An Improved Approach to Evaluation of the Efficiency of Energy Saving Measures Based on the Indicator of Products Total Energy Intensity

Olena Maliarenko (ID)**, Vitalii Horskyi** (ID)**, Valentyna Stanytsina** (ID)**,
Olga Bogoslavska** (ID)**, and Heorhii Kuts** (ID)

Abstract Existing methodological approaches to determining the total energy intensity of products and its components are presented. The methodological approach to determining the direct (technological) energy intensity of products on the example of combined production of energy at Combined Heat and Power (CHP) plants with the allocation of energy costs for certain stages of the technological process is improved: preparation of fuel, its submission to burners, burning in a boiler plant and the implementation of natural resources. This detailing of energy costs makes it possible to compare options for upgrading power equipment across all power plant workshops. Two types of CHP plant are considered: coal and gas, appropriate equipment structure, technologies that can be implemented to replace existing, less efficient ones. Three variants of possible modernization of the CHP plant on coal fuel and two—on natural gas are presented. The technological potential of energy saving in the case of implementation of the modern technologies for the production of energy at the coal CHP plant as more environmentally hazardous has been calculated, provided that the environmental requirements and the implementation of environmental measures are achieved. Effective technologies for reducing emissions of nitrogen oxides, sulfur oxides and particulates have been considered as environmental measures.

Keywords Energy · District heating · Energy supply · Energy efficiency · Direct energy intensity · Through technological energy intensity

1 Introduction

Combined generation of electricity and heat is a major trend in modern development of energy supply systems in the world. The share of electricity production at the CHP plants in Ukraine coincides with the share of district heating production in the G8 + 5 countries and is 11–19% [1]. In the EU countries, the heat utilization rate of the CHP plants reaches 75%, compared to 55% in Ukraine. The development of the latest

O. Maliarenko · V. Horskyi · V. Stanytsina (✉) · O. Bogoslavska · H. Kuts
Institute of General Energy of NAS of Ukraine, Kyiv, Ukraine
e-mail: st_v_v@hotmail.com

201

technologies indicates the widespread implementation of innovative solutions at the CHP plant with using renewable energy sources, including heat pumps, biomass, solid waste incineration, electric boilers that use excess electricity from wind farms and solar power station (SPS) with centralized heat storage.

The potential for the development of CHP plants in Ukraine is determined by the extensive infrastructure of the district heating system, powerful heating boilers, and backbone and distribution heat networks. Heating boilers with a thermal capacity exceeding 20 Gcal (23.26 MW) make up 2% of the total installed capacity of all heating boilers in Ukraine and produce about 60% of the total heat production. This is the potential for the introduction of combined electricity generation technology in cogeneration units.

In Ukraine, the combined production of heat and electricity at CHP plants, is carried out at 34 city utility power plants, with an installed power of 2856.23 MW and a heat capacity of 13466 Gcal/h, and at 87 thermal power plants of enterprises with an installed power of 2705 MW and a thermal capacity of 17897 Gcal/h [2], among which the largest installed capacity is the Kiev CHP-6 (750 MW), CHP-5 (700 MW) and Kharkiv CHP-5 (540 MW). In 2017, 6371 million kWh of electricity and 11571 thousand Gcal of thermal energy were produced at the city CHP plants. In 2017, the industrial CHP plants produced 4224 million kWh of electricity and 17522 thousand Gcal of thermal energy [2].

The structure of used fuel, according to the statistical report for 2017, is presented in Fig. 1 [3].

As can be seen from Fig. 1, natural gas (51.1%) occupies the largest share in the CHP plants, while coal (39%) occupy the second place.

Accordingly, CHPs that burn natural gas are large (500–2550 tonnes steam per hour), medium (200–420 tonnes steam per hour) and low capacity (less than 200
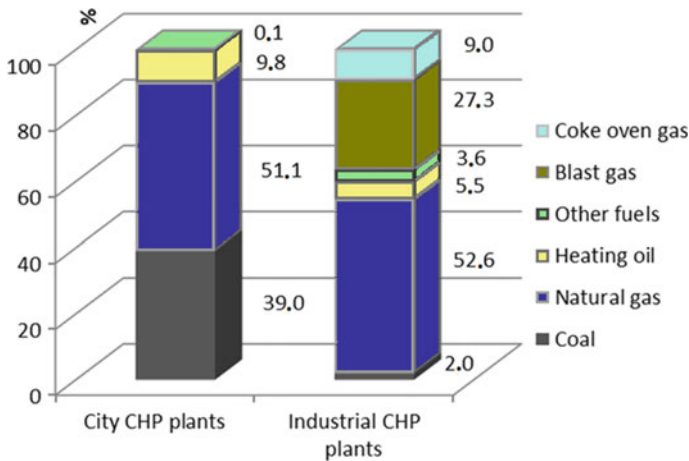

Fig. 1 Structure of fuel use for conversion to thermal and electric energy at different CHP plants in 2017 [3]

tonnes steam per hour). Coal CHP plants—medium and low capacity. The last are few: Sumy CHP plant (40 MW, 350 Gcal/h), Darnytsia CHP plant (180 MW, 1080 Gcal/h), Chernihiv CHP plant (210 MW, 500 Gcal/h), Kalush CHP plant (210 MW, 500 Gcal/h). All CHP plants have steam turbine technologies. Types of boiler installations are different in design (with U-, T-shaped and tower layout and combustion chamber), different types of burner devices are used [4, 5].

The share of natural gas in the structure of fuel use at industrial CHP plants (Fig. 1) is almost the same as for city CHPs (52.6%), but blast furnace gas (27.3%) occupies second place. Due to the greater variety of fuel used, boilers of industrial CHP plants differ in their burners and accessories.

Increase the energy efficiency of the main and auxiliary equipment of a CHP plant is an important task, since the National Emission Reduction Plan for large combustion plants includes the following CHP plants: Darnytsa, Dneprodzerzhinsk, Kramatorsk, Kremenchuk, Lviv, Mykolaiv, Odesa, Ohtyrka, Severodonetsk, Sumy, Kharkiv, Kherson, Cherkasy, Chernihiv, Shostka, Mariupol (2 CHP plants), Simferopol, Saky, Kamysh-Burun and industrial CPHs: Lisichans oil refinery, Alchevsk metallurgical plant (MP), Makiivka MP, Avdiivka coke and chemicals plant, Ilyich Iron and Steel Works of Mariupol, Sumy Machine-Building Science-and-Production Association, Pervomaysk "Energohimproekt", three CHP plants Kryvorizhstal, CHP plant Zaporizhstal, CHP plant DniproAzot, CHP plant PivdenMashbudzavod, CHP plant Azovstal. Reducing fuel use is the main direction for reducing greenhouse gas emissions [6].

The most commonly used energy efficiency indicators that can be used to evaluate the operation of a CHP plant are the utilization heat fuel factor, the energy conversion efficiency of the equipment by type of energy, unit energy recourses consumption by type, energy intensity of products (heat and electricity) and energy loss (fuel and energy carrier) [7]. Efficiency is usually defined for separate equipment (steam generator, turbine) or power plant as a whole as a result of multiplying of the efficiency of power installation along the technological system [8]. In determining most of these indicators, except utilization heat fuel factor, it is necessary to divide the total energy of the fuel to two energy products with different quality.

An important indicator of energy efficiency, that characterizes the complete technological cycle of production, is the total energy intensity of products [9], which allows to calculate the energy efficiency of replacement, modernization, reconstruction of technological equipment with detail, which is absent in the calculation of other indicators of energy efficiency.

2 Literature Review and Problem Statement

Various aspects of ensuring the efficient functioning of energy and its environmental impact are discussed in many papers [10–19]. Problems of efficient functioning and development of combined production of heat and electricity were addressed by famous scientists Sokolov Ye.Ya., Yakovlev B.V., Dolinsky A.O., Basok B.I.,

Klimenko V.N., Arkelyan E.K., Kozhevnikov N.N., Zaitsev Ye.D., Dubovsky S.V. and others [1, 20–29].

Existing methods for the distribution of energy consumption in multi-product industries have been described in many literary sources [1, 24, 25, 30], but the fuel distribution for CHP is considered only for the fuel burned in the boiler plant, without taking into account the energy costs for its storage, preparation, distribution. etc.

DSTU 3682–98 (GOST 30583–98) was introduced in Ukraine [9], which approved the indicator of total energy intensity of products. The Russian standards [31–33] introduce two indicators of energy intensity: total energy intensity of production and energy intensity of production. According to these standards, the energy intensity of production is the amount of energy and fuel consumption for the main and auxiliary technological processes of production based on a given technological scheme. When manufacturing any kind of products for each technological process that is part of the production schemes, its energy intensity is determined. Energy intensity in production of products is the integration of costs at a certain level of management. When calculating indicators of energy intensity in production, only fuel and energy resources (FER) for main and auxiliary production processes are taken into account. Expenditures on fuel and energy resources for heating, illumination, various auxiliary needs are not to be included in the amount of consumption of energy resources, which are included in the energy intensity of production. The Russian standard [33] classifies energy efficiency indicators by groups of homogeneous products (electric motors, turbines, refrigerators, etc.), type of energy resources or energy carriers used (energy efficiency indicators of fuel use (boiler, motor), electricity, thermal energy (steam, hot water, refrigerants), compressed air, oxygen, and other methods of indicators determination.

Full energy intensity determines the final energy saving, depends on the improvement of all components of the technological chain of production, development of new technologies, changes in the structure of production processes, reduction of material capacity and energy losses, increased use of secondary material resources, etc.

According to the standard of full energy intensity of products [9], it is defined as full energy consumption throughout the entire production chain: production of raw materials, transportation costs to the enterprise and for intra–plant transport, energy consumption for the main technological processes in which, in addition to direct costs of energy resources, energy resources produced in auxiliary shops are used (compressed air, oxygen, nitrogen, argon, circulating water supply for technological needs, steam and electricity production in industrial CHP plants, boiler houses and utilization plants), energy consumption, which is fixed in fixed production assets (equipment, appliances, premises, etc.), energy consumption of recreated workforce and on elimination of harmful influence on environment of production wastes.

In accordance with [9], the total energy intensity of products is calculated by the formula

$$e = e_e + e_{sm} + e_f + e_r + e_{env} \tag{1}$$

where e_e—full energy intensity of energy resources that directly are consumed for the production of products (services); e_{sm}—full energy intensity of original products, raw materials and materials required for the production of products (works, services); e_f—full energy intensity of fixed production assets amortized in the production of products (services); e_r—full energy intensity of recreated workforce in the production of products (services); e_{env}—full energy intensity of costs used for environmental protection in the production of products (services).

According to [9], direct energy intensity of products (full energy intensity of energy resources, through technological energy intensity) is defined in general terms as follows:

$$e_p = \sum_s e_s (b_{ps} + \sum_i a'_{pi} b'_{\text{pis}}), \tag{2}$$

where s is the index of the type of energy resources; e_s—full energy intensity of s-th type of energy resources; b_{ps}—specific consumption of s-th type of energy resources in the main production, i—index of the type of auxiliary production; a'_{pi}—specific consumption of i-th type of auxiliary production; b'_{pis}—specific consumption of s-th type of energy resources for the production of i-th type of auxiliary production.

Full energy intensity of energy resources is defined as follows:

$$e_s = e_p + e_{tr} - e_g + e_{imp} \tag{3}$$

where e_p—full energy intensity of energy resources directly consumed in the manufacture of products (services)—direct energy intensity; e_{tr}—full energy intensity of energy resources used to transport the original products, raw materials and supplies; e_g—reduction of full energy intensity of products (services) through the use of secondary energy resources formed in the manufacture of combustible; e_{imp}—increase in full energy intensity due to the import of energy resources.

In fact, it is not known how e_s is defined in standard [9] since the algorithm for calculating the components of formulas (2–3) is not provided. For an example of calculating with formula (2), the energy intensity of energy carriers (electric and thermal energy as products) at CHP plant, b_{ps} is specific fuel consumption for the output of heat and electric energy separately. The second component (2) is electric power consumption for water feeding into steam generator and air feeding into furnace. As a rule, these specific costs are not calculated but taken as averages across the country from the statistical reporting forms. Type of fuel preparation, determined by the type of mill used for grinding solid fuel, type of fuel feeding system for solid fuel, liquid fuel heating, expenses for gas distribution networks as components of energy costs in the basic technological process of electricity and heat production in the formula are absent. If changes occur in these processes when replacing this equipment, then the reduction in unit costs cannot be calculated.

When calculating direct energy intensity of products (energy carriers) according to [9] it is not clear how to compare fuel combustion efficiency using different technologies (different burners and furnaces). The average rate of specific fuel consumption

for heat and electricity output may not account for this. Made in boiler unit steam
can be directed to different types of turbines (with different types of steam exhaust):
industrial, heated, regenerative. Foreign CHP plants already use gas turbine units and
steam-gas units (gas turbine unit of turbine waste heat recovery boiler). It also does
not stand out when using the average specific fuel consumption for electricity and
heat output. Besides, energy resources are also used for neutralization of emissions,
waste and effluents. In other words, it is very difficult to calculate the change in energy
consumption of energy carriers (electric and thermal energy) during modernization
or detailed renewal of energy equipment according to the existing methodology. The
existing methodology allows comparing technologies where certain components are
different: technology for extraction (collection) of fuel (except solar and wind), type
of fuel transportation (except solar and wind), type of energy generation (thermal,
nuclear, solar, wind, biofuel). Energy costs for the production of electricity and heat
itself are included in the component of full and direct energy intensity through the
averaged across the country indicator of specific fuel consumption for the output
of energy carriers without analysis of options for improving this indicator. Own
requirements of CHP plants are not taken into account at all (electric and thermal
energy). Among auxiliary expenses electric energy for water and air supply is taken
into account.

A mathematical model for determining the full energy costs of production in
natural, conditional or cost terms per unit of output (by the example of ferrous
metallurgy), which clarified the concept of direct energy consumption of products
was developed in the Institute of General Energy of the National Academy of Sciences
of Ukraine [34]:

$$E = \frac{B_{o.p} - \left(B_{g.er} + B_{t.er} + B_{e.er}\right)}{N_{o.p}} - \frac{\sum_l B_{m.rl}}{N_{m.r}}$$
$$+ m_{c.m} \cdot \frac{\sum_j B_{c.mj}}{N_{c.m}} = \frac{\sum_s B_{ens}}{N_{en}} \tag{4}$$

where $B_{o.p}$—the volume of fuel and energy resources used for the manufacturing of
products in the main and auxiliary production during the year, taking into account
losses of energy resources in the technological process and the costs of intra-
factory transportation (ton coal equivalent per year (tce/year)); $B_{g.er}$—the volume
of combustible recycled energy resources received during the production of prod-
ucts (tce/year); $B_{t.er}$—amount of thermal recycled energy resources utilized during
the year in the production of products (tce/year); $B_{e.er}$—amount of fuel, which was
replaced by recycled energy resources of excess pressure in the generation of elec-
tricity produced during the year by utilization units (tce/year); $N_{o.p}$—amount of prod-
ucts produced by the enterprise during the year, in natural, conditional or cost terms;
l—index of the type of recycled material resources, taken from the data of the enter-
prise; $B_{m.ri}$—the amount of energy resources, which accounts for the formation of
recycled material resources in the technological process (tce/year); $N_{m.r}$—the amount

of recycled material resources in physical, conditional or value terms, received during the year in the production of products; $m_{c.m}$—the share of raw materials, materials, intermediate products used in the technological process itself; j—index of type of raw materials, materials, intermediate products or assembly units; $B_{c.mj}$—amount of energy resources used during the year for the manufacture of j-ro type of raw materials, materials, intermediate products or assembly units, (tce/year); $N_{c.m}$—amount of j-type of raw materials, materials, intermediate products or assembly units in natural, relative or value terms, used during the year according to the data of the enterprise; m_{en}—amount of energy resource used directly in the technological process according to the data of the enterprise; s—energy resource type index; B_{ens}—amount of fuel and energy resources used for the production of s-type of energy resource (tce/year); N_{en}—amount of s-type of energy resource used for the year in natural, relative or value terms according to the data of the enterprise.

In multi-product industries for formulas (2–4) the distribution of energy expenses on a range of manufactured products in one technological unit should be performed. The most striking example, which requires the distribution of these costs, is primary refining. In [35] an analysis of existing methods for assessment of the energy efficiency of oil refining processes has been carried out on the basis of enlarged balances (energy, thermal and exergy) of the main technological units using various methods of distribution of total energy costs, and the exergy of fractions of primary oil refining at the output of the unit has been calculated. A methodological approach to determining the total energy consumption of oil products is provided, taking into account the technological scheme of the plant and the range of produced oil products. The algorithm for calculating the full energy intensity of oil products was defined as follows:

$$
e_f^{op} = \sum_f \frac{m_{fr,f}^{op}}{m_f^{op}} \left[\frac{m_{fr,f}^{per}}{m_{oil}} \left(e_{oil}^{out} + e_{log}^{or} + e^{per} \right) + e_f^{sec} + \sum_g e_g^d \frac{m_{op,g}^d}{m_{raw}^d} \right]
$$
$$
+ \frac{m_f^{op}}{m_{oil}} \left(e_f + e_{env} \right) \tag{5}
$$

where $m_{fr,f}^{op} \big/ m_f^{op}$—the portion of the intermediate product supplied to the blending unit of commercial oil products from the processes of primary, secondary and deep processing; $m_{fr,f}^{per} \big/ m_{oil}$—the portion of f-th fraction, comes out of the process of primary oil processing; e_{oil}^{out}—the direct energy intensity of the extracted oil that comes to the oil refinery for processing; e_{log}^{or}—the energy intensity of transporting oil to refineries; e^{per}—the full energy intensity of the primary oil processing process; e_f^{sec}—full energy intensity of the secondary refining process for f oil products in the technological chain of production; e_g^d—full energy intensity of the g-th process of deep processing; $m_{op,g}^d$, m_{raw}^d—the mass output of oil products and the bulk of processed raw materials in the g-th process of deep refining, respectively;

$m_f^{op} \big/ m_{oil}$—the portion of oil products obtained from oil in the balance of oil and petroleum products; e_f,e_{env}—as in formula (2).

It is proven that in the processes of physical fracturing of oil the most acceptable method of distribution of energy expenditure is in proportion to the mass output of fractions, because the thermal abilities of fractions are similar and slightly affect the refinement of distribution coefficients.

A similar approach was applied to the allocation of energy expenses for coke-chemical products [36], which made possible to calculate the energy intensity of 4 chemical products manufactured as side products during coke gas purification.

In the given examples (oil refining, coke chemistry), the received kinds of production are comparable on physical and chemical properties: have weight, density, temperature, pressure, their characteristics for various products can be measured by corresponding devices. When considering combined energy generation, two dissimilar products with different properties are produced and cannot be measured with the same instruments.

DSTU [37] developed in 2014 provides a methodical approach to the allocation of total fuel consumption at thermal power plants depending on the exergy of steam, which performs work in steam turbines of different types. This thermodynamic method makes it possible to determine the energy consumption of electric and thermal energy from the coefficient of thermodynamic value of heat, which depends on the type of steam turbine cycle (efficiency of steam exhaust) or gas turbine, but it is not possible to analyze the energy consumption efficiency from improvement of burner devices and systems of fuel preparation and feeding, as well as to use the potential of recycled energy resources of natural gas excess pressure again.

3 Purpose and Objectives of the Study

The purpose of the study is to analyze and improve the existing methodical approach to determining the direct end-to-end energy consumption on the example of energy carriers—electric and thermal energy, simultaneously produced at a combined heat and power plant from a steam turbine unit during the combustion of coal and natural gas, and include both the direct use of fuel to obtain steam, and support costs of energy resources for the preparation and supply of fuel to the burners of steam generators (own needs of the plant), reduction of which directly affects efficiency of energy production, use of recycled energy resources (RER), consideration of energy efficiency costs for environmental protection measures; use of improved approach to assessment of technological potential of energy saving in selection of efficient technologies.

The objective of the study is to analyze methodological approaches to determining the efficiency of energy costs in combined production, the use of indicators of technological energy efficiency along the production chain for energy saving potentials in various options for replacing the existing equipment with more efficient ones.

4 Improved Methodological Approach to Determination of Direct Technological Energy Intensity of Products

For multi-product industries, formula (2) takes the form:

$$e_p = k_n'' \sum_s e_s (b_{ps} + \sum_i a_{pi}' b_{pis}') + e_{env}^n, \tag{6}$$

where k_n'' is the partition coefficient choice for a n-th specific multi-product manufacturing technology.

In the study is considered as combined energy production simultaneous production of thermal and electric energy. When splitting energy consumption into 2 energy products, different approaches can be applied, for example, the current one (50:50) and the approach that takes into account the seasonal demand for energy carriers, that is, the main product in the heating period will be thermal energy, by-product—electric. In the non-heating period, when the CHP will be included in the regulation of schedules of electric loads, the main product will be electricity, the by-product—thermal in the form of hot water or cold.

On the example of a coal-fired CHP plant with a T-type turbine with heating steam extraction for the needs of utility consumers, a chain of energy resources consumption was created from the supply of fuel to the CHP plant to the production of heat and electricity.

We have detailed the methodical approach for taking into account all the listed energy costs that can affect the energy intensity of energy carriers.

This structural sequence consists of the following steps [38]:

1. Determination of the main type of fuel (coal, fuel oil, natural or other industrial gases);
2. Definition of basic equipment;
3. Definition of auxiliary equipment;
4. Investigation of the efficiency of existing equipment and research of the possibility of introduction of the latest technologies;
5. Estimation of possible reduction of energy consumption when replacing existing technologies with promising ones.

An improvement in formula (2) is as follows. Not used as an indicator of energy intensity of energy resources specific fuel consumption for energy carriers supply of country. Energy intensity of energy resources is determined for a specific set of thermal equipment, taking into account the use of secondary thermal energy resources for coal CHP plants and the potential of secondary energy resources of excess pressure of natural gas for gas CHP plants [39]:

– coal CHP plant:

$$b_{sk}^{coal} = \sum_s \sum_k b_{sk} = b_{heat}^{sk} + b_{mill}^{sk} + b_{transp}^{sk} + b_{comb}^{sk} - b_{regen}^{sk} + b_{env}^{sk} \tag{7}$$

– gas CHP plant:

$$b_{sk}^{gas} = \sum_{s} \sum_{k} b_{psk} = b_{transp}^{sk} + b_{comb}^{sk} - b_{regen}^{sk} - k_w W + b_{env}^{sk} \qquad (8)$$

where k—is the type of equipment; s—kind of energy resource; b_{heat}^{sk}, b_{mill}^{sk} b_{transp}^{sk} $b_{comb}^{sk} b_{regen}^{sk} b_{env}^{sk}$—respectively specific consumption of fuel (energy resource) for heating the fuel (for coal and heating oil), grinding coal at the used or new type of mill, supply of fuel through the pipeline, consumption for combustion, fuel savings as a result of the use of regenerative installations (air heater and water economizer) and energy costs to operate environmental equipment, depending on the type of burned fuel; $k_w W$—the amount of produced electricity in the turbo-expander due to the secondary energy resources of excess pressure (reduction of pressure at the gas distribution substation).

5 Analysis of Results Obtained

By formulas (6–7) the energy intensity of energy carriers (electric and thermal energy) is calculated together (Fig. 2) with allocation of all energy intensity components. Distribution of fuel consumption for generation of energy carriers should be done according to the method [37], while allocation of other fuel consumption can be done by different methods, e.g. proportional to the volumes of energy supply translated
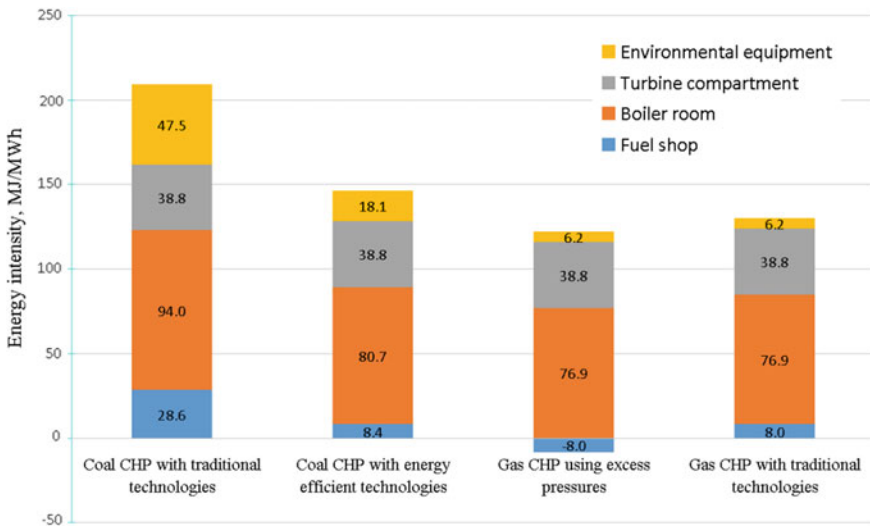

Fig. 2 The energy intensity of auxiliary costs of energy carriers (electricity and thermal energy) produced at the CHP plant depending on the type of equipment and used fuel

into the same units of measurement. It should also be added that the installed capacity utilization factor is applied to each type of equipment and at each stage, because not all equipment at the power plant is constantly in operation, but some equipment is operating only in a certain season (for example, defrosting of coal fuel in winter).

An information database was created for the implementation of this approach and model calculations, which contains a list of main and auxiliary equipment in various configurations, various manufacturers and with various energy indicators. By means of the given algorithm depending on type of the applied equipment energy intensity indicators, which can be compared and chosen more effectively as an indicator of decrease in energy intensity of energy carriers [38], are received.

Figure 2 shows the obtained calculations for production of 1 ton of steam by boiler units taking into account energy costs for fuel preparation and storage, operation of auxiliary equipment of boiler and turbine departments, as well as energy costs for environmental protection measures. The energy intensity of the burned fuel has not been presented as it remains unchanged when the auxiliary costs is reduced or increased. The energy intensity of the combusted fuel is 2718.38 MJ/t of produced steam or 4264.796 MJ/MWh of energy supply. An analysis of the possible replacement of auxiliary costs (without combustion fuel in the boiler) is included in the calculation model for the four variants of the CHP plants.

The first variant characterizes the technologies of a coal CHP plant with the most widespread main and auxiliary equipment currently operating in Ukrainian CHP plants using gas turbines for defrosting fuel in winter, ball mills for grinding, coal dusting with normal dust concentration in the air stream for flaring coals in chamber furnaces with hydro ash and slag removal, wet precipitation for particle removal, semi-dry lime technology for sulfur removal and selective catalytic reduction for reducing nitrogen oxide emissions.

The second case includes the improved coal power units with technologies which are partially used at separate thermal power plants and are perspective now, including the following main and auxiliary equipment have been put in place: gas radiation defrosting panels, roller or hammer mills, coal dusting with a high concentration of dust in the air stream for boilers with the technology of circulating fluidized bed allowed to organize measures on reduction of nitrogen oxides at once in the furnace at combustion without additional equipment.

From the data in Fig. 2 we can see that fuel preparation technology can significantly affect the overall energy intensity of products. It should also be noted that the combustion technology is more efficient, which allows to burn lower quality fuel with lower auxiliary energy expenses, which can be clearly seen when comparing the first and second variants.

The third option is a natural gas-fired combined heat and power plant using a turbo-expander at a gas distribution substation (GDU) while reducing pressure to a working one and the most common main and auxiliary equipment. Option 3 shows the full technological consumption of energy resources through the technological chain when using the energy of natural gas overpressure that emitted when gas pressure decreased to the worker pressure. According case Option 4, with which Option 3 is compared, the energy costs are higher by this value.

Energy intensity of environmental measures in direct energy intensity of energy resources is calculated according to the method [40] using the data from [41].

The results presented in Fig. 2 allow to determine energy saving potential (maximum possible fuel and energy saving) for thermal power plants at alternative replacement of auxiliary costs. For gas CHP plants, this potential is determined by additional energy, which can be produced by using recycled excess pressure energy resources.

For coal-fired cogeneration and power plants to estimate technological potential of energy conservation, it is possible to consider additional technology using an innovative turbine [42] (Table 1). This potential is determined by the product of the difference in energy intensity by variants of implementation volume (energy output). The difference in energy intensity is determined between the first and second and first and third variants. The energy saving potential can be determined for 1 MWh of energy carriers production (electric or electric and thermal energy—together).

The third variant is coal-fired power plants with the equipment listed in variant 2 (Fig. 2), in combination with a 100 MW electric turbine, which has a detachable coupling between medium and low pressure cylinders(CMP and CLP respectively), which has a higher efficiency (43.6% compared to 42–42.4%), can provide the power unit operation at sliding pressure at a reduced load, provides work on the thermal schedule 130/70°C without using peak water boilers. The use of a turbine with a split coupling allows increasing the maneuverability of the power plant, switching off the CLP during the heating period and eliminating ventilation losses in the CLP.

Table 1 Energy intensity of energy carriers before and after modernization of coal CHP plant, MJ/MWh

Equipment set options	Workshops of CHP plant				Energy intensity (technological) of energy carriers is an option
	Fuel shop	Boiler room	Turbine compartment	Environmental equipment	
1—Traditional technologies	28.59	93.97	38.85	47.48	208.89
2—Circulating fluidized bed furnace (CSF) and efficient assistive technologies	8.36	80.66	38.85	18.12	145.99
3—CSC furnace, detachable turbine and state-of-the-art assistive technology	8.36	80.66	28.17	18.12	135.31

Table 2 Energy saving potential for coal CHP plants from auxiliary equipment modernization, MJ of energy consumed/1 MWh of produced energy carriers together

Options	Energy intensity of energy carriers production (technological) at auxiliary equipment, MJ/MWh	Energy saving potential at alternative replacement of auxiliary technologies concerning Option 1, MJ/MWh
1—Traditional technologies[a]	208.89	0
2—Circulating fluidized bed furnace (CSF) and efficient assistive technologies	145.98	62.91
3—CSC furnace, detachable turbine and state-of-the-art assistive technology	135.30	73.59

[a]without the amount of fuel burned in the boiler, as its size does not change and is given above in the text

Coefficient of fuel heat utilization in the power unit under the third variant makes 95.17% against 88–89% for power units with traditional turbine unit [43].

The results of the assessment are presented in the Table 2.

The Table 2 shows, the technically possible energy saving potential at alternative replacement of auxiliary technologies for the production of energy carriers at coal-fired power plants can be achieved by upgrading the equipment according to option 2—62.9 MJ per 1 MWh of produced energy carriers, according to option 3—73.6 MJ per 1 MWh of produced energy carriers. Coal-fired power plants have a significant reserve to increase energy efficiency in the production of energy carriers. With a shortage of natural gas and unstable supplies of energy resources from renewable sources, coal-fired power plants can take their place in the structure of generating capacities.

6 Conclusions

The existing methodological provisions for determining the total energy intensity of the products and its components as a through-flow specific energy consumption was analyzed and compared.

Methodical approach to determining the direct energy intensity of products for multi-product energy intensive industries has been improved. The calculation is given for cogeneration of energy carriers at CHP plants, which burns different fuels. The proposed detailing has made it possible to calculate the amount of energy savings in the transition from widespread technologies to high-efficiency modern technologies for coal-fired CHP plants using three variants of applied technologies, and in natural gas—for two, taking into account the use of secondary energy resources of excess pressure for additional electricity production for own need.

Direct energy intensity includes energy intensity of enviromental measures, as the neutralization of pollutants occurs at the place of pollution formation, and the coefficient of distribution of common energy consumption at the point of distribution of products is introduced into the calculation algorithm.

An analysis of the latest technologies that can be implemented at coal power plants has shown a significant reserve for improving energy efficiency in energy carriers production. In the face of natural gas shortages and unstable energy supplies from renewable sources, coal power plants can take their place in the structure of generating capacity.

References

1. Dubovsky, S.V.: Energy-economic analysis of interconnected systems of electricity and heat generation. Naukova dumka, Kiev p. 182 (2014)
2. Report on energy supply and use. Ukraine, The State Statistics Service of Ukraine. Kiev (2017). Access mode: www.ukrstat.gov.ua
3. Report on use and stocks of fuel. Ukraine, The State Statistics Service of Ukraine. Kiev (2017). Access mode: www.ukrstat.gov.ua
4. Plachkov, I.S.: Types of thermal power plants. Access mode: http://energetika.in.ua/en/books/book-3/part-1/section-1/1-2
5. Smihula, A.V., Sigal, I.I., Bondarenko, B.I., Semeniuk, N.I.: Technologies for reducing harmful emissions to the atmosphere by thermal power plants and boilers of large and medium capacity of Ukraine, p. 108. FOP Maslak, Kyiv (2019)
6. National Emissions Reduction Plan for Large Combustion Plants. Website of the Ministry of Energy and Coal of Ukraine. Access mode: http://mpe.kmu.gov.ua/minugol/control/publish/article?art_id=245255506
7. DSTU 3755–98. Nomenclature of energy efficiency indicators and procedure for their inclusion in regulatory documents. Kyiv (1998)
8. Vagin, G.Ya., Dudnikova, L.V., Zenyutich, E.A.: Energy saving in industrial technologies (2001)
9. DSTU 3682–98 (GOST 30583–98). Energy saving. The methodology for determining the total energy intensity of products, works and services. Kyiv (1998)
10. Lytvynchuk, V.A., Kaplin, M.I., Bolotnyi, N. P.: The method of design an optimal under-frequency load shedding scheme. In: IEEE 6th International Conference on Energy Smart Systems, pp. 14–17 (2019) https://doi.org/10.1109/ess.2019.8764241
11. Kulyk, M.M., Kyrylenko, O.V.: The state and prospects of hydroenergy of Ukraine. Techn. Electrodyn. **4**, 56–64 (2019). https://doi.org/10.15407/techned2019.04.056
12. Popov, O.O., Iatsyshyn, A.V., Kovach, V.O., Artemchuk, V.O., Kameneva, I.P., Taraduda, D.V., Sobyna, V.O., Sokolov, D.L., Dement, M.O., Yatsyshyn, T.M.: Risk assessment for the population of Kyiv, Ukraine as a result of atmospheric air pollution. J. Health Poll. **10**(25), 200303 (2020). https://doi.org/10.5696/2156-9614-10.25.200303
13. Bilan, T., Rezvik, I., Sakhno, O., But, O., Bogdanov, S.: Main approaches to cable aging management at nuclear power plants in Ukraine. Nucl. Radiat. Saf. **4**(84), 54–62 (2019). https://doi.org/10.32918/nrs.2019.4(84).07
14. Babak, V.P., Babak, S.V., Myslovych, M.V., Zaporozhets, A.O., Zvaritch, V.M.: Technical provision of diagnostic systems. In: Diagnostic Systems For Energy Equipments. Studies in Systems, Decision and Control, vol. 281, pp. 91–133. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-44443-3_4

15. Xin-gang, Z., Pei-ling, L.: Is the energy efficiency improvement conducive to the saving of residential electricity consumption in china? J. Clean. Produc, 249 (2020). https://doi.org/10.1016/j.jclepro.2019.119339
16. Mokhtar, A., Nasooti, M.: A decision support tool for cement industry to select energy efficiency measures. Energy Strat. Rev., 28 (2020). https://doi.org/10.1016/j.esr.2020.100458
17. Chakravarty, K., Kumar, S.: Increase in energy efficiency of a steel billet reheating furnace by heat balance study and process improvement. Energy Rep. **6**, 343–349 (2020). https://doi.org/10.1016/j.egyr.2020.01.014
18. Reuter, M., Patel, M.K., Eichhammer, W., Lapillonne, B., Pollier, K.: A comprehensive indicator set for measuring multiple benefits of energy efficiency. Energy Policy, 139 (2020). https://doi.org/10.1016/j.enpol.2020.111284
19. Leoni, P., Geyer, R., Schmidt, R.: Developing innovative business models for reducing return temperatures in district heating systems: approach and first results. Energy, 195 (2020). https://doi.org/10.1016/j.energy.2020.116963
20. Sokolov, E.Ya.: District heating and heat networks: a textbook for universities, 5th ed., Revised, p. 360. Energoizdat, Moscow (1982)
21. Yakovlev, B.: Improving the efficiency of district heating and heating systems, p. 448. Education and upbringing, Minsk (2002)
22. Utilities of Ukraine: state, problems, ways of modernization. In: Dolinsky, A.A., Basok, B.I., Bazeev, E.T., Pyrozhenko, I.A. (eds.), vol. 2, p. 820. Kyiv (2007)
23. Klimenko, V.N., Mazur, A.I., Sabashuk, P.P.: Cogeneration systems with heat engines: reference manual. In 3 parts. Part 1. General issues of cogeneration technologies, p. 560. Kiev, CPI ALKON NAS of Ukraine (2008)
24. Arakelyan, E.K., Kozhevnikov, N.N., Kuznetsov, A.M.: Tariffs for electricity and heat from the CHP. Heat Pow. Eng. **11**, 60–64 (2006)
25. Zaitsev, E.D.: Thermodynamic method for calculating the specific fuel consumption for various types of energy released by CHP. Heat Supp. News **12**(148), 24–26 (2012)
26. Dubovsky, S.V.: Increasing the maneuverability of the energy system through the introduction of heat pumps-regulators in the TPP. Prob. Gen. Energy **4**, 16–23 (2013)
27. Shubenko, O.L.: The transfer of a small cogeneration plant to burning local fuel in volumes that ensure its operation in the summer. Energy Sav. Energy Aud. **4**, 17–26 (2014)
28. Maliarenko, V.A.: Cogeneration technologies in the energy sector based on the use of low-power steam turbines: monograph. Institute of Engineering Problems of the NAS of Ukraine, Kharkov (2014)
29. Kesova, L.O., Horskyi, V.V.: Improving the efficiency of thermal power plants using low-cost technologies. Prob. Gen. Energy **2**(53), 60–64 (2018)
30. Brodyansky V.M.: Exergy method of thermodynamic analysis. Moscow, Energy (1973)
31. GOST R 50-605-100-94. Standardization Recommendations. Energy saving. The main directions of energy conservation in the steel industry. Technological measures to reduce the consumption of boiler and furnace fuel
32. GOST 51387–99. Energy saving. Normative and methodological support. The main provisions
33. GOST R 51541–99. Energy saving. Energy efficiency. General Provisions (2002)
34. Gnidoy, M.V., Kuts, G.O., Tereshchuk, D.A.: The method of calculating the total energy costs of production. Ecotechnol. Res. Conser. **5**, 67–72 (1997)
35. Gnidoy, M.V., Maliarenko, O.Ye.: Energy efficiency and determination of energy saving potential in oil refining. Kiev, Naukova Dumka (2008)
36. Maliarenko, O. Ye., Teslenko, O.I.: The use of the method of full energy intensity of products for the analysis of energy production efficiency. Prob. Gen. Energy **3**(23), 19–24 (2010)
37. DSTU 7674:2014 Energy Saving. The energy intensity of the technological process of generating electrical and thermal energy released by a thermal power plant. Method of determination. Kyiv (2014). 34 c
38. Horskyi, V.V., Maliarenko, O. Ye.: Methodical approach to the evaluation of the efficiency of modernization of the TPP of Ukraine. Access mode: http://molodyvcheny.in.ua/files/conf/other/37june2019/37june2019.pdf

39. Maliarenko, O. Ye., Horskyi, V.V.: An improved approach to the evaluation of the efficiency of energy saving measures and technologies at the TPP. Prob. Gen. Energy **4**, 24–31 (2019)
40. Stanytsina, V.V.: Development of full energy consumption method for determination of energy efficiency indicators and energy saving potentials. PhD thesis. Institute of General Energy of NAS of Ukraine, Kyiv (2016)
41. Artemchuk, V.O., et al.: Theoretical and applied bases of economic, ecological and technological functioning of energy objects (2017)
42. Horskyi, V.V., Maliarenko, O. Ye.: Estimation of energy saving potential for coal-fired thermal power plants in the implementation of innovative technologies. Research Practice Conference "Science, Technology and Technology: Global and Modern Trends." Prague, Czech Republic (2019)
43. New generation coal power plant. Access mode: https://docplayer.ru/26842769-Razrabotka-vysokoeffektivnyh-i-ekologicheski-chistyh-ugolnyh-tec-novogo-pokoleniya.html