Information and analytical platform for evaluating the effectiveness and choosing directions for improving the energy and water supply systems of oil and gas chemical complexes

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Abstract. The paper presents the structure and content of a specialized enterprise information system that can be used to calculate the parameters of energy generation process and complex structure and to study and develop specific equipment for individual plants and create autonomous energy and water supply systems for oil and gas chemical complexes. The paper proposes a three-dimensional hierarchical model with orthogonal connections that includes the object of study, the problems of increasing energy performance of such object and potential methods of solving these problems. The paper presents calculation algorithms and the results of numerical modeling of energy supply systems operating within the conditions of dynamically developing oil and gas chemical complexes. Schematic solutions of the developed optimal resource-efficient energy supply systems for various technological processes are also provided. The paper discusses the potential beneficial modifications of energy supply system structure of raw hydrocarbon processing facilities; these modifications are based on the principles of polygeneration and further integration between energy supply system and processing units.

1. Introduction

Fuel, electric and thermal power and process water supply systems of currently operational oil and gas chemical complexes (OGCC) were designed at the very early period of the corresponding hydrocarbon feed (HCF) deposits development; therefore, these systems do not account for dynamics of such deposits development and interconnections with external energy supply systems (EESS). Currently, the concept of constructing promising energy and water supply systems (EWSS) for OGCC is based on the principles of energy resource (ER) generation by autonomous units utilizing various types of heat engines [1-5], and potential application of combustible low-pressure gases from process facilities and renewable energy sources [6-9]. In order to analyze and design a EWSS that is highly effective at all stages of the life cycle of an OGCC, it is necessary to develop a specialized enterprise information system that complies with the following requirements to dynamically developed technological and energy elements:

- maximal utilization of facilities' own supply of secondary resources to produce ER and water;
- creation of closed process cycles that minimize power consumption from EESS, exclude

industrial wastes and prevent the loss of resources;

- creation of resource-efficient energy-technology modules (ETM) based on the principle of polygeneration (simultaneous production of ER, water and processed goods) involving utilization of low-pressure hydrocarbon gases and fire-based disposal of industrial wastes and effluents;
- the combination of ETM with the main production facilities of OGCC that account for variations in pressure and composition of the HCF and the range of products;
- multicriterial analysis of technical decisions regarding the composition and parameters of modern equipment of autonomous EWSS that account for reliability indicators, interconnections with EESS and partial uncertainty of technological, economic and environmental factors.

Analysis of existing models and enterprise information systems utilized by energy complexes of industrial enterprises (technological counterparts to OGCC) showed that their use is limited both by the hardware design of the EWSS and the range of tasks they have to solve including logistics support for the maintenance of chemical equipment [10]; energy saving management of electric and heat power equipment [11] and optimization of operation modes of cogeneration power plants [2]. There are other information systems [12, 13], software systems [14, 15], and simulation models [4, 16, 17] that, unfortunately, cannot be used (either as full systems, or as separate elements) to calculate the parameters of energy generation process or system structure or to study and develop equipment for individual units that can be used to design autonomous EWSS and PEM for OGCC, as these systems or models do not comply with above listed specific requirements for the studied object. It is obvious that development of a specialized information-analytical platform (IAP) capable of solving the aforementioned tasks must be based on the principles of systemic analysis and design of complex objects, namely, the decomposition and aggregation technique consisting of the following steps:

- decomposition of the object (development of models capable of describing various operations used in the production process and providing a distinct visual representation of such operations; identification of internal and external relationships separated by their degree of importance; identification of most important elements and relationships that determine the process flow);
- analysis of individual elements (selection of analysis technique and formulation of mathematical models for various processes and functions of systems that are related to the studied technologies and methods of ER and water production and consumption; development of reasonable algorithms and calculation software);
- designing the optimal EWSS and ETM for OGCC (development of methods, calculation of the parameters of designed systems in order to justify their application and compare these parameters according to multicriteria performance indicators).

The implementation of the above steps to design a specialized IAP will allow, in accordance with the trends of digital transformation of projects and the creation of digital counterparts of enterprises, to carry out simulation modeling, analysis and design of optimal EWSS for OGCC, and promote novel technological and engineering solutions.

2. IAP structure and properties of its constituent elements

The formulated space of the developed IAP (Figure 1) is represented by a three-dimensional hierarchical structure with orthogonal connections between elements using the following coordinates ("planes"): object (*a*), problem / task (*b*) and solutions (*c*).

The studied object is represented within the hierarchical levels by the following main elements:

- *a1* – production-technological system (PTS) and EWSS. At this level, the enterprise's scope of operation and the range of its products are determined;
- *a2* – productions of PTS and the subsystem of EWSS (electro-energy subsystem – EES, fuel supply subsystem – FSS, heat-power subsystem – HPS, water supply subsystem – WSS, wastewater disposal subsystem – DS). Here, the general structure of the object, sufficient to achieve the goal, is formed;

- *a3* – units with specific topological structure that are capable of manufacturing products of a given quality compliant with their accepted design and operation efficiency criteria;
- *a4* – devices (units) that allow to carry out the process in a given mode while taking into account the variable parameters of raw materials and the environment at different periods of the life cycle of production facility.

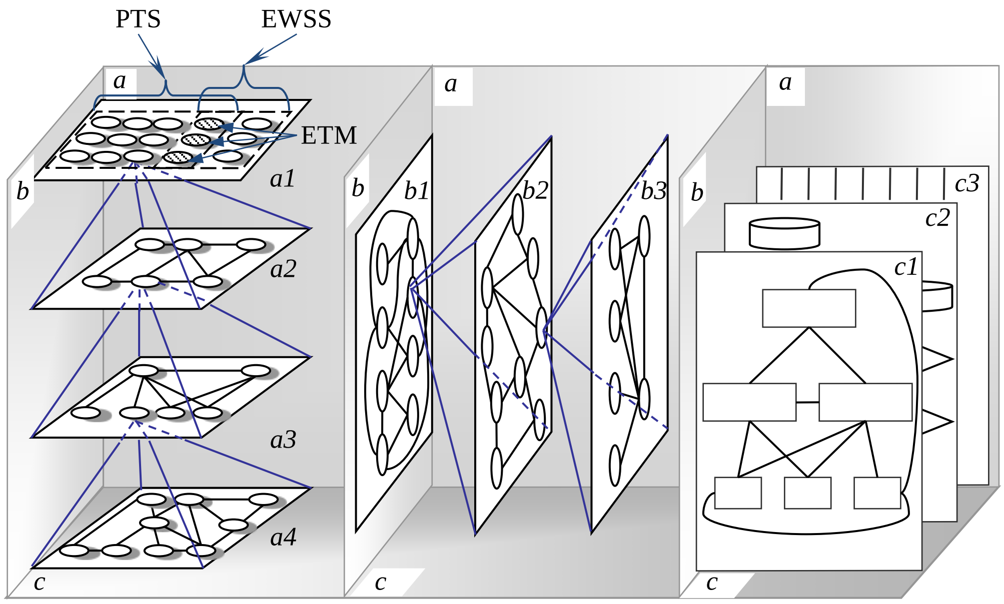


Figure 1. Three-dimensional hierarchical structure of IAP.

Plane *b* contains the results of structuring of the efficiency problems of the EWSS of OGCC; this plane contains three distinctive levels: *b1* – goals (functions), *b2* – tasks, and *b3* – control procedures for ER generation and consumption processes. Objectives of this plane include designing an object while performing a multi-criteria efficiency evaluation and providing the rational basis for its operation based on multi-criteria optimization of operating process. The set of tasks contains subsets of ER generation and consumption, water consumption and waste and effluents disposal. The primary procedures include analysis, rationing and structural and parametric optimization. Each of the procedures also includes solving a number of independent problems. For example, analysis of ER generation includes experimental and theoretical studies, while rationing involves the formation of an updatable database of typical facilities, processes, units and experimental and theoretical studies. Optimization of the EWSS of existing OGCC consists of defining rational operating modes (parametric optimization) and subsequent reconstruction of existing systems or construction of new ones. In the case of designed OGCC, optimization is a change in the structure of production and equipment designs (structural and parametric optimization) and the process of designing optimal EWSS for OGCC.

Solutions (plane *c*) are developed in several interrelated directions represented by the following sets of elements: mathematical modeling (*c1*), experimental studies (*c2*), energy audit (*c3*) and other sets of methods for implementing procedures of multi-criteria optimization of ER consumption and generation processes and analysis of efficiency parameters of equipment, facilities and EWSS as a awhole. Each method contains a series of interconnected sequences of operations. For example, mathematical modeling involves formulating a problem, choosing a research method, developing a mathematical model and modeling algorithms and programs, evaluating the model adequacy for studied object and using the results of analysis.

Each element of the object (plane *a*) represents a specific instance with its properties used to describe its general and particular characteristics, such as its functional features and purpose; attribution to a specific abstraction of the subject area (HCF-processing and product output; fuel, ER and water supply to EMS production facilities; waste disposal and other technological processes of OGCC); design characteristics (at the *a4* hierarchical level). Properties of elements are reflected in the database (DB). The data units of the DB are connected to each other via one-to-many (1:M); one-to-one (1:1) and many-to-many (M:M) connection types.

Map of 1:M connections characterizes the interconnections between the EWSS, the EMS and the elements of *a2* level –production facilities and systems (EWSS and EMS structure contains several produciton facilities / systems, but each production facility refers to a single EWSS associated with the EMS of OGCC). The 1:M map also connects the elements of *a2* and *a3* levels - “production facilities” and “units”: each production facility has several units, but any of these units refer to only one production facility. 1:M maps can be applied to the elements of *a3* and *a4* hierarchy levels. Each unit is equipped with several aggregates (type M association), while each piece of equipment belongs to only one unit (type 1 association). The aggregate consists of a number of devices, while any of the devices that make up the aggregate belongs only to this aggregate (1:1 mapping). For example, a boiler aggregate includes evaporation surfaces, a superheater, a block of burner devices, a water economizer and an air heater. All of these components (except the burner block) can be considered heat exchange surfaces (devices) of various types. A pump or compressor aggregate consists of, respectively, a certain type of pump or compressor and a drive (electric engine, steam turbine or gas turbine). Aggregation of compression refrigerators can be carried out at the level of “compressor-drive”, “compressor-condenser”, “compressor-evaporator”, “condenser-evaporator”, and “refrigeration machine” connections.

It should be noted that the division of EWSS and PTS into the “aggregate” and “device” elements is conditional. For example, process tube furnaces are generally considered an aggregate. They include radiation and convection chambers, burners and convective heat exchange surfaces for heating air, fuel gas or steam. But a 1:M mapping if it is converted to the 1:1 map, will be applied only to the burner device, as it is considered a device of a tube furnace by the developed DB.

The structure of the OGCC includes numerous standardized series of typical devices and aggregates. It is obvious that storing a complete list of characteristics for every single available device and aggregate belonging to a limited range of typical models in the DB is inefficient, as this will cause an unjustified increase in the size of the DB and make it difficult to fill out and edit it. It is more expedient to highlight the “device model” and “aggregate model” (or “device mark” / “aggregate mark”) data units.

In this case, the structure shown in Figure 2*a* will be obtained for the aggregate level. The associations depicted show that each aggregate belongs to a single particular model and is a part of one of the units. In the case of “aggregate model” data unit, there are two distinct groups of data: the first describes the aggregate in assembly, and the second is composed of data on its components. This is implemented by the structure shown in Figure 2b.

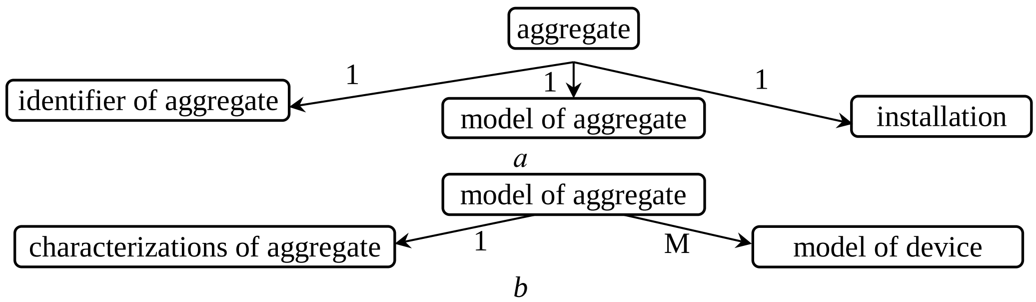


Figure 2. Information element associations: *a* – aggregate; *б* – model of the aggregate.

The combination of properties of the *b1 – b3* and *c1 – c3* elements is a theoretical knowledge base for solving the problems posed. Its creation was carried out in stages and included the development of models of the object elements and subsequent implementation of analysis and design procedure to EWSS [18]. The main stages contents include:

- methodological foundations of systemic analysis represented by a block and hierarchical structure of an object and a DB of *a1 – a4* elements, a system of indicators and performance criteria for various periods of the life cycle of production facility and a mathematical description of an object;
- methodological foundations of design and structural and parametric optimization developed via the decomposition and search technique utilizing elementary decomposition strategy for tasks and cutting-off decomposition for solutions; these foundations are implemented in the form of algorithms and programs with examples of interpretation of theoretical positions in the problems of rationalization of EWSS of OGCC;
- design procedures for the optimal parameters of *a1 – a4* elements that, if implemented in the form of tasks for systems of automated control over the processes of fuel and ER generation and consumption, water consumption and water disposal, can improve the energy and resource efficiency of the EWSS and PTS;
- procedures for designing the optimal structure of the EWSS, allowing designing the EWSS that take into account the dynamics of OGCC development and developing a strategy for the modernization of EES, FSS, HPS, WSS and DS, taking into account changes in the PTS;
- the DB of promising technological and circuit solutions for multifunctional EWSS integrated with units and production facilities of PTS.

3. Performance indicators and algorithms of structural and parametric optimization

Efficiency assessment of the designzed EWSS of OGCC with various topology of the PTS based on the developed IAP is carried out in accordance with partial technological (T_i), energy (E_i), engineering and economic (C_i) and complex (U_i) indicators.

A generalized characteristic of the EWSS of OGCC is a multi-criteria efficiency index (MEI) [18], which was developed by ranking the T_i, E_i and C_i indicators according to the hierarchy analysis [19]. The MEI includes two groups of indicators characterizing, on the one hand, the properties of the OGCC as an economic asset (performance *p*), and on the other, the efficiency *l*, that allows assessing the autonomy of EWSS in terms of required ER consumption (its independence from EES) and the degree of using recovered energy resources (RER), combustible wastes and effluents to generate electric power, as well as determining the environmental safety and reliability of ER supply throughout the life cycle of the OGCC. The *p* and *l* sets are equivalent, since structural and parametric optimization of the EWSS in order to increase its efficiency must also preserve (or improve) the profitability of the OGCC. Each set includes 6 indicators characterizing alternative (rational) options for EWSS as compared with the basic (most often with a designed or existing) option:

- *p*: C_1 - the value of sold products; C_2 - the cost of HCF and materials; C_3 - the costs of ER from EESS and water from external sources; C_4, C_5 - costs for maintenance, repair and depreciation of EWSS and PTS equipment; C_6 - payment to external enterprises for processing and disposal of waste and effluents;
- *l*: U_1 - the utilization of HCF, materials and technological waste; U_2 - rationalization of material, energy and fuel balances; U_3 - the utilization of RER and fuel generated in the PTS to generate the ER; U_4 - performance of HCF processing; U_5 - reliability of ER and water supply; U_6 - environmental, industrial and general technical safety.

The vector performance criteria U_2 - U_6 are represented by the algebraic sums of the normalized (dimensionless) characteristics of the EWSS and PTS with the corresponding rank coefficients of particular indicators.

$$U_1 = 0{,}417\overline{T}_1 + 0{,}263T_2 + 0{,}160T_3 + 0{,}097\overline{T}_4 + 0{,}062T_5, \tag{1}$$

where $\bar{T}_1$ is the normalized (relative to the base variant) performance for the target products of the OGCC; T_2 is the utilization factor of HCF ($0 < T_2 \leq 1$); T_3 is the utilization factor of HCF and waste that were used to produce the by-products; $\bar{T}_4$ is the normalized difference between the value of sold products and the cost of HCF and materials; T_5 is rationalization coefficient of the costs of fuel and ER provided by external systems.

$$U_2 = 0{,}381\bar{E}_1 + 0{,}252E_2 - 0{,}160E_3 - 0{,}101E_4 - 0{,}064E_5 - 0{,}043\bar{E}_6, \tag{2}$$

where $\bar{E}_1$ is the normalized specific (per unit of target product or recycled HCF) consumption of fuel and ER; E_2 is the coefficient of relative deviation (saving) of fuel and ER consumption; E_3, E_4, E_5 are rationalization coefficients of power engineering, water consumption and water disposal balances, correspondingly; $\bar{E}_6$ is the normalized value of the technically feasible potential for utilization of all types of ER and RER.

$$U_3 = 0{,}417E_7 + 0{,}263E_8 + 0{,}160E_9 + 0{,}097E_{10} + 0{,}062\bar{E}_{11}, \tag{3}$$

where E_7 is energy efficiency coefficient equal to the ratio of the amount of useful and additionally generated energy to the sum of the energy supplied from the EESS and EWSS of OGCC; E_8 is the efficiency coefficient for utilization of all types of ER; E_9 is the efficiency coefficient of RER utilization for the generation of heat energy for own needs of the OGCC; E_{10} is the exergy efficiency of the OGCC (excluding the so-called “transit” exergy of the HCF and processed hydrocarbon products [20]); $\bar{E}_{11}$ is the normalized value of systemic fuel savings resulting from installing internal generating sources based on the EWSS.

U_4 criterion is the normalized value of the productivity of the OGCC for HCF processing:

$$U_1 = \bar{T}_6. \tag{4}$$

$$U_5 = 0{,}5(\bar{C}_7 + \bar{C}_8), \tag{5}$$

where $\bar{C}_7$ is the cost (normalized value for alternative EWSS options) of creation of reserve electric and thermal capacities, as well as additional costs of EESS for the maintenance of this reserve (additional fuel in start-up and shutdown modes, all types of repairs, equipment replacement) and compensation costs resulting from changes in the balance of electric and thermal power of the system; $\bar{C}_8$ is the capital costs for reserve process equipment, depending on technological and design factors, and operating time.

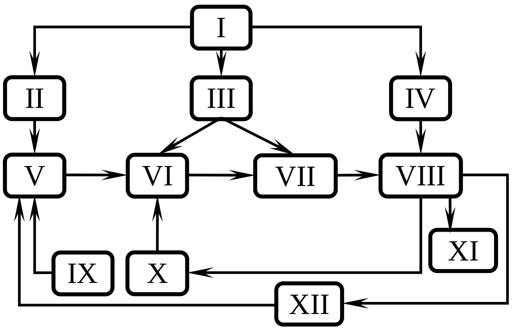
$$U_6 = -0{,}540E_3 - 0{,}297E_4 - 0{,}064E_5 + 0{,}163\bar{C}_9, \tag{6}$$

where $\bar{C}_9$ is the capital expenditures in the technological equipment of waste disposal installations of industrial effluents and emissions, depending on technological and design factors, and operating time.

Structural and parametric optimization of the EWSS in conjunction with the PTS and EESS is performed according to the operators of mathematical models of elements presented in the IAP. Discrete calculations of performance indicators are carried out according to the corresponding dependence or algorithm that display (imitate) continuous action in a real object. At the conceptual level of modeling, this is described by system of interconnected functions.

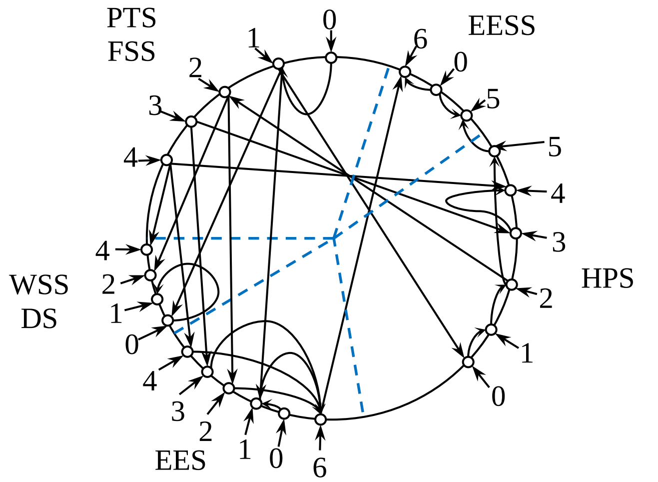
The simulation algorithm for designing a rational version of the EWSS is presented in Figure 3,*a* in the form of logical steps and computational blocks. Figure 3,*b* depicts the connections between element calculation modules.

The developed algorithms are implemented as software used for calculating the power engineering characteristics of the EWSS and PTS equipment and the performance indicators of the OGCC.



a

I – technical task; II – performance requirements; III – independent input data; IV – criteria efficiency; V – structure formation; VI, VII – formation and description of the model; VIII – eligibility analysis to accordance with criteria; IX – DB of equipment and circuits; X – parameter optimization; XI – optimal option EWSS; XII – change structure



b

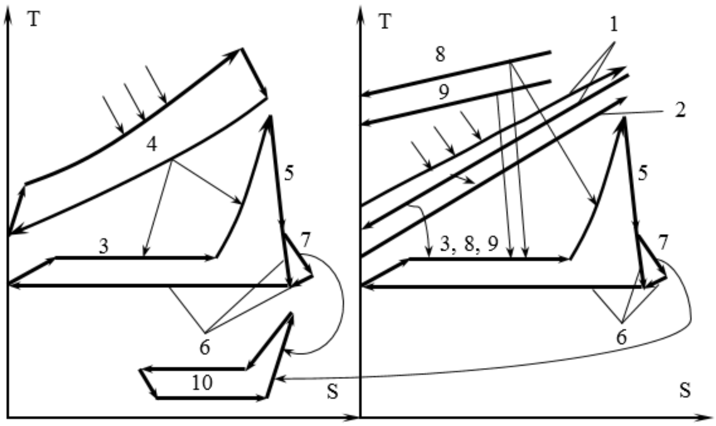
0 is the input parameters of systems; 1 – 6 is the nodes for calculating balances and performance indicators (1 material balance; 2 generation of heat RER; 3 thermal consumption OGCC; 4 water consumption; 5 generation in heat systems; 6 power generation)

Figure 3. Simulation algorithms: *a* is the designing optimal EWSS; *b* is the communication of modules for calculating and the characteristics of systems elements.

4. EWSS schematics for PTS elements

Using the developed IAP, we designed an optimal EWSS. Its schematics are provided in the RF patents for utility models and inventions no. 2652237, 164323, 118360, 157326, 149419, 138474 and 134993. Along with standard cogeneration equipment in combined cycle plants (CCGT), the developed schemes use a new unit - a unit used for decontamination of industrial waste and effluents (RU 2523906) via an injection torch (RU 135080).

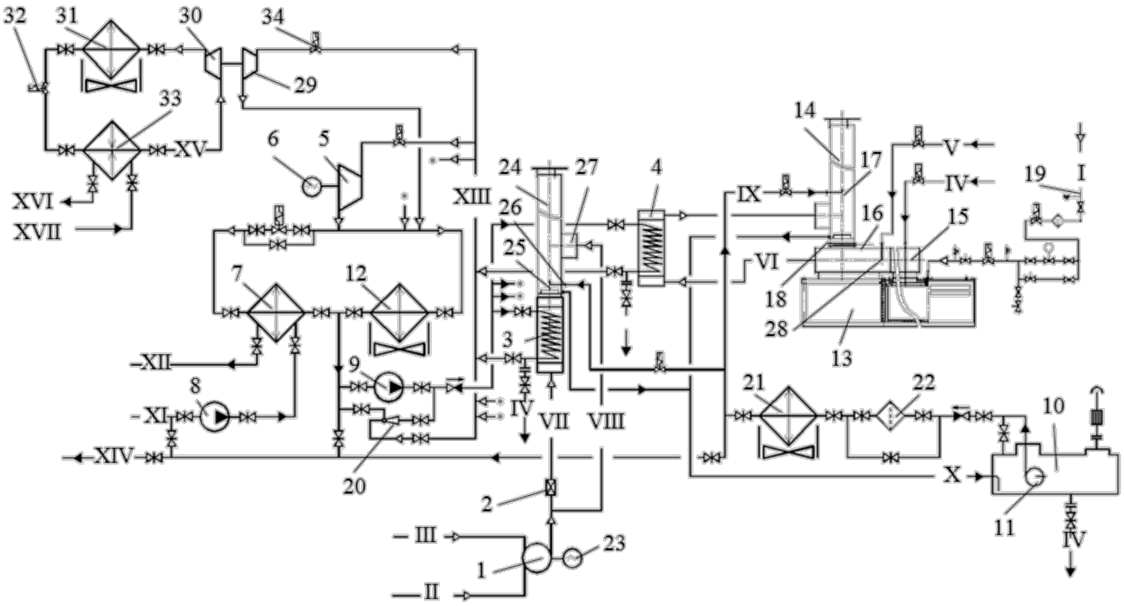
The principle of EWSS formation is shown in Figure 4 in the coordinates of temperature vs. entropy.



1–10 is the processes:
1 – utilization waste and effluent;
2 – utilization of the heat of the vapor-gas flow in the PTS aggregates;
3, 4, 5, 6 – thermal and electric energy generation at CCGT; 7, 10 – production cold in a compression refrigeration unit;
8, 9, 3, 5, 6 – production RER in an ETM and their utilization in a steam turbine installation with exhaust heat boilers

Figure 4. Processes in the multifunctional elements of EWSS.

One of the possible variations of the schematics of autonomous EWSS used as a part of a hydrocarbon processing enterprise is shown in Figure 5.



1 – gas turbine unit (GTU) – thermal engine; 2 – smoke gate; 3, 4 – exhaust heat boilers; 5 – steam extraction turbine; 6, 23 – electric power generators; 7 – condenser – heat exchanger; 8, 9, 11, 20 – pumps (8 – network circulation pump, 9, 11 – feed pumps, 20 – steam jet pump); 10 – condensed water de-aeration (de-carbonization) unit; 12, 21, 31 – air conditioning condensers; 13 – thermal neutralizer of industrial waste water; 14, 24 – smokestack; 15 – gas pipe; 16 – smoke gate; 17, 25 – nozzles; 18, 19, 26, 27 – branch pipes; 22 – filter; 28 – reagent input device; 29 – steam drive of compression refrigerator; 30 – compressor; 32 – thermal expansion valve; 33 – evaporator; 34 – steam flow regulator; I, II – I, II – fuel gas (hydrocarbon fuel); III – air; IV – industrial and utility wastes (effluents); V – reagent solution (for absorption of sulfur oxides); VI, VII, VIII – combustion gases; IX – water condensate; X – unpurified condensed waster steam; XI, XII – reverse and direct water flows of heat supply system; XIII – overheated steam; XIV – water flow going to utility water pre-processing unit; XV – cooling agent; XVI, XVII – cooled and heated coolant; * is the module connection

Figure 5. Scheme of a system of heat-, electric-, cold- and water supply and utilization of combustible waste and effluents.

A multicriteria analysis of the schematics developed with the help of IAP showed that introduction of multifunctional EWSSs in the composition of OGCC allows to reduce the consumption of electric power from EESS by 25–30% and water consumption from external systems by 16–19%. The volume of industrial emissions into the atmosphere and wastewater is also reduced (by 96–98%), while the reliability of energy supply and environmental safety are increased.

5. Conclusion

The developed enterprise information system, including its operating methods, software and databases of equipment and circuit solutions that can be used for energy generation, allows to perform hierarchical structuring of the OGCC, perform its structural and parametric optimization and conduct research work on the creation of promising EWSSs, and their multi-criteria assessment under the conditions of dynamic technological processes and partial uncertainty of economic factors. The obtained complex of technological and engineering solutions show that the main areas of improvement of the EWSS of OGCC include integration of process and power generation units and maximal utilization of the potential of industrial wastes and effluents to generate electric power, produce water and process the raw materials into final products.

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