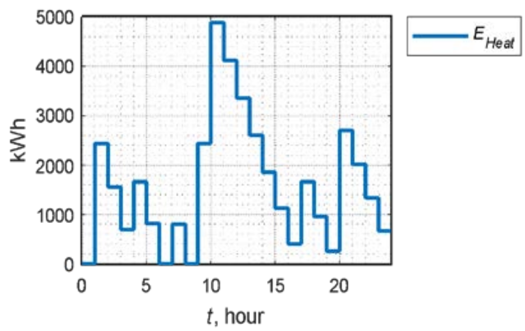

Figure 10 – Energy stored in heat storage

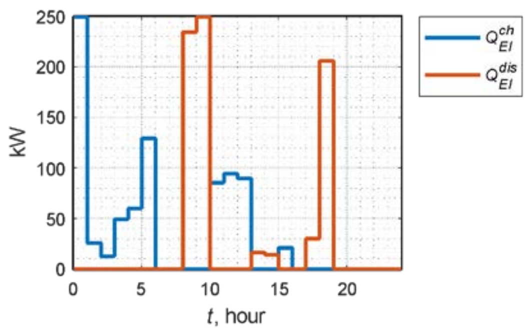

Figure 12 – Power exchange with electric accumulator

As can be seen from the graphs, the surplus of generated electricity was observed during the day. This is due to the need to provide a fairly significant constant demand for heat, which is covered by the work of cogeneration units. Combustion of biogas was not enough to produce the required amount of thermal energy; therefore, a biogas cogeneration plant should operate almost all the time, and biogas installation is included only in certain hours.

The graphs show that the presence of electricity and thermal energy storages has enabled better use of available energy resources and facilities. Figure 10 and 13 indicate intense accumulation of energy in batteries in hours of minimum power system, when the market price is minimal. At the same time, in the hours of maximum loads, the accumulated electricity is sold at the most favorable price. Also, in these hours, we observe peak performance of energy that contributes the most advantageous electricity sales. The received heat excess is accumulated in a thermal accumulator.

The results using only ecological criterion are shown in Figures 13–16. It can be seen that in this scenario, the volume of exchange of electricity with the power grid has significantly decreased. Electricity on the market is sold significantly less, which leads to a decrease in the total profit of the energy hub, which is expected because the economic criterion is not considered. It can also be seen that the loading of the cogeneration unit on biomass has become more uniform, and the heat accumulators are used significantly less. Electric batteries for the use of ecology criterion are also practically not used.

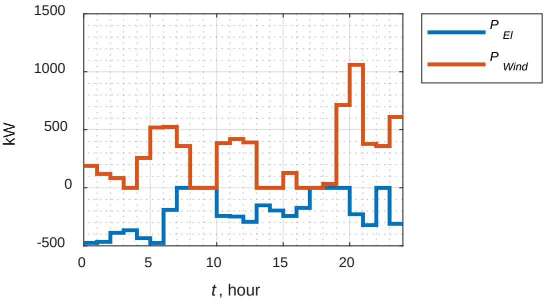

Figure 13 – Electric power exchange with power system and generated on the wind generator using only ecological criterion

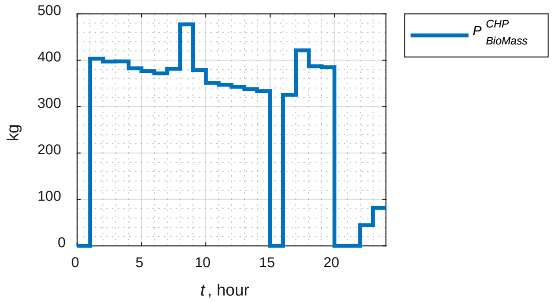

Figure 15 – Biomass CHP productivity using only ecological criterion

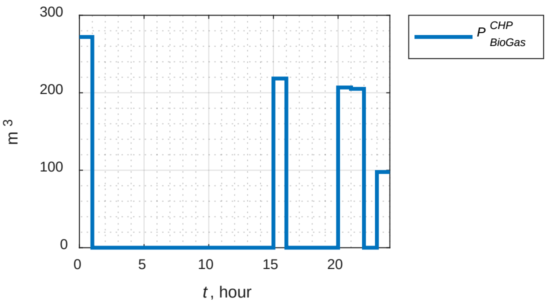

Figure 14 – Biogas CHP productivity using only ecological criterion

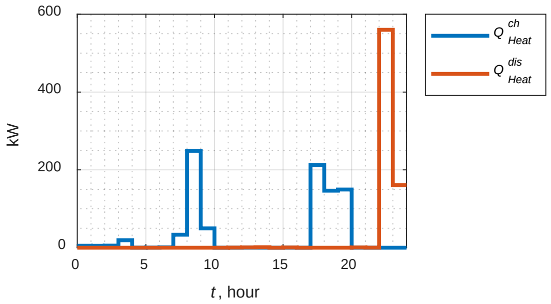

Figure 16 – Power exchange with heat storage using only ecological criterion

The results using multicriteria approach are shown in Figures 17–20.

The value of the objective functions obtained for the various study cases are presented in Table 3. As can be seen from Table 3, when using the economic criterion, CO2 emissions are significantly higher than the minimum achievable value. Similarly, for an ecology criterion, energy hub profit is 30 % less than the optimal one. At the same time, sharing the two criteria allows for an effective compromise, in which profit are only 8 % less than optimal, with CO2 emissions close to the minimum.

An interesting scenario of using the proposed model is the selection of optimal parameters of the power hubs elements. For example, the actual task is to select the capacity of storage batteries [20] for the electricity accumulation.

With the growth of this capacity, increases the power supply system's opportunities to redistribute the amount of electricity consumed and sold during the day and accordingly, the economic effect of its purchase and sale prices.

Table 3 – Values of the objective functions for different criteria

	Economic criterion	Ecology criterion	Multicriteria approach
Energy hub profit, UAH/day	10550	7294	9678
CO2 emissions, kg/day	11703	8331	8407

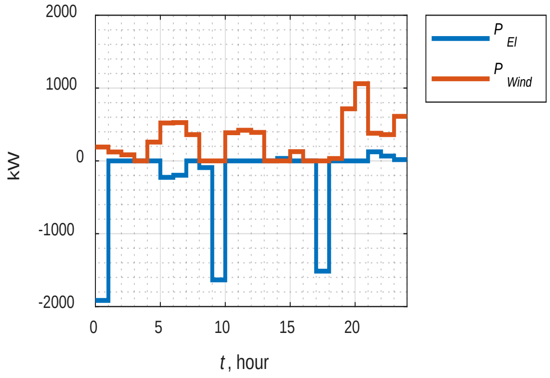

Figure 17 – Electric power exchange with power system and generated on the wind generator using multicriteria approach

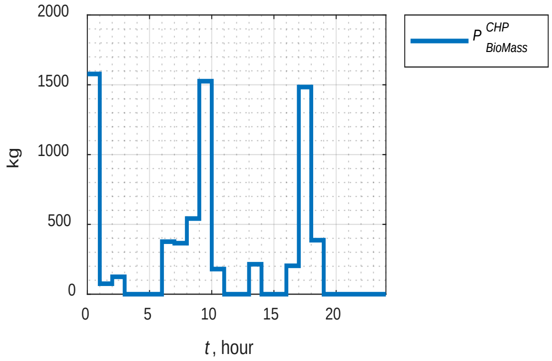

Figure 19 – Biomass CHP productivity using multicriteria approach

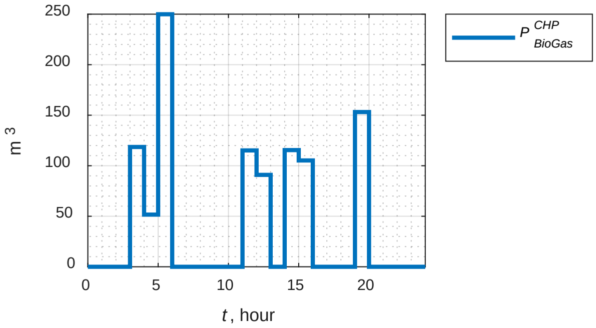

Figure 18 – Biogas CHP productivity using multicriteria approach

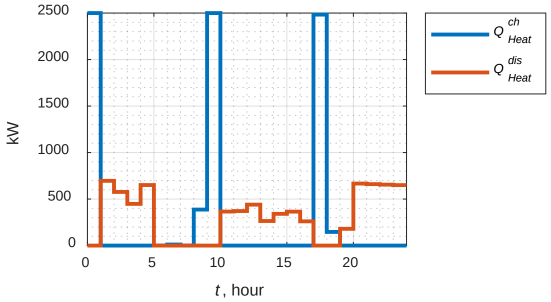

Figure 20 – Power exchange with heat storage using multicriteria approach

Using the proposed model, it is possible to estimate the influence of the energy hubs elements parameters on the value of the target optimization function, which in fact is the profit of the enterprise. For this purpose, a multiple simulation of the operation mode of the considered power hub was performed at the values changes of the electric battery capacity. The results are shown in Figure 21.

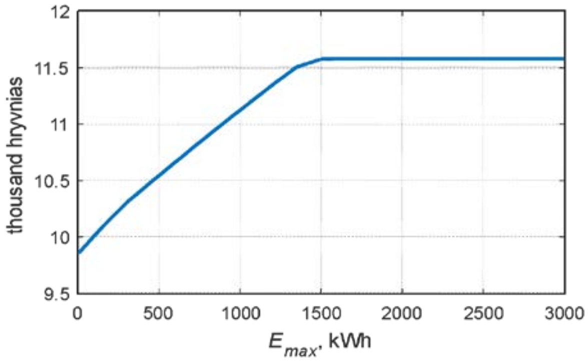

Figure 21 – Mode of the energy hub operation while changing the values of the electric battery capacity

It can be seen that with an increase of the battery capacity to 1500 kWh, the profit from electricity sales increases from 9.8 thousand UAH to 11.6 thousand UAH. However, with a further increase of the battery capacity, the profit remains unchanged. It can be concluded that with the energy consumption values and the parameters of the energy hub, which were used in the simulation, the most expedient batteries capacity is just 1500 kWh.

The designed energy hub system with the use of renewable energy sources (wind, biomass) in the modern conditions, enables effective use of the bioenergy potential of agricultural enterprises in Ukraine.

4. Conclusions

The energy sector of the country depends on the degree of energy resources diversification used to meet its energy needs. The development of bioenergy is an important part of ensuring the energy security of many countries, as it enables to reduce fossil fuel consumption, dependence on imported energy sources and ensure sustainable local energy supply. At the same time, the restructuring of power generation on the basis of decentralized power generating capacities of renewable energy sources into energy hubs enables the efficient use of energy resources.

Usage of a cogeneration plant in the structure of the energy hub gives the opportunity to provide energy resources and the possibility of generated electricity trading. A multicriteria approach to the planning and optimization of the operation of such energy hub is proposed. According to the simulation results using the example of an energy hub, it is shown that this method is suitable for planning hourly energy consumption with a compromise in terms of the minimum cost of these energy resources and CO2 emissions.

References

1. Bioenergy Association of Ukraine. URL: http://uabio.org.
2. State Agency on Energy Efficiency and Energy Saving of Ukraine. URL: http://saee.gov.ua.
3. Geleznaia T., Oleinic E., Geletuha A. Prospects for the production of electricity from biomass in Ukraine. Industrial Heat. 2013. Vol. 35 (6). Pp .67–75.
4. Haghifam M.-R., Pazouki S., Pazouki S. Renewables and Plug in Electric Vehicles modeling on electricity and gas infrastructures scheduling, 3rd International Conference on Electric Power and Energy Conversion Systems, 2–4 October 2013.
5. Veremiichuk Y., Prytyskach I., Yarmoliuk O., Mahnitko A., Varfolomejeva R. Analysis of the results of optimal energy consumption planning for residential complex energy hub. IEEE 58th International Scientific Conference on Power and Electrical Engineering of Riga Technical University, 12–13 October 2017.
6. Voropai N.I., Stennikov V.A., Barakhtenko E.A. Methodological principles of constructing the integrated energy supply systems and their technological architecture. Journal of Physics: Conf. Series. 2018. Vol. 1111.
7. Saberi K., Pashaei-Didani H., Nourollahi R., Zare K., Nojavan S. Optimal performance of CCHP based microgrid considering environmental issue in the presence of real time demand response. Sustainable Cities and Society. 2018.
8. Moazeni S., Miragha A.H., Defourny B. A risk-averse stochastic dynamic programming approach to energy hub optimal dispatch. IEEE Transactions on Power Systems. 2018.
9. Moghaddam I.G., Saniei M., Mashhour E. A multi-slack Optimization Model for Scheduling Energy Hubs in Smart Grids. Journal of Power Technologies. 2018. Vol. 98 (3). Pp. 287-295.
10. Parisio A., Vecchio C., Vaccaro A. A robust optimization approach to energy hub management. Electrical Power and Energy Systems. 2012. Vol. 42. Pp. 98–104.
11. Bozchalui M. Optimal operation of residential energy hubs in smart grids. IEEE Trans. Smart Grid. 2012. Vol. 3. Pp. 1755–1766.
12. Rastegar M., Fotuhi-Firuzabada M., Lehtonen M. Home load management in a residential energy hub. Electric Power Systems Research. 2015. Vol. 119. Pp. 322–328.
13. Strelkov M. Static model of electricity market system composition. Power engineering: economics, technique, ecology. 2015. Vol. 3. Pp. 117–123.
14. Mahnitko A., Berzina K., Zamulko A., Veremiichuk Y., Nakhodov V. Research of Electrical Power Consumers Reaction in Power Consumption Management System. The 9th International Scientific Symposium Elektroenergetika, 12–14 September 2017.
15. Salvatore J. World Energy Perspective. Cost of Energy Technologies Bloomberg New Energy Finance. London: World Energy Council, 2013. 48 p.
16. Cost and performance data for power generation technologies. Black & Veatch Holding Company, prepared for National Renewable Energy Laboratory, 2012. 105 p.
17. Kostiuk V. The modified technique for levelized energy cost computing to provide deterministic and stochastic modeling of new generating facilities. Power engineering: economics, technique, ecology. 2015. Vol. 2. Pp. 64–77.
18. Veremiichuk Y., Prytyskach I., Yarmoliuk O., Opryshko V., Mahnitko A., Gerhards J., Berzina K. Energy hub functioning model considering perspectives for development of bioenergy in Ukraine. IEEE 18th International Conference on Environment and Electrical Engineering and 2nd Industrial and Commercial Power Systems Europe. Italy, Palermo, 12–15 June 2018. Pp. 1–6.

19. Gabrielaitiene I., Melica G., Bertoldi P. How to develop the "Action Plan for Sustainable Energy Development (SEAP) in the cities of the Eastern Partnership and Central Asia JRS sciece and policy report JRC 90401. Luxembourg: Publications Office of the European Union, 2014.

20. Chaudhari K., Kandasamy N., Kanamarlapudi R., Gooi H. Abhisek Ukil Modeling of charging profiles for stationary battery systems using curve fitting approach. Industrial Electronics Society, 43rd Annual Conference of the IEEE. 29 October–1 November 2017.

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МОДЕЛЬ ФУНКЦІОНУВАННЯ ІНТЕГРОВАНОЇ СИСТЕМИ ЕНЕРГОПОСТАЧАННЯ З ВИКОРИСТАННЯМ БЛОКІВ КОГЕНЕРАЦІЇ ТА ВРАХУВАННЯМ ПЕРСПЕКТИВ РОЗВИТКУ БІОЕНЕРГЕТИКИ В УКРАЇНІ

Актуальним на сьогодні є розвиток біоенергетики у структурі системи енергопостачання за умов розвитку відновлюваних джерел енергії та впровадження сучасних технологій в енергетиці. Розвиток біоенергетики є важливою складовою енергетичної безпеки багатьох країн, оскільки дає змогу зменшити споживання викопного палива та залежність від імпортних джерел енергії, забезпечити постійне енергопостачання у безпосередній близькості до споживачів. У роботі представлено модель функціонування інтегрованої системи енергопостачання (energy hub) з залученням когенераційних установок при врахуванні перспектив розвитку біоенергетики в Україні. Основним завданням було у повній мірі використати власні джерела енергії energy hub для задоволення потреб споживачів в енергоносіях з найефективнішими фінансовими показниками. Наявність засобів акумулювання електричної та теплової енергій дасть можливість більш ефективно використовувати наявні енергоресурси й обладнання (технології). Використання когенераційної установки в структурі energy hub дає змогу забезпечити енергоресурсами споживачів та можливість продажу надлишку електроенергії у мережу. У роботі запропоновано багатокритеріальний підхід для планування й оптимізації роботи energy hub. Запропонована система energy hub з використанням відновлюваних джерел енергії (вітер, біомаса) у сучасних умовах дасть можливість ефективно використовувати біоенергетичний потенціал сільськогосподарських підприємств в Україні. Відповідно до результатів моделювання на прикладі energy hub, показано, що цей спосіб підходить для прогнозування погодинного споживання енергії з точки зору мінімальної вартості енергоресурсів та викидів CO_2. Цікавим сценарієм використання запропонованої моделі energy hub є підбір оптимальних параметрів елементів живлення.

Ключові слова: інтегровані розподільні енергосистеми, розподільна генерація, активний споживач, технологія когенерації, energy hub, мікромережа на основі когенерації, біомаса, біогаз.

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