Development Trends of Combined Heat and Power Production

E.A. Volkova, A.S. Makarova, A.A. Khorshev

The paper presents the results of the investigation of CHP efficiency in Russia made by ERIRAS. Local level estimations allowed us to unify the diversity of energy supply schemes and create a comparable system of cost-performance characteristics for heat and power production and distribution technologies. Based on these results, system-wide investigation of CHP efficiency is done on a basis of economic assessment and system-wide optimization of different types of CHP and boiler technologies affected by many local and system-based factors including also a payment for greenhouse gas emissions. This investigation resulted in evaluation of optimal scale and technological trends of CHP development in Russia to 2030.

Index Terms: **power industry, combined heat and power, efficiency, mathematical modeling, system-wide investigation, optimal scale, sustainable development trends**

1. INTRODUCTION

Radical changes of economic development and a reform of the electric power industry and heat supply management system over the last twenty years have drastically changed past conceptions about the areas of efficient Combined Heat and Power plants (CHP) use in Russia. Specifically strong impact can be produced by intensive development of advanced gas-fired technologies [1, 2], which in principle enable to extend areas of efficient use of CHP through involving combined-cycle units (CCGT) and gas turbines (GT), primarily, small ones. Another important factor contributing to development of gas-fired cogeneration is an implementation of active policy on restriction of greenhouse gases (GHG) emission by many countries.

A fundamental change of CHP development conditions and a need to take them into account in a number of strategic documents on developing electric power industry and fuel-energy complex (FEC) in Russia to 2030 have defined an extraordinary urgency of CHP efficiency investigation under new conditions. At this stage of investigations this problem is solved in a simplified definition with the following assumptions:

1) Investigation only deals with a pre-feasibility development stage of combined and separate heat and power supply schemes, when there is no information on a long-term demand growth for heat and power of specific cities and cost-performance characteristics of their heat and power supply from the certain energy sources.

2) All variety of factors affecting the efficiency of combined and separate heat and power supply schemes is arbitrary divided into two large classes (local and system-based) and they are investigated stage by stage (Fig. 1).

3) At the first stage [3] the problem is significantly narrowed through consideration only of a growing demand for heat by the housing and public services of the cities (including private households, commercial business, hotels, restaurants, health care and education establishments and “other needs”). In this respect, combined scheme efficiency is evaluated as applied to gas-fired CHP plants; the efficiency of coal-fired CHP is taken into consideration only partially, and the efficiency of nuclear CHP is not considered at all.

4) At the second stage [4] a system-wide investigation of CHP efficiency is carried out with regard to both local and system-based factors.

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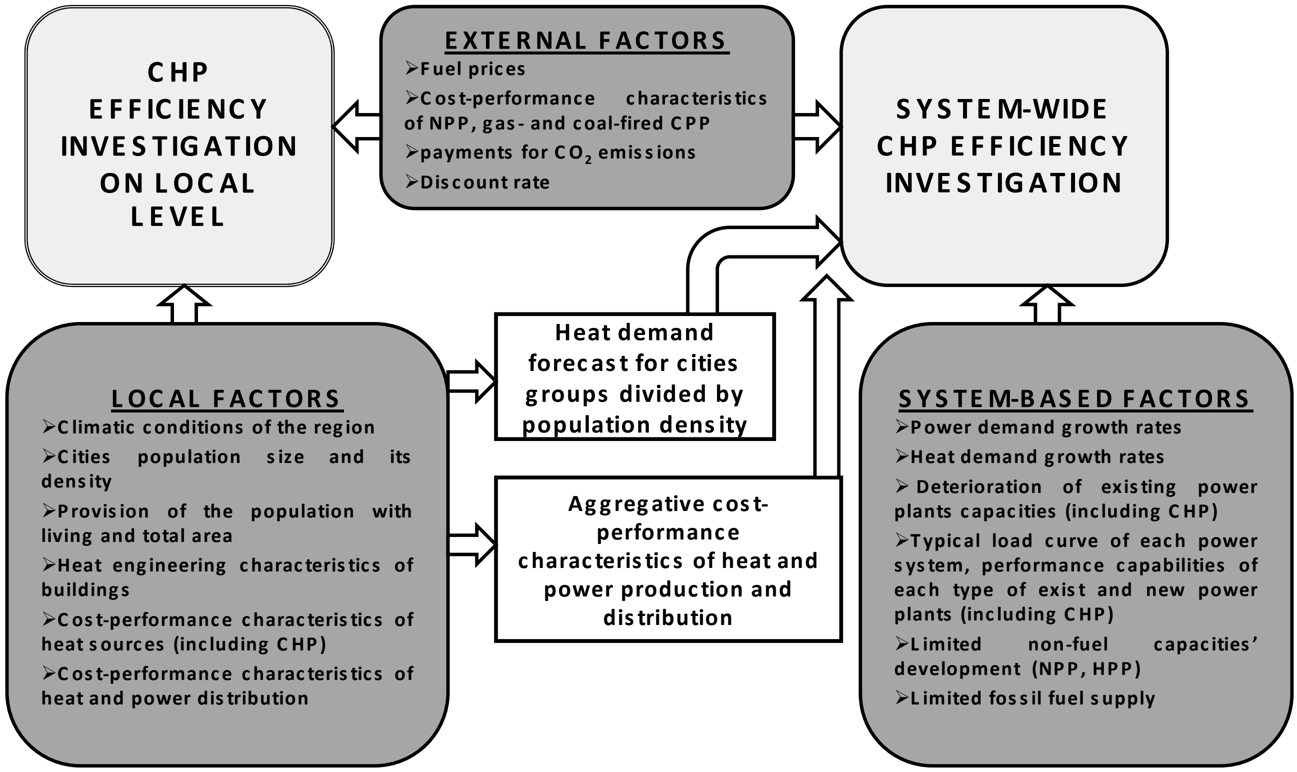


Fig. 1. General scheme of CHP efficiency investigation

II. CHP EFFICIENCY INVESTIGATION ON LOCAL LEVEL

The main purpose of this first stage is to obtain a unified description of a real variety of cities and their potential heat and power supply schemes using a small number of integrated characteristics.

A. The consumption of heat and electricity by cities' housing and public services is determined by the following integrated characteristics:

1) climatic conditions of the subject territory (Table 1) which is characterized by a reference outdoor temperature (t^{o}_{ref}), used in heating systems engineering, (by this parameter the country is divided into 5 zones: South – 20 ºC, Center – 25 ºC, Ural – 30 and - 35 ºC, Siberia – 40 ºC) and by duration of a heating season (by this parameter two representative regions are marked in each of the five climatic zones, Table 1 shows only one region in each zone).

2) rate of heat consumption per one citizen in each considered climatic zone depending on a variety of local factors, namely provision of the population with living and total area, number of floors and heat engineering characteristics of buildings (brick, panel buildings and others), etc. As seen from Table 1, hourly (and annual) rate of heat consumption can vary within a very wide range.

The identified ranges of hourly and annual rates of heat consumption are used to further determination of a total demand for heat by the housing and communal services of the cities with a different population size. In subsequent investigation a conventional city with a population of 100 thousand persons is considered as a basis in each climatic zone. The bigger cities are formed as a set of these 100-thousand "basic"cities (as districts).

B. Integrated characteristics of combined supply scheme heat and power production are determined for typical two-unit CHP of a different capacity (Table 2), which are split into three groups (small, medium and large). In a separate heat and power supply scheme large condensing power plants of a different type (nuclear power plants (NPP), gas-fired combined cycle plants (CCGT) and coal-fired power plants (Coal CPP)) (Table 2) and boiler-houses of a different capacity on gas and coal (Table 3) are considered.

TABLE 1

RATE OF HEAT CONSUMPTION*) FOR HEATING AND HOT-WATER SUPPLY

Reference outdoor temperature		**Provision with total area**					
		25 m² per person				30 m² per person	
		Building with 1-3 floors		Building with 4-10 floors		Building with 1-3 floors	Building with 4-10 floors
-20 °C	Volgograd region (Volga)	**3780 (10,1)**	1930 (5,5)	2120 (6,0)	**1650 (4,8)**	**2260 (6,3)**	1920 (5,5)
-25 °C	Bryansk region (Center)	**3930 (10,6)**	2060 (5,7)	2280 (6,3)	**1780 (5,0)**	**2410 (6,7)**	2070 (5,8)
-30 °C	Chelyabinsk region (Ural)	**4180 (12,5)**	2180 (6,7)	2400 (7,4)	**1930 (6,0)**	**2560 (7,8)**	2260 (7,0)
-35 °C	Tyumen region (North Ural)	**4430 (12,4)**	2340 (6,7)	2560 (7,3)	**2120 (6,1)**	**2750 (7,8)**	2480 (7,1)
-40 °C	Irkutsk region (Siberia)	**4590 (13,4)**	2460 (7.3)	2710 (8,0)	**2250 (6,7)**	**2900 (8,5)**	2630 (7,8)

** hourly – kcal per hour-person (annual – Gcal per year-person)*

To estimate the annual figures of heat production by different sources (CHP and boiler-houses) in a typical city of any climatic zone traditionally used annual heat load duration curves (Rossander curve).

TABLE 2 COST-PERFOMANCE CHARACTERISTICS OF TYPICAL TWO-UNIT CHP (at α_{CHP}=0,5), CPP AND NPP

Equipment type	**Installed electric power capacity, MW**	**Heat capacity, Gcal per hour**		**Overnight capital costs (OCC), dollars of 2007 per kW**
		Of two CHP units	Of total CHP plant*	
I. Small CHP				
GT-6+HRSG	2 * 6 = 12	12,5 * 2 = 25	50	1475 – 1620
GT-16+HRSG	2 * 16 = 32	21,5 * 2 = 43	86	1385 – 1520
CCGT-16 (2*GT-6+T-4)+HRSG	2 * 16 = 32	10 * 2 = 20	40	1675 – 1840
II. Medium CHP				
GT-25 + HRSG	2 * 25 = 50	33,8 * 2 = 67,6	135,2	1290 – 1415
CCGT-46 (2*GT-16+T-14)	2 * 46 = 92	32,2 * 2 = 64,4	128,8	1575 – 1730
CCGT-70 (2*GT-25+T-20)	2 * 70 = 140	50,7 * 2 = 101,4	202,8	1465 – 1610
III. Large CHP				
GT-110 + HRSG	2 * 110 = 220	149 * 2 = 298	596	990 – 1085
CCGT-450 (2*GT-150+T-150)	2 * 450 = 900	354 * 2 = 708	1416	1120 – 1230
Conventional steam turbine T-115-130	2 * 115 = 230	175 * 2 = 350	700	1790 – 1985
System-level CPP				
WWER-1150	1150 * 4 = 4600			2350 – 2600
CCGT-800	800 * 4 = 3200			1020 – 1120
Coal CHP K-660-300	660 * 4 = 3960			1890 – 2090
Coal CHP K-660-240	660 * 4 = 3960			1760 – 1945

** - including 50% of heat produced by heat peak boilers*

TABLE 3 COST-PERFOMANCE CHARACTERISTICS OF BOILER-HOUSES

Equipment type		Heat capacity, Gcal per hour	Overnight capital costs, dollars of 2007 per Gcal/hour
Gas-fired boiler-houses	GFMB-3	3	125 – 150
	GFMB-5	5	100 – 125
	GFMB-10	10	85 – 100
	GFB-20	20	64 – 85
	GFB-30	30	63 – 84
	GFB-50	50	55 – 73
	GFB-100	100	65 – 70
Coal-fired boiler-houses	CFB-3	3	150 – 210
	CFB-5	5	126 – 175
	CFB-10	10	102 – 140
	CFB-20	20	77 – 120
	CFB-30	30	76 – 100
	CFB-50	50	66 – 102

C. Integrated characteristics of heat distribution are determined as applied to the aggregated scheme of heat distribution from CHP or boiler-houses to a typical 1 km^2 district, which a conventional town with a population of 100 thousand persons is divided into (Fig. 2).

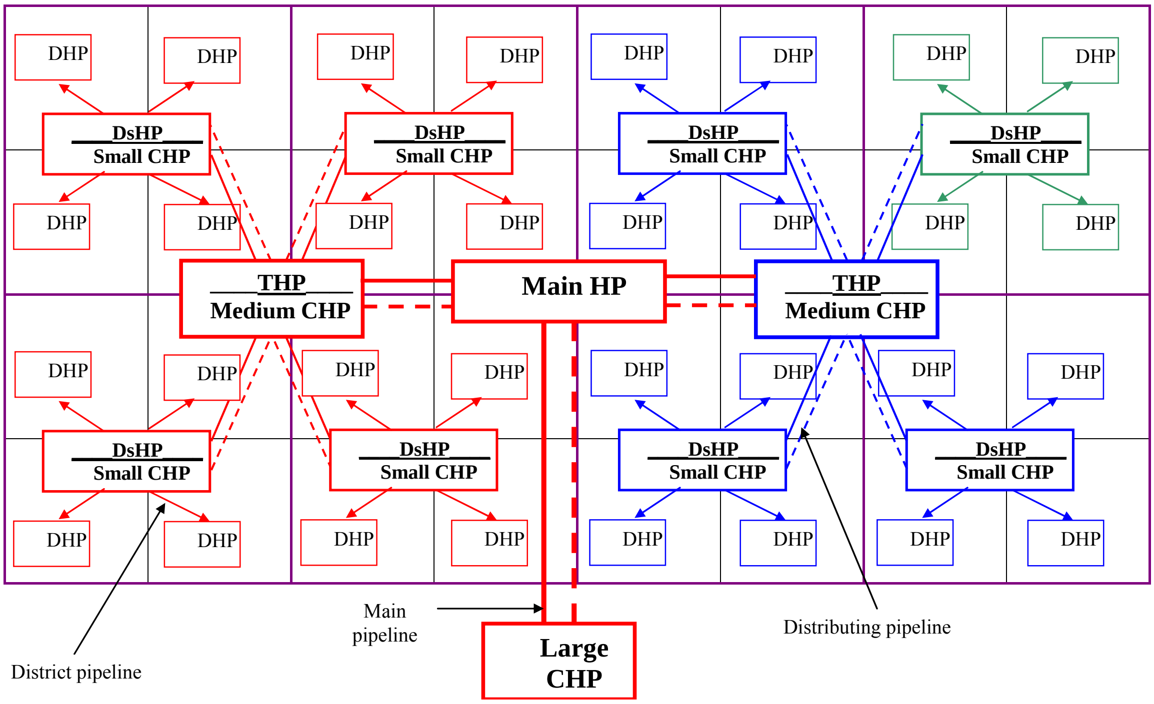


Fig. 2. Aggregated scheme of heat distribution from small, medium and large CHP.

In the scheme developing the following assumptions are taken:

– A district heat point (DHP) is considered to be a load center of each typical 1 km^2 district; heat distribution between separate buildings is not taken into account, as this distribution is similar in any supply scheme;

– A location of any heat source (CHP, boiler-house) relative to DHP is unambiguously defined by its capacity: the service area of small CHP is several neighboring districts considered as a small-size residential area; the service area of medium CHP is a set of small-size residential areas (through distributing heat points - DsHP) and a larger number of districts; large CHP are located outside the city at a distance of 1 - 3 km transferring heat via a high-capacity main pipe to the main heat point (MHP), and further to transit heat points (THP) placed instead of medium CHP.

– one-, two- and three-step heat distribution scheme corresponds to each of three groups of sources (divided by their capacity); herewith all heat pipelines except for the smallest (district) are duplicated for the reserve purposes (in Fig. 2 they are marked by a dash line).

In a separate heat and power supply scheme two options of boiler-houses location are considered: small boiler-houses are located directly in the middle of the district, where in a combined supply scheme a district heat point is located, and larger boiler-houses are situated in small and medium CHP locations (respectively DsHP and THP), equal them in heat supply and respectively in length and capacity of the heat network.

Selecting one of three potential heat distribution schemes, it is easy to determine not only an hourly demand of each 1 km^2 district, but also a number of CHP (or boiler-houses) of different capacity required to meet the typical city demands in heat, an area of the city and service area of each CHP (or boiler-house) of a different capacity, length, diameters and heat leakage in the pipelines.

The second purpose of the first stage is to prepare comparable aggregative cost-performance characteristics of heat and power production and distribution.

In the lack of real investment projects at the pre-feasibility stage we are restricted to use only aggregative cost-performance characteristics of heat and power production and distribution technologies. These characteristics shall take into account a predictable scientific and technological advance in power plants, heat and electric networks equipment. They also have to be comparable at least conventionally, i.e. expressed in same year prices and normalized to a similar project-implementation stage.

The scientific and technological advance in heat and power production and distribution in this paper corresponds to a Concept of heat supply development in Russia (including public utilities) for a medium-term perspective developed by the Ministry of Energy of the RF [7]. In combined heat and power production gas turbines and combined cycle plants with waste heat boilers are taken as a basis. For large-scale condensing power plants 800 MW CCGT, 660 MW coal-fired power plants with supercritical (SC) or ultrasupercritical (USC) steam units or NPP with WWER-1150 reactors are considered (optionally). Large gas-fired boilers (GFB) or coal-fired boilers (CFB) or smaller gas-fired module boilers (GFMB) are proposed to be installed in boiler-houses. For heat distribution underground channel-free laying of metallic pipelines with a foam polyurethane insulation is provided. For power distribution cable lines laying in a ditch and sulfurhexafluoride circuit breakers are used [8].

A forecast of overnight capital costs of various power plants types has been made in this paper based on the analysis of domestic projects and ratios [1] being permanently performed at ERIRAS, as well as based on the study of international data [2, 6]. Table 2 and Table 3 depict one of the recent versions of overnight capital costs of electric power plants and boiler-houses (given in dollars of 2007).

The cost-performance characteristics of heat and electric networks are taken based on expert evaluations of Russian specialists, namely of heat networks mainly based on evaluations by VNIPIenergoprom specialists, and of power networks in accordance with Standard of OAO RAO «UES of Russia» [8].

Based on aggregative cost-performance characteristics of heat and power production and distribution formulated in the paper for all unified heat and power supply schemes an economic evaluation of CHP overnight capital costs with required heat and power networks development in varying initial conditions was made. Fig. 3 demonstrates a function between the structure of overnight capital costs of heat and power production and distribution for three CHP groups (small, medium, large) and the main integrated factor, namely population density of a typical town. Its analysis shows an important role of a network component in these costs, specifically at a low population density (less than 2 thousand persons per km^2).

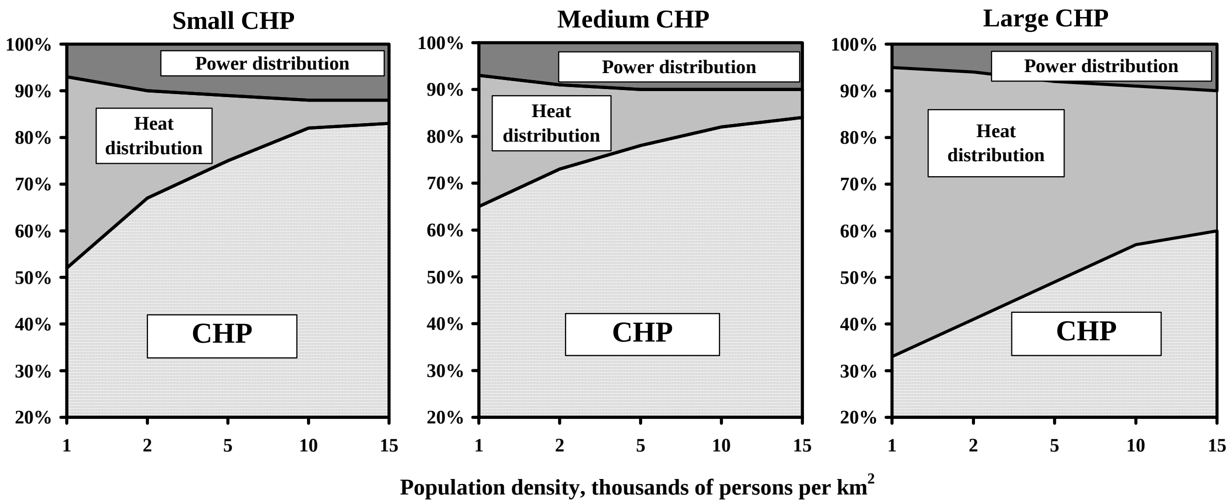


Fig. 3. Structure of overnight capital costs (%) of heat and power production and distribution from CHP

III. SYSTEM-WIDE CHP EFFICIENCY INVESTIGATION

For realization of the second stage of the investigation the following first stage results are necessary to provide:

- acceptable differentiation of heat consumption of all cities located in different administrative units of Russia into a small number of groups depending on the population density: the first group with less than 2 thousand persons per km^2, the second group with 2-10 thousand persons per km^2 and the third group with more than 10 thousand persons per km^2; this differentiation is provided based on the analysis of the report information on a population size and area of cities on the territory of each administrative unit;

- short-list of new CHP technologies including: small CHP (GT-6, CCGT-16 and T-25-90); medium CHP (GT-25 and CCGT-70); large CHP (GT-100, CCGT-450 and T-115-130);

- comparable aggregative cost-performance characteristics for each type of supply sources (CHP and boiler-houses) developed at the first investigation stage;

- account of heat and power networks development using additional overnight capital costs added to the ones of the unified types of CHP and boiler-houses (Fig. 3).

Along with the cost-performance characteristics of new different-type sources obtained at the first investigation stage, a great work has been done on typification and generation of aggregated characteristics of each type of the existing power plants, which are currently of a paramount importance in electric power industry and heat supply. In doing so, the whole set of existing CHP plants of each administrative unit has been aggregated into several typical groups depending on a type of fuel (gas, coal), type of the main equipment (steam turbine, gas turbine, combined cycle), steam pressure parameters (24 MPa, 13 MPa, 9 MPa and less) for steam power plants or depending on a size of units for gas turbine and combined cycle CHP.

The whole set of all these results has been used in doing a system-wide investigation of the combined heat and power efficiency affected by many local and system-based factors. The instrument of the system-wide investigation is a dynamic LP model of electric power industry within fuel-energy complex of the country development (EPOS) [5]. In this model a joint optimization of electric power and heat supply, gas coal industries' development is performed for the long-term period (to 2030) under the minimization of total discounted costs.

Making this model both complicated correlation of the electric power industry and heat supply system development with the development of economy and fuel sectors, and internal interrelations between the development and operation of electric power plants and electric networks, which are technologically combined into the power systems, are taken into account. Main system-based factors which having a stronger effect on the CHP efficiency are identified from this interlacing relations. Here they are: cumulative levels of energy consumption of the country and regional correlations between the dynamics of power and heat consumption; prices and resources of various fuels; dynamics of existing power plants' capacities, before their decommissioning; requirements of the consumers defining a configuration of typical load curve of each power system, performance capabilities of each type of power plants located in each power system; limits of inter-system capacity and electricity exchange via the existing power grid.

Commonly model EPOS [5] approximately accounting for all listed system-based factors makes it possible to identify: an optimal structure of power plants capacities and corresponding territorial placement of new electric power plants of a various type; annual electricity generation structure; fuel consumption for each year or stage of the period. This model has been modified by a significant heat supply block development based on the results of the first stage of the investigation.

The main purpose of the system-wide investigation of CHP efficiency by means of a modified version of model EPOS is not only to define an optimal scale and structure of CHP capacities (by their types), but also to evaluate an optimal fraction of CHP in a total installed capacity and a fraction of CHP in a total volume of centralized heat production in the country.

Similar system-wide investigation of the CHP efficiency using an optimization model has been performed within the correction of the «General plan of electric power stations allocation throughout 2020 regarding a perspective until 2030» (hereinafter referred to as «General plan») as applied to two baseline scenarios of developing power industry and fuel-energy complex of the country (Table 4).

TABLE 4 BRIEF CHARACTERISTIC OF BASELINE SCENARIOS OF DEVELOPING POWER INDUSTRY AND FUEL-ENERGY COMPLEX OF RUSSIA UNTIL 2030

	Units	Present	Power-efficient scenario					Innovative scenario				
		2008	**2010**	**2015**	**2020**	**2025**	**2030**	**2010**	**2015**	**2020**	**2025**	**2030**
Domestic electric consumption	TWh	1023	982	1122	1278	1420	1555	986	1162	1393	1622	1860
	to 2008	1,00	0,96	1,10	1,25	1,39	1,52	0,96	1,14	1,36	1,59	1,82
Domestic heat consumption	Pcal	1362	1329	1347	1415	1465	1505	1329	1350	1449	1534	1609
	to 2008	1,00	0,98	0,99	1,04	1,08	1,11	0,98	0,99	1,06	1,13	1,18
Domestic capacity requirements	GW	197	202	234	261	283	305	203	240	280	315	354
	to 2008	1,00	1,02	1,19	1,32	1,44	1,55	1,03	1,22	1,42	1,60	1,79
Gas price at west Russian border	dollars of 2007 per tce			123	156	172	186		139	171	191	208

A change of a total CHP capacity identified during the system-wide investigation in variation of levels of power and heat consumption of the country within a period until 2030 is shown in Figure 4a. From this figure it's obvious that optimum CHP capacity will significantly increase by 2030 as compared to the current status (2008): in a innovative scenario by 19 GW, and in a power-efficient scenario by 13 GW, i.e. by 23 and 15 % respectively. In this connection above all CHP capacity is increased in the Center Integrated Power System (IPS) (by 6,8-4,6 GW depending on the scenario), Ural (by 3,8-2,2 GW) and North-West (by 2,2-1,6 GW) IPS.

From Figure 4b it is obvious that in spite of the grounded growth of CHP capacity within a period until 2030, in each of the analyzed scenarios a clear trend of reducing a CHP fraction in a structure of power plants installed capacity is visible (by 7-10% by 2030 as compared to 2008) while increasing their share in a total heat production (by 3-4% by 2030 as compared to 2008). Substantially this trend is predetermined by electricity and heat consumption growth ratio in Russia over a period until 2030 (see Table 4): depending on the scenario electricity consumption will be increased by 1,82-1,52 times by 2030, while the heat consumption will be increased only by 1,18-1,11 times.

It is obvious that the key system-based factors considered below can contribute to or counteract a development of these trends. The factor analysis of their effect performed hereafter is aimed at sensitivity estimation of identified trends of changing a role of CHP in the long term until 2030.

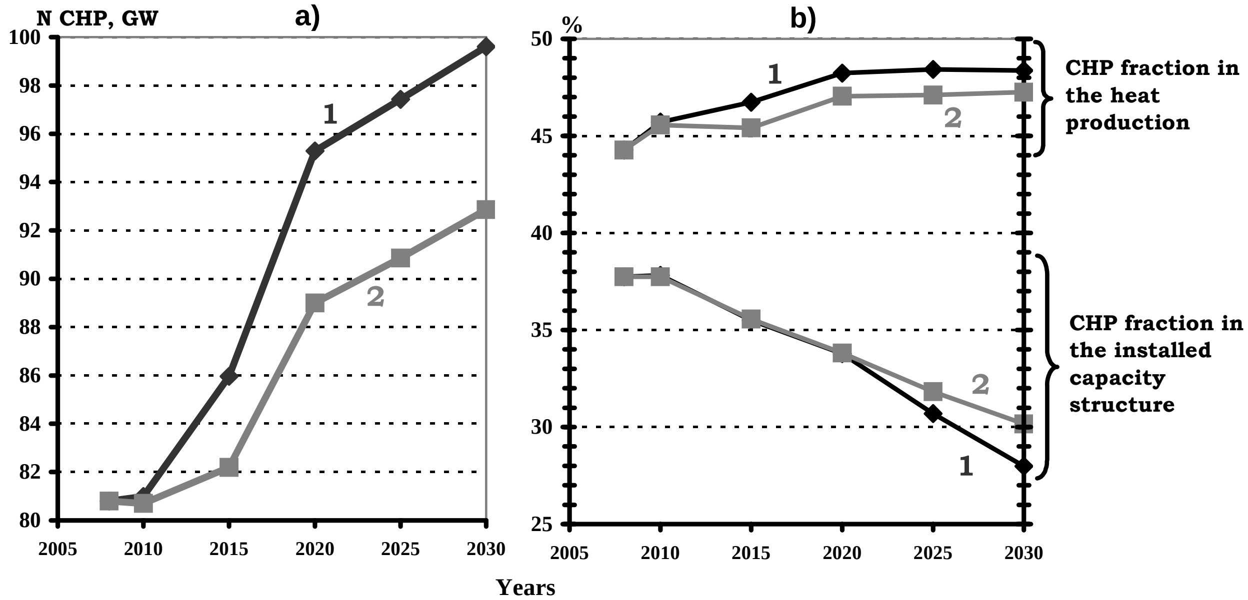


Fig. 4. a) Dynamics of optimal capacity of CHP in Russia; b) Variation of a CHP fraction in the installed capacity structure and in the heat production structure (1 - in a innovative scenario, 2 - in power-efficient scenario)

Being a flexible investigation tool the optimization model EPOS makes it possible to define a total amount and a structure of generating capacities (including CHP) and evaluate the efficiency of CHP in variation of the key system-based factors: 1) export gas price on the western border of Russia, which serves the basis for :net-back" domestic gas pricing; 2) ratio of overnight capital costs of large system-level power plants: NPP and coal-fired CPP; 3) overnight capital costs of new CHP and re-equipment of existing CHP plants; 4) payment for CO_2 emissions.

The impact of these factors on the efficiency of CHP is illustrated below by optimization results at a level of 2030 in an innovative scenario, in which all trends are expressed more explicitly as compared to the power-efficient scenario.

1) Level of export gas prices is one of the most uncertain factors affecting not only the CHP development scale but also the whole fuel-energy complex (Figure 5a).

2) Overnight capital costs ratio of new NPP and coal-fired CPP markedly affects the selection of a trailing power plant, and, therefore, the CHP efficiency in different regions of the country (Figure. 5b).

3) High overnight capital costs of new CHP (see Table 2) specifically with heat and power networks expenses are a serious limiting factor for augmenting the CHP development scales. As seen from Figure 6a, when reducing overnight capital costs of new CHP by 20% as compared to their basic values a total capacity of CHP (N_{CHP}) in 2030 is increased approximately by 12 GW. As opposed to new CHP a reduction of overnight capital costs in re-equipment of existing CHP does not lead to a significant growth of the total CHP capacities. However, as seen from Figure 6b, such reduction results in a serious modification of a CHP technological structure, related to an efficiency increase of replacing obsolete gas-fired steam turbines by modern CCGT and gas-turbine plants.

Along with the above «traditional» factors this investigation deals with another system-based factor, namely, payment for CO_2 emissions, which with regard to the results of International investigations [6] and ERIRAS experience varies in a very wide range from zero to 100 dollars per ton of CO_2 (Figure 7).

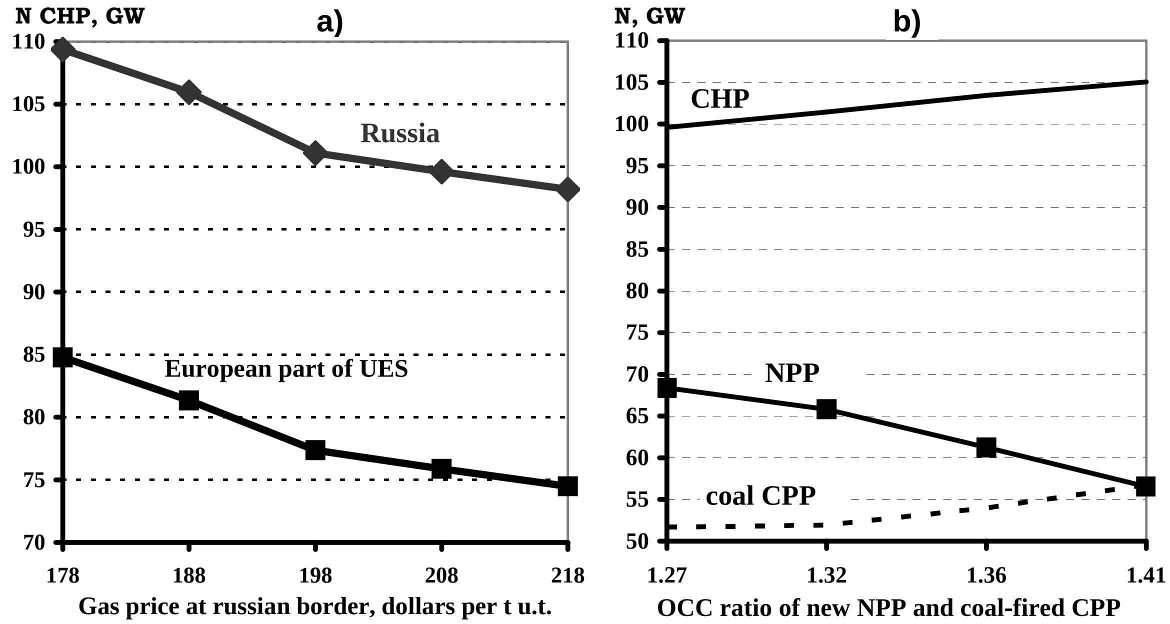
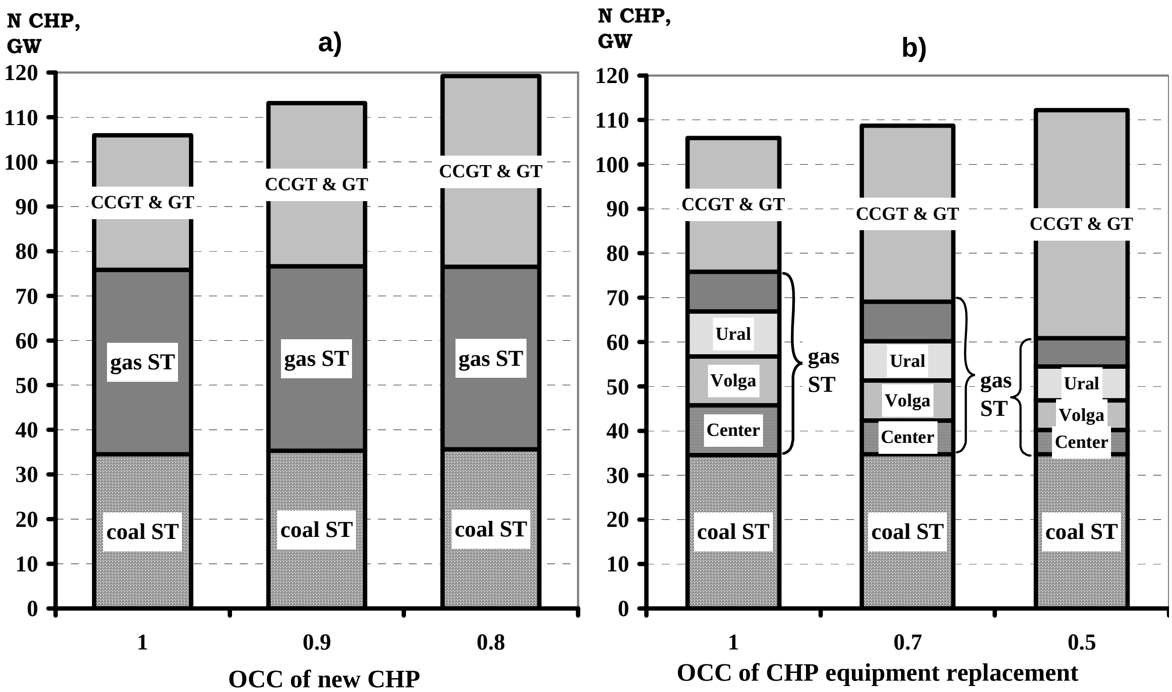


Fig. 5. Effect of a) export gas prices; b) overnight capital costs ratio of NPP and coal-fired CPP on a total CHP capacity in Russia (and European part of UES of Russia) in



2030.

Fig. 6. Effect of a) overnight capital costs (OCC) of new CHP and b) overnight capital costs (OCC) in equipment replacement of the active CHP on a total CHP capacity and their structure in Russia.

The optimization results demonstrated a strong effect of payment for CO_2 emissions on scales of CHP development and their structure. If the payment for CO_2 emissions increases, the main capacity gain of CHP falls on CCGT and GT. But the capacity of gas- and coal-fired steam turbine (ST) power plants steadily decreases, through their accelerated decommissioning (due to high fuel rate and, therefore, high specific CO_2 emissions of steam-turbine units).

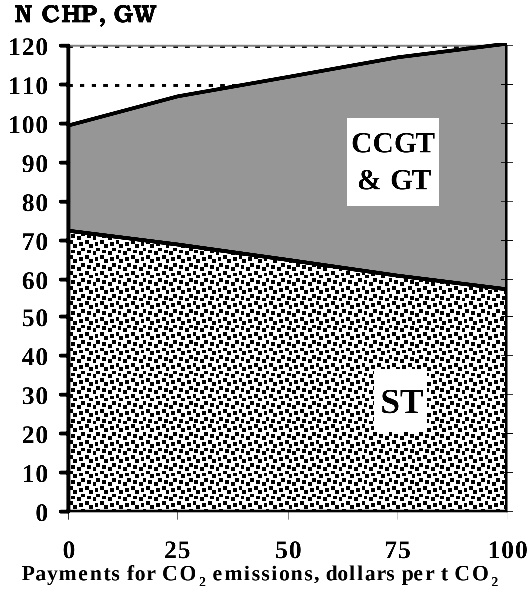


Fig. 7. Effect of payment for CO_2 emissions on CHP development scales and their structure in Russia.

As noted above, along with the CHP development scales significant integrated indices of CHP development efficiency is a dynamics of their share in the installed power plants capacity and in centralized heat production in Russia. Figure 8 shows a time change of these indices for the innovative scenario when exposed to «traditional» factors, and payments for CO_2 emissions. It is obvious from the Figure 8 that a variation of «traditional» factors and account of a moderate (25 dollars per t of CO_2) CO_2 emissions payment have a more strong effect on a CHP fraction in the heat production structure, as compared to the installed capacities structure: a CHP fraction in heat production at a level of 2030 can increase by 6 – 10% higher as compared to the present level, whereas the CHP fraction in the installed capacity of the country can be maximum varied by 3%, and anyway it will be significantly lower than the current one (2008).

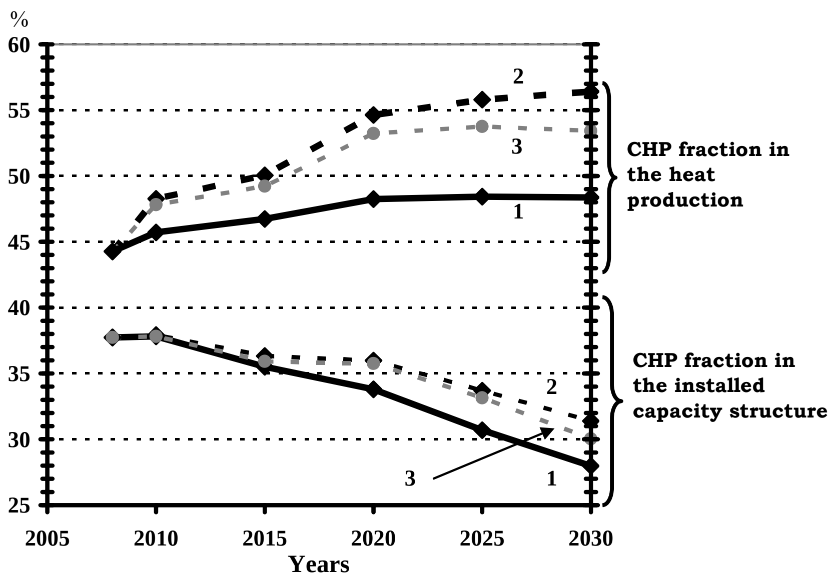


Fig. 8. A change of CHP fraction in the installed capacities and centralized heat production in Russia: 1 with basic values of affecting factors; 2 under effect of «traditional» factors; 3 under effect of a moderate (25 dollars per t) payment for CO_2 emissions.

IV. CONCLUSIONS

The investigation of the CHP efficiency made it possible to make a robust conclusion about the appropriateness of a further CHP development and of a CHP heat production growth in Russia within a period until 2030, primarily, through using advanced gas-turbine and CCGT units (including small ones). Alongside with that a stable trend of sequential reduction of CHP fraction in the generating capacities structure throughout the investigation period should be noted.

The conclusions about the CHP development efficiency in Russia in the long term until 2030 are tentative, as many aspects of CHP development (including the use of coal, nuclear and other technologies) are to be further investigated.

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VI. BIOGRAPHIES

Volkova Evgeniya Aronovna worked as leading scientist and the Head of the Lab (till 2007) at the Energy Research Institute of RAS, Moscow, Russia. She graduated from Moscow Engineering-Economic Institute in 1956 and was PhD in economics. Her major scientific interests were: analysis of major trends of scientific and technological advance in power industry and assess the extent of development of new technologies in technical renovation and new construction of energy facilities (including CHP), assessment of system-based effects from the implementation of investment projects, formation of balanced and network infrastructure development alternatives, placement of electric power facilities across the country.

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