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Involving 4th generation district heating technologies: residential buildings in remote areas of Russia

Involucrando tecnologías de calefacción distrital de 4ª generación: edificios residenciales en zonas remotas de Rusia

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ABSTRACT

This study aims to justify the possibility of expanding the energy and economic efficiency of a district heating [DH] system. The case study territory is a remote area of the Omsk region (Russia); the method is electric heating. To address this issue, we (1) considered the potential of modernizing these DH systems, (2) analyzed available options, (3) designed the main and auxiliary heat generation equipment, and (4) committed a feasibility study. The design heat consumption was 0.24 MW. To achieve this goal, we suggested two heat pumps; their capacity was 280 kW, and the investment required to install two heat pumps of 150 kW was 2.6 billion rubles. The total capital cost was 4.0 billion rubles. The annual effect after the heat pumps were installed was 0.7 billion rubles. The payback period was 5.6 years; to decrease it, one should install multiple heat pumps on the consumer side. The reason is to avoid heat distribution losses. Replacing traditional DH plants with electric boilers is feasible only if the cost of heat is 6,600 rubles per MWh or above. This cost has already been achieved for several DH plants. Ground source heat pumps are viable at lower prices, approximately 4,100 rubles per MWh. This option is especially helpful in remote areas of the Omsk region where the billing tariff is already high. When modernizing the heat supply infrastructure of the northern areas of the Omsk region, one can increase annual electricity consumption by 6%, decrease tariffs, and become more ecologically friendly at the same time.

Keywords: Heat, Energy, Pump, Demand, Electricity, Boiler, Substation

RESUMEN

Este estudio pretende justificar la posibilidad de ampliar la eficiencia energética y económica de un sistema de calefacción urbana [DH]. El territorio del estudio de caso es un área remota de la región de Omsk (Rusia); el método es calentamiento eléctrico. Para abordar este problema, (1) consideramos el potencial de modernizar estos sistemas de DH; (2) analizó las opciones disponibles; (3) diseñó el equipo de generación de calor principal y auxiliar; y (4) comprometió un estudio de factibilidad. El consumo de calor de diseño fue de 0,24 MW. Para lograr este objetivo, sugerimos dos bombas de calor; su capacidad era de 280 kW, y la inversión necesaria para instalar dos bombas de calor de 150 kW fue de 2.600 millones de rublos. El costo total de capital fue de 4.000 millones de rublos. El efecto anual después de la instalación de las bombas de calor fue de 700 millones de rublos. El período de recuperación fue de 5,6 años; para disminuirlo, se deben instalar múltiples bombas de calor en el lado del consumidor. La razón es evitar pérdidas de distribución de calor. Reemplazar las plantas de DH tradicionales con calderas eléctricas solo es factible si el costo del calor es de 6600 rublos por MWh o más. Este costo ya se ha logrado para varias plantas de DH. Las bombas de calor geotérmicas son viables a precios más bajos, aproximadamente 4100 rublos por MWh. Esta opción es especialmente útil en áreas remotas de la región de Omsk, donde la tarifa de facturación ya es alta. Al modernizar la infraestructura de suministro de calor de las áreas del norte de la región de Omsk, se puede aumentar el consumo anual de electricidad en un 6 %, reducir las tarifas y volverse más ecológico al mismo tiempo.

Palabras clave: calor, energía, bomba, demanda, electricidad, caldera, subestación.

1. INTRODUCTION

In any remote region, there are the same issues, which are as follows:

- Considerable emigration rate;
- High tariffs for utilities, especially in small settlements;
- Low heat and electricity availability.

The same problems exist in remote areas of the Omsk region where there is no gas or oil network connection. Nearby areas are supplied with commodities from Tyumen gas fields; however, some areas set high prices for fuel distribution.

Out-migration is another factor affecting power supply grids because of insufficient use of high-voltage transformers, while the part of the electric capacity selected for their own needs is the same. The way-out process was electric heating.

Typically, the use of electrical power is to overcome pressure losses in the network. In order to achieve this goal, a circulating pump is used to increase the water pressure and, therefore, ensure that hot water is delivered to the consumer’s substation at the appropriate mass flow rate and pressure (Harney, Gartland & Murphy, 2020). If 4th generation district heating [DH] technologies are applied, a heat pump utilizes waste heat sources with lower electricity consumption, and more electricity can be extracted from combined heat and power [CHP] plants (Averfalk & Werner, 2018). Most researchers assume no conversion between the three energy carriers (active electric, reactive electric, and heat powers) (Ayele, Haurant, Laumert & Lacarrière, 2018). However, if the energy systems covered by the CHP plants peak heat demand, which occurs during a period of high electricity prices, it can be helpful for the service provider since it can bring profit from increased electricity generation (Luc, Li, Xu & Nielsen, 2020). Moreover, there is usually no option to increase heat production in CHP plants owing to distribution losses or its availability. This fact also establishes new constraints for electricity production related to heat production. This situation influences the competitiveness of the system in the electricity market (Guelpa, 2021). These are typical assumptions in Estonia, Croatia, Poland, China, and Russia where the heating market never existed (Chicherin, 2020).

If no CHP plant is available (as in remote areas of Russia), the substations are connected to the power grid and equipped with an electric heater that can be turned on when it is necessary for the system. C. Saletti et al. (Saletti, Zimmerman, Morini & Kyprianidis, 2020) had the same view: We consider that the classical thermal-electrical analogy, typically exploited in heat transfer problems, should reveal the potential within the DH network. These measured data are also helpful for presenting the operational instability of a DH substation. Some studies (Chicherin, 2020) show that fluctuations in the network flow rate occur when the supply temperature is relatively high. Such variations may damage the hydraulic stability of the DH system, increase the electricity demand for pumping hot water, and reduce the life span of the regulation valves.

According to M. H. Kristensen et al. (Kristensen, Hedegaard & Petersen, 2020), most buildings in Denmark (83.5%) did not have auxiliary heating equipment reported and, therefore, depended solely on DH for both space heating [SH] and local domestic hot water preparation. The rest (16.5%) of the considered buildings are equipped with at least one additional heating device (e.g., heat pumps, electric radiators, oil-fired boilers, wood-burning stoves, etc.). Further consideration of the application of supplementary heating facilities in Denmark is presented in other works (Kristensen, Hedegaard & Petersen, 2020). Here, only buildings without auxiliary SH devices were specified for further study.

The results depend on hourly heat demand profiles. For the summer months, the obtained electricity production is equal for both systems. On the other hand, during the year, higher electricity production is obtained with SH consumption (although the delivered heat is produced with the help of the bleed steam from a CHP plant) (Barone, Buonomano, Forzano & Palombo, 2020). Fuel alternatives have also been considered. For instance, L. Björnebo et al. (Björnebo, Spatari & Gurian, 2018) have concluded that natural gas-based DH is dominated by the negative cost from electricity sales.

The research relevance lies in devising a list of options to enhance both availability and efficiency.

The contribution to the pool of knowledge is as follows:

- Analysis of the current socio-economic situation and performance indicators of the heat supply industry;
- Review of options to increase indicators with a particular focus on local conditions;
- Comparative study of heat production in existing DH plants given modernizing options and their potential payback period.

The paper is especially relevant according to the Program of Accelerated Industrial and Innovative Development started by Rosseti PJSC (Russia). The horizon of the program is 2025; it is supported by Russian legislation (Russian Federation, 2009) and is compatible with the provisions of the *Energy Strategy of the Russian Federation for the Period up to 2035* (Russian Federation, 2020).

2. MATERIALS AND METHODS

The study aims to develop a method to justify replacing traditional DH plants with electric heating.
The following tasks were accomplished to achieve this aim:

- The potential of modernizing the DH systems was considered;
- Available options were analyzed;

- Main and auxiliary heat generation equipment was designed;
- The feasibility study was committed.

The methodology includes (1) separating areas with and without an option to switch to gas supply, (2) analyzing the current socio-economic situation, (3) committing a statistical survey of primary energy consumption and performance indicators of the heat supply industry, (4) justifying the modernizing option, (5) listing the methods for calculating performance indicators, (6) solving questions about whether any changes are worth it or not, and (7) summarizing the total positive or negative effect.

There are several areas in the Omsk region where gas or oil supply is unavailable; they are depicted in Fig. 1.

Figure 1: Location of non-gasified municipal districts of the Omsk region: 1 – Ust-Ishimsky municipal district; 2 – Tevrizsky municipal district; 3 – Znamensky municipal district; 4–Tarsky municipal district; 5 – Bolsheukovsky municipal district; 6 – Kolosovsky municipal district; 7 – Muromtsevsky municipal district; and 8 – Sedelnikovo municipal district.

The current socio-economic situation is quite complicated and exacerbated by the out-migration of the population (Table 1) (Omsk Region, 2019).

Table 1: The population of the northern municipal districts of the Omsk region

Indicator	Period									
Muromtsevsky municipal district										
	2002	2009	2010	2011	2012	2013	2014	2015	2016	2017
Population	28,380	25,082	23,795	23,702	23,382	22,989	22,637	22,319	22,103	21,740
Annual change	-	-3,298	-1,287	-93	-320	-393	-352	-318	-216	-363
Sedelnikovo municipal district										
	2002	2009	2010	2011	2012	2013	2014	2015	2016	2017
Population	12,211	11,742	10,943	10,934	10,854	10,834	10,674	10,537	10,380	10,299
Annual change	-	-469	-799	-9	-80	-20	-160	-137	-157	-81
Tarsky municipal district										
	2002	2009	2010	2011	2012	2013	2014	2015	2016	2017
Population	-	-	46,650	46,542	46,456	46,083	45,834	45,682	45,424	45,145
Annual change	-	-	-	-108	-86	-373	-249	-152	-258	-279
Tevrizsky municipal district										
	2002	2009	2010	2011	2012	2013	2014	2015	2016	2017
Population	18,090	16,805	15,485	15,432	15,076	14,814	14,603	14,569	14,482	14,335
Annual change	-	-1,285	-1,320	-53	-356	-262	-211	-34	-87	-147
Ust-Ishimsky municipal district										
	2002	2009	2010	2011	2012	2013	2014	2015	2016	2017
Population	16,479	14,645	13,480	13,415	12,964	12,509	12,272	12,057	11,864	11,601
Annual change	-	-1,834	-1,165	-65	-451	-455	-237	-215	-193	-263
Znamensky municipal district										
	2002	2009	2010	2011	2012	2013	2014	2015	2016	2017
Population	13,876	13,257	12,427	12,380	12,150	12,012	11,854	11,654	11,518	11,475
Annual change	-	-619	-830	-47	-230	-138	-158	-200	-136	-43
Bolsheukovsky municipal district										
	2002	2009	2010	2011	2012	2013	2014	2015	2016	2017
Population	9,707	8,581	8,174	8,145	8,025	7,880	7,742	7,621	7,522	7,360
Annual change	-	-1,126	-407	-29	-120	-145	-138	-121	-99	-162
	2002	2009	2010	2011	2012	2013	2014	2015	2016	2017
Total population	-	-	130,954	130,550	128,907	127,121	125,616	124,439	123,293	121,955
Total annual change	-	-	-404	-1,643	-1,786	-1,505	-1,177	-1,146	-1,338	-404

There are no detailed statistical data on electricity consumption, although general information is available. The total consumption accounts for 10,900 billion kWh (Table 2).

Table 2: Statistical data on electricity consumption for the Omsk region (billion kWh)

Electricity demand	Year						
	2009	2010	2011	2012	2013	2014	2015
	10,184	10,392	10,480	10,902.4	10,888.1	10,992.5	10,880.8
	Year						
	2016	2017	2018	2019	2020 (forecast)	2021 (forecast)	2022 (forecast)
	10,862.4	10,806.9	11,015	10,681.2	10,136	10,959	11,255

Tables 1–2 show that the electricity consumption level is almost fixed. The reason for this is the increase in the regional center city, Omsk, while electricity consumption in remote areas tends to decrease. This

trend leads to an increase in operation and maintenance costs because part of the electric capacity, which is selected for one's own needs, is almost the same.

Several methods are available to overcome these limitations. To comprehend this, a close look at the fuel consumption can be helpful. This indicator depends on hourly and annual heat consumption and includes predicted and actual values of fuel demand, as well as tons of fuel equivalent. Within the given case study area, these facts are summarized in Table 3.

Table 3: Information on annual fuel consumption and heat production in the Omsk region

Area	Annual heat production, Gcal	Coal demand		Oil demand		Natural gas demand		Firewood demand	
		tons of fuel equivalent	%	tons of fuel equivalent	%	tons of fuel equivalent	%	tons of fuel equivalent	%
Ust-Ishimsky municipal district	42,936	6,359	76.93	0	0	0	0	1,907	23.07
Tevrizsky municipal district	46,775	6,391	71.58	441	4.94	187	2.09	1,857	20.80
Tarsky municipal district	184,905	14,976	46.68	12,116	37.77	1,427	4.45	3,541	11.04
Sedelnikovo municipal district	64,431	11,617	96.38	0	0	0	0	296	2.46
Muromtsevsky municipal district	97,332	17,966	98.36	0	0	0	0	299	1.64
Kolosovsky municipal district	65,950	12,176	95.45	0	0	0	0	580	4.55
Znamensky municipal district	63,742	11,457	95.87	0	0	0	0	340	2.84

The main methodological limitation is the appropriate design of an object under planned reconstruction, which affects the results and their integrity and veracity. The most relevant here is assumed to be an option that incorporates a heat pump as the main generation unit of a boiler plant. A heat plant ensures electricity savings because water is not directly heated, but energy is converted to utilize the hidden energy of a low-temperature source, for example, soil or natural water.

Given a seasonal coefficient of performance [COP] of 4.0 and an upper limit of the temperature of 45ºC, the predicted electricity demand is listed below.

3. RESULTS

Table 3 indicates that the main fuel for all heating technologies is coal, which is quite expensive in remote areas due to high transportation costs. Moreover, in the Tevrizsky and Tarsky districts, oil and natural gas from the Tevrizsky gas field are combusted; its key disadvantage is the interruption of supply from November to March every year. Since 2019, a state of emergency has been imposed every winter. The reason for that is accidents in the gas field; inhabitants have to use electric heaters or local boilers fed by liquified gas. This situation suggests a reconstruction in the heat supply industry and a fuel shift.

The total amount of energy considered when utilizing electric heating accounts is 566,000 Gcal or 657.8 billion kWh (6.5% of the total electricity demand in the Omsk region). The feasibility study is presented below.
Typical options to involve electric heating are as follows:

- Installing apartment heating, for instance, of the *Evan* type, which has already been installed in the Krasny Yar village in the Bolsherechye area of the Omsk region;
- Introducing individual electric heaters with oil inside, for example, in the Nadezhdino village in the Omsk area of the Omsk region.

The main limitation is the lack of SH in hallways, which may damage utilities. In addition, requirements to upgrade a power supply grid and a low-voltage switchboard also arise.

More advanced technical solutions include establishing a local boiler room to supply the entire building. The main idea is to apply electric boosters, increasing the temperature of the SH system or the DH network return line, as depicted in Fig. 3.

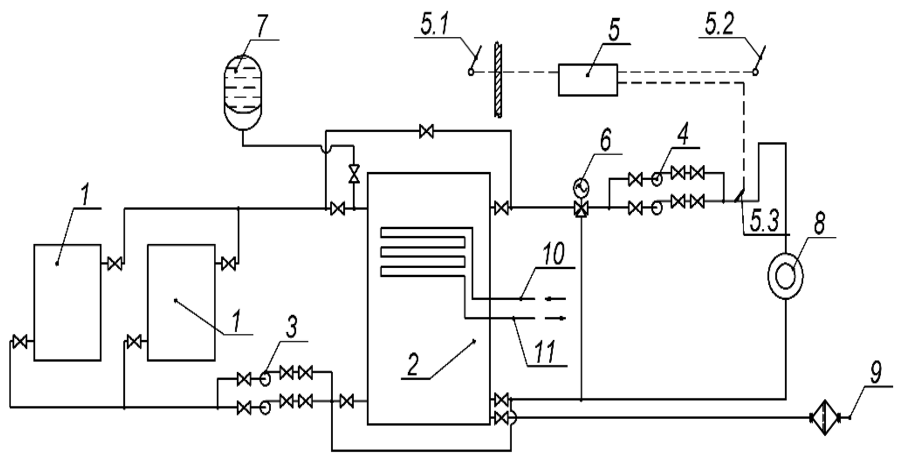

Figure 3: The layout of heating equipment within the boiler room for a residential house: 1 – electric boiler; 2 – hot water tank; 3 – primary side pump; 4 – SH system pump; 5 – electronic controller; 6 – regulating valve; and 7 – hot water expansion tank.

This system provides more secure services, but it is cost-intensive, which is not typical in small settlements. In addition, utilities can be combined (cold water + hot water), which is another urgent problem when severe weather comes, and hot water is not distributed.

Another option is to design a local DH plant housing an electric boiler to replace a traditional fossil fuel-based plant and install industrial (large) or domestic heat pumps inside a DH plant or residential buildings, respectively. The most effective heat pumps are typically ground or water sources.

A boiler plant in the Rozental village of the Moskalensky area of the Omsk region was studied to detail these ideas. The results are presented in Table 4.

Table 4: The results of studying the boiler plant located in the Rozental village

No.	Indicator	Value	Unit
1	2	3	4
1	Capacity	1.30	MW
2	Heat demand	0.24	MW
3	Power use	18.46	%
4	Annual heat production	578.35	MWh
5	Own needs	0	MWh

6	Distribution losses	196	MWh
7	Amount of heat charged to consumers	382.35	MWh
8	Fuel consumption	192.67	tons of equivalent
		264.3	tons
9	Electricity demand	21.47	10^3 kW·h
10	Coldwater demand	28	m^3
11	Primary energy prices	-	-
11.1	Coal	2,737.47	rubles/t
11.2	Electricity	4.63	rubles / kW·h
11.3	Coldwater	73.61	rubles / m^3
12	Total expenditure, including	2,267.64	thousand rubles
12.1	Fuel	723.51	thousand rubles
12.2	Electricity	99.36	thousand rubles
12.3	Coldwater	2.10	thousand rubles
12.4	Shift salary	516.00	thousand rubles
12.5	Engineering staff salary	155.84	thousand rubles
12.6	Operation and maintenance	44.52	thousand rubles
12.7	Depreciation	8.36	thousand rubles
12.8	Rent	93.53	thousand rubles
12.9	Facility costs	113.64	thousand rubles
12.10	Operational expenses	446.21	thousand rubles
12.11	Other direct costs	64.58	thousand rubles
13	Average production cost	5,930.80	rubles / MWh
14	Average tariff	4,020.81	rubles / MWh
15	Profit(+)/loss(-)	-730.28	thousand rubles per year

Table 5 presents the modeling results of the fuel shift according to Options 1, 2, and 3: (1) installing electric boilers only (given the current electricity tariff); (2) involving electric boilers and hot water tanks (given the night when a lower electricity rate is in effect); and (3) installing heat pumps (given the current electricity tariff). All options include reducing staff costs due to increasing the amount of automatized processes.

Table 5: The option study of the boiler plant located in the Rozental village

No.	Indicator	Option #1	Option #2	Option #3	Unit
4	Annual heat production	578.35	578.35	578.35	MWh
5	Own needs	0	0	0	MWh
6	Distribution losses	196	196	196	MWh
7	Amount of heat charged to consumers	382.35	382.35	382.35	MWh
8	Electricity demand (heat-generating units)	***679.30***	***679.30***	***169.82***	10^3 kW·h
9	Electricity demand (auxiliary equipment and pumps)	21.47	21.47	21.47	10^3 kW·h
10	Coldwater demand	28	28	28	m^3
11	Primary energy prices	-	-	-	-
11.2	Electricity	4.63	***2.59***	4.63	rubles / kW·h
11.3	Coldwater	73.61	73.61	73.61	rubles / m^3
12	Total expenditure, including	***3,921.53***	***2,453.20***	***1,562.67***	thousand rubles
12.1	Fuel	-	-	-	thousand rubles
12.2	Electricity	***3,244.51***	***1,858.74***	***885.65***	thousand rubles

12.3	Coldwater	2.10	2.10	2.10	thousand rubles
12.4	Shift salary	***180.00***	***180.00***	***180.00***	thousand rubles
12.5	Engineering staff salary	***54.36***	***54.36***	***54.36***	thousand rubles
12.6	Operation and maintenance	44.52	44.52	44.52	thousand rubles
12.7	Depreciation	8.36	8.36	8.36	thousand rubles
12.8	Rent	93.53	93.53	93.53	thousand rubles
12.9	Facility costs	36.71	36.71	36.71	thousand rubles
12.10	Operational expenses	192.87	36.71	36.71	thousand rubles
12.11	Other direct costs	64.58	64.58	64.58	thousand rubles
13	Average production cost	10,256.4	6,632.05	4,087.10	rubles / kW·h
14	Average tariff	4,020.81	4,020.81	4,020.81	rubles / kW·h
15	Profit(+)/loss(-)	- 2 384.1	-998.41	-25.31	thousand rubles per year

Table 5 presupposes that by installing a heat pump only, it is possible to decrease the annual costs by 705 thousand rubles. If hot water tanks are charged during the night when a lower electricity rate is in effect, there is no drastic change in the performance indicators of the DH heat-only boiler plant.

4. DISCUSSION

The design heat consumption is 0.24 MW, and two heat pumps of 150 kW are suggested to cover it; its type is *Ovanter*. This assessment method and the natural monopoly of DH networks usually result in consumers being locked in the agreement with the heat supplier without being able to appeal for price changes, as is the case in liberalized electricity and gas markets (Chicherin, Mašatin, Siirde & Volkova, 2020).

Capital costs to install two heat pumps (2x150 kW) are 2.6 billion rubles, while a ground source heat exchanger is the most expensive unit accounting for 0.8 billion rubles. Therefore, total investments, including the modernization of necessary equipment, are 4 billion rubles. According to G. Barone et al. (Barone, Buonomano, Forzano & Palombo, 2020), this result is due to the increased running hours of a CHP plant due to the decreased minimum selling price of the produced electricity (during these hours, the traditional reference system would be switched off because of economic inconvenience).

The annual effect is 0.705 billion rubles. Although L. Björnebo et al. believed so (Björnebo, Spatari & Gurian, 2018), it is much lower than the income from electricity gains and 2–4 times higher than that of the combined variable costs for both biomass and natural gas-based DH. Natural gas-based DH plants usually have higher income from electricity sales given initially more efficient combined-cycle CHP plants with a higher power-to-heat ratio.

In Europe, electricity prices are particularly high in winter. Similar to J. Fitó et al. (Fitó et al., 2020), our scenario is only viable if the benefits from selling waste heat could outweigh the higher costs of electricity consumption.

5. CONCLUSION

In summary, replacing traditional DH plants with electric boilers is only feasible if the cost of heat is 6,600 rubles per MWh or higher. This cost has already been achieved for several DH plants.

The contribution to the pool of knowledge suggests a methodology to assess the payback period by considering the ecological effect. Given the conditions of the case study, the payback period is 5.6 years. The practical relevance of this research lies in achieving energy conservation expressed in financial units.

For instance, if consumers start using decentralized heating solutions to minimize distribution losses, total expenditure will drop by 0.95 billion rubles per year (Table 5, Row 6). The methodological relevance of the research lies in improving the existing basis to provide a guide for the feasibility study of using ground-source heat pumps. Ground source heat pumps are feasible at lower prices, approximately 4,100 rubles per MWh. This option is exceptionally helpful in remote areas of the Omsk region where the billing rate is already high. New scientific insight is establishing a methodology to justify reconstructing DH heat-only boilers. When the heat supply infrastructure of the northern areas of the Omsk region is modernized, it is possible to increase annual electricity consumption by 6%, decrease tariffs, and become more ecologically friendly at the same time.

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