Energy Potential of Wastewater Sludge: Economic and Ecological Efficiency

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Abstract. Recently, many major cities in the world have faced a serious environmental problem caused by the presence of a large amount of waste and the established practice of their treatment. The paper presents an assessment of the energy potential of wastewater sludge (WWS) in the context of Novosibirsk city. According to our estimates, the total amount of generated semi-liquid WWS is about 132,000 tons per year, the theoretical energy output amounts to 67 GW per year, which is more than three times the total heat produced by small boiler plants in the region. Chemical compositions of WWS and stone/brown coals differ slightly. WWS contains 24.5% less carbon than coal and 5% less carbon than brown coal. The proportion of sulfur in WWS exceeds its specific content in coal by only 0.2% and in brown coal – by 4%. Seven alternative wastewater sludge utilization options have been developed, based both on new non-traditional waste incineration technologies and on finished turnkey technologies. WWS utilization options are evaluated in terms of economic efficiency, energy value, and environmental impact. The efficient option is the one associated with the utilization of WWS based on combustion with coal in a thermal power plant.

1. Introduction

The major problem and the basic direction of power policy at present is energy-wise efficiency development that will allow reducing essentially consumption of power resources, raising power safety of the country, and at the same time reduce the environmental load. These issues have gained the greatest importance in connection with the signing of the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol.

Wastewater treatment is an inevitable part of the lifestyle and the structural organization of society in industrialized countries of the world.

Municipal sewage sludge is a specific type of waste that is generated in everyday life, during work and leisure activities, as well as in industrial processes. Sewage sludge refers to the residual, semi-solid waste that is originated as a by-product during the wastewater treatment process. It is important to note that the wastewater facility operations can be easily accessible by representatives of the professional community and the general public.

For more than 30 years scientists have been exploring methods for both disposal and utilization of wastewater sludge (WWS) as an energy resource. One method of WWS disposal that is growing in popularity is incineration. Currently, incineration is the third most popular method for dealing with WWS (10.8%). This method allows resolving ecological problems associated with WWS storage, increasing the energy production, reducing consumption of fossil fuels and investments.
current predictions, the application of the incineration method of disposal is expected to grow to 40% despite its high cost.

The present research focuses on urban wastewater treatment. The study evaluates the economic feasibility of using WWS as an energy-generating fuel source in the context of Novosibirsk city. The municipal wastewater treatment plant (WWTP) treats more than 800,000 m$^3$/day of wastewater. Only 30% of humid waste is treated using a centrifugal press, which produces more than 125 tones of sludge cake (dry weight) per day. This sludge cake has 15.8 MJ/kg calories, which is comparable to the lignite coal of the Kansk-Achinsk Coal Reservoir. The sludge cake is stored in open areas outside the city. Currently, this waste amounts to one million tons of solid material, which is a biohazard.

According to our estimates, the total quantity of generated semi-fluid sludge is about 132,000 tons per year. The usage of this quantity of waste yields a theoretical energy output of 67,000 MW per year. This energy leads to savings of 77,400 tons of coal per year.

The utilization of the WWS in the amount of million tons, accumulated in the city, can theoretically yield about 1,090,000 MW of potential energy.

The present work explores several possibilities for WWS utilization at the Novosibirsk WWTP. Different options are compared in terms of technological and economical feasibility, energy generation potential, and environmental impact. The applied method is based on the net present value (NPV), internal rate of return (IRR), and payback period (PBP), which is calculated using cash flow sheets.

2. Current trends in energy policy development
At present, 76% of the world’s energy is generated using fossil fuels (24% of coal, 33% of oil, and 19% of gas), and only 19% – using renewable power resources (RPR) - water power and biomass energy [1] (figure 1).

![Figure 1. Structure of world energy production, %.

2.1. Environmental Issues
It is necessary to note, that coal is the cheapest fossil fuel for energy generation, it is also the dirtiest fuel. Coal contributes to the highest levels of pollutants into the air in comparison with oil and gas [2] (table 1).
Table 1. Fossil Fuel Emission Levels

| Pollutant          | Gas (natural) | Oil       | Coal       | Coal/Oil | Coal/Gas |
|--------------------|---------------|-----------|------------|----------|----------|
|                    | Pounds per Billion Btu of Energy Input | Comparison in % |
| Carbon Dioxide     | 117,000       | 164,000   | 208,000    | 126.8    | 177.8    |
| Carbon Monoxide    | 40            | 33        | 208        | 630.3    | 520.0    |
| Nitrogen Oxides    | 92            | 448       | 457        | 102.0    | 496.7    |
| Sulfur Dioxide     | 1             | 1,122     | 2,591      | 230.9    | 259.1    |
| Particulates       | 7             | 84        | 2,744      | 3.3      | 39.2     |
| Mercury            | 0.00001       | 0.007     | 0.016      | 228.6    | 160,000  |

For example, coal contributes 259.1% more sulfur dioxide in comparison with gas, 230.9% more in comparison with oil, as well as other pollutants. In comparison with other energy resources, coal produces more sulfur dioxide; 0.2–7% compared with black oil at 0.5-4.0%, diesel fuel at 0.3-0.9%, and natural gas with only an insignificant share [3].

The World Energy Council (WEC) estimates that the annual consumption of primary energy in the world will increase in comparison with the present time by 50-70% by 2020, and nearly five times by 2100 assuming that the growth rate is 2-3% per year. Under these conditions the influence of the world’s fuel and energy balance (FEB) on the environment will be the following [4]:

- CO₂ emissions into the atmosphere will triple;
- CO₂ concentration in the atmosphere will double;
- global environmental problems will appear.

In this respect, it makes a lot more sense to use environmentally friendly RPR (fuel cells, solar, wind, hydro, geothermal, biomass, WWS, etc.) as energy resources. Use of RPR releases very small amounts of sulfur dioxide and nitrogen oxides, virtually no ash or particulate matter, and none or lower net levels of carbon dioxide, carbon monoxide, and other reactive hydrocarbons.

In the countries of the European Union (EU), about 3% of total electric energy is generated by renewable power resources. When broken down by country, RPR is as follows: Finland, 9.2%; Austria, 8.7%; Denmark, 6.3%; Sweden, 5.3%; France, 2.2%; and Great Britain, 0.7%. One of the long term purposes of world energy policy is to increase the share of RPR in the FEB. Among the EU countries, growth in the use of RPR is about 6% now and planned to be 12% in 2010 [5].

The main idea of the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol is long term global power development focused on:

- creating know-how and energy production technology with little environmental impact;
- reducing consumption of «dirty» energy resources (ER);
- searching for and using new non polluting ER (fuel cells, solar, wind, hydro, geothermal, etc.);
- ensuring effective utilization of RPR (biomass, sewage sludge, etc.).

To protect the environment in the 21st century, the development of the energy industry must include ecologically clean and energy-saving alternative energy technologies that do not require mineral fossil fuels. Examples of these include fuel cells, solar and hydrogen power installations, and the waste (biomass, sewage sludge, etc.) utilization.

In this connection, we have studied the experience of European countries in utilizing sewage sludge and identified emerging theoretical and practical approaches for this utilization.
2.2. *The European experience in utilizing wastewater sludge*

At the beginning of the 21st century, the amount of semi-liquid sludge was more than 7 million tons (dry weight). Following the European Water Association (Group on Sewage) forecast, this amount will double by 2010. Other forecasts, for example, of the Committee of EU, predict more moderate growth.

In 2015, the European Commission adopted an ambitious Circular Economy Action Plan, which establishes a concrete and ambitious action plan, with measures covering the whole cycle: from production and consumption to waste management and the market for secondary raw material, as well as a revised legislative proposal on waste. These proposed activities will contribute to “closing the loop”: Through the redesign of production and consumption lifecycles making profit for both the economy and the environment [6-8].

Annual sewage sludge generation is presented in Table 2 in million tons of dry matter per year (mtDM/year) [9].

**Table 2. Annual sewage sludge generation statistics**

| No | Country             | Sewage Sludge, mtDM/year | References |
|----|---------------------|--------------------------|------------|
| 1  | EU                  | 13.5                     | [10]       |
| 2  | Germany             | 1.821                    | [10]       |
| 3  | Poland              | 0.568                    | [10]       |
| 4  | China               | 6.25                     | [11]       |
| 5  | USA                 | 12.56                    | [12]       |
| 6  | Russian Federation  | 2.5                      | [13]       |
| 7  | Japan               | 2.4                      | [14]       |

Sewage sludge is expected to remain a permanent waste problem requiring an appropriate solution. European countries have been actively exploring methods of wastewater sludge utilization as an energy resource for more than 30 years [15]. Figure 2 shows this experience in 12 European countries.

The most popular technology was the use of WWS as fertilizers in farming. The share of this technology varies from 10% in Greece to 58% in France, with an average of 36%. This method is losing attractiveness, because of the dangers associated with the accumulation of harmful elements in the soil. At present, several countries have forbidden waste utilization in agriculture, for instance, the Netherlands (since 1995).

The disposition of the largest quantity of waste in 2000, 41.5%, was waste storage. This method demands a lot of land for storage in many countries. The third most common disposition was disposal by incineration, accounting for 10.8% of the total.
Figure 2. Methods of sewage sludge utilization in the European countries in 2000, %.

The dynamics of sewage sludge utilization methods in 12 European countries is shown in Figure 3.

Figure 3. Dynamics of sewage sludge disposition methods in 12 European countries, thousand tons/year.
The share of waste storage decreased from 50% in 1992 to 17 % in 2005. The share of incineration increased from 15% in 1992 to 40% in 2005 despite its high cost. Incineration solves the ecological problems connected with WWS storage and can increase energy production, reducing the consumption of fossil fuels and investments.

So, the basic advantages to use of WWS for energy generation are the following:

- mineral fuels (coal, oil, and natural gas) can be partially replaced by WWS;
- environmental problems connected with waste storage can be solved;
- the effective utilization of waste will lower pollution of the environment.

WWS can be used for generating energy at coal fuel power plants (CFPP) as a supplement to fossil fuel, for example.

2.3. Technologies of wastewater sludge incineration
The prevailing technologies for WWS incineration in Europe are:
- I. Separate burning (burning in a liquid boiling bed and multistage furnaces);
- II. Combined burning at CFPP or cement and asphalt factories.

Germany has accumulated the greatest amount of theoretical and practical knowledge and experience regarding the combined burning of WWS. There are two power stations where WWS has been used constantly as a fuel component and co-fired with coal. At other facilities, similar tests of technical, economical, and ecological factors are being done. In most cases, such studies have been conducted at coal power stations. This specific work is being performed at modern lignite-fired stations (for example, Schwarz-Pump station with a capacity of 700 MW). Serious research was also performed by companies, such as Steinmuller and Babcock, and also the VGB technical association of energy plant operators.

Research has shown that combined burning of WWS and coal in available CFPPs is an ecologically and economically sustainable alternative to separate burning. Thus, emissions depend on their percentage parity in a mix. With the restriction of the maximum percentage of waste in the fuel at 10%, the effect on emissions is generally insignificant. Emissions of SO₂ are in direct dependence on the quantities of sulfur in the waste and the coal. In most cases, combined burning of WWS and coal is possible without significant changes in the technical equipment (a type of furnaces, boiler, and gas purification system). The only changes needed are modifications to mix the coal with WWS.

Another effective method of WWS utilization is its use as fuel in the manufacture of cement and asphalt. Research at one cement works in Switzerland, having productivity of 1,500 tons straight cement per day, has shown that wastewater sludge can be used successfully as both the core and additional fuel.

The temperature of combustion in the furnace (up to 2500 °C) and the long residence time for the combustion gases (up to 8 seconds at temperatures above 1000 °C) leads to all organic elements being completely burned. The chemical composition of the raw material for the manufacture of cement is changed slightly compared to that prepared using conventional fuel sources. This raw material can replace up to 50-60% of conventional cement raw material per ton of dry material. At such levels, there is no significant increase in SO₂ emissions or heavy metal emissions, a decrease in emissions of NOₓ to 85%, and a doubling of emissions of CO.

Combined burning of WWS at cement and asphalt plants in Russia is currently at the stage of research and design testing. A successful example is the combined burning technology practiced at WWTP Zurich since 1994. The general annual energy potential of WWS in the European countries from burning at cement works is estimated to be of the order of 30 thousand TOE (WEC Standard Energy Units, 1 tonne of oil equivalent, = 42 GJ (net calorific value), = 10 034 Mcal) and at asphalt plants – of the order of 250 thousand TOE. Some of the technologies for burning WWS can only apply to dry waste. Thus, lamellar dryers and rotating dryers with indirect heating which are intended for removal of moisture and manufacture of hygienic odorless granules, are used.
3. Municipal WWS as energy resource (as exemplified by the city of Novosibirsk, Russia)

3.1. Description of the municipal wastewater treatment system
The study evaluates the economic efficiency of using municipal WWS as a fuel resource at a CFPP. This research focuses on wastewater treatment in the Russian city of Novosibirsk (figure 4).

![Figure 4. The map of Russia](image_url)

Novosibirsk is the third-largest city in Russia after Moscow and St. Petersburg. It is situated in the middle of Russia, in the Southwest of Siberia. The city lies on both banks of the Ob River. It occupies an area of 477.2 square kilometers and has a population of about 1.5 million people. The climate is sharply continental with very cold and snowy winters and hot and dry summers. The difference between the highest and lowest temperatures is can reach 88°C.

Industrial and household wastewater (sewage) effluent in Novosibirsk is treated at the municipal WWTP located at the distance of 25 km from the city on the bank of the Ob River. It treats over 800,000 m³/day of wastewater; about 70% is residential in origin while the other 30% is an industrial waste [16]. First, sewage gets to a pumping plant, then to collectors for biological filtration, and then clean water is disposed to the river. Only 30% of humid waste is treated using centrifugal machines. This produces more than 125 tones/per day of sludge cake (dry weight). This sludge cake has 65% water content and 15.8 MJ/kg energy, which is comparable to lignite coal deposited from in the Kuzbass Coal Reservoir.

3.2. Environmental aspects of sewage treatment residue utilization
The present situation represents a serious problem for the Novosibirsk Region, which can later lead to an environmental catastrophe. The main environmental issues of Novosibirsk are as follows.

- one million tones of solid sludge are stored outside the city;
- the storage ground is being used up rapidly and if the sludge is not disposed of in some other way another disposal site must be found;
- there is a risk of the Ob River becoming contaminated by spring run-off water from the site which could affect the drinking water quality downstream of the site.

It also represents a biological hazard. As an alternative to disposal, the sludge could be utilized as a fuel for energy generation.
The contents of heavy metals in the WWS of the Novosibirsk Region is within the limits of the West-European recommendations [17] (table 3).

**Table 3.** The contents of heavy metals in the WWS of the Novosibirsk WWTP, mg/10⁻³ TOE/

| Metal          | The maintenance of metal in waste | Recommendations |
|----------------|-----------------------------------|-----------------|
|                | average | maximal | minimal | West-European | Germany |
| Silver         | 30.85   | 49.0     | 5.5     | –              | –       |
| Cadmium        | 31.49   | 57.0     | 3.4     | 20–40          | 10/5    |
| Cobalt         | 14.94   | 18.0     | 6.4     | –              | –       |
| Chrome 3-valent| 1,678.0 | 1,845.0  | 427.0   | 1,000–1,500    | 900     |
| Copper         | …       | …        | …       | 1,000–1,750    | 800     |
| Zinc           | …       | …        | …       | 2,500–4,000    | 2,500/2,000 |

However, the presence of heavy metal makes use of this WWS as fertilizers inadmissible.

Comparison by the chemical composition of the ash resulting from the combustion of Novosibirsk municipal WWS, coals, and lignite shows that their elements differ very little (table 4).

Sewage sludge (6.2% moisture) contains 24.5% less carbon than black coal (12% moisture), and 5% less than lignite (39% moisture). The share of sulfur exceeds its relative density in black coal by only 0.2%, and in lignite by 0.4%. Nitrogen content in sewage sludge approximately matches that of black coal and exceeds that in lignite by 2%.

The chemical composition of the ash from the combustion of the Novosibirsk WWS makes it possible to utilize it in road construction and as additional material in cement production.

3.3. Possible options for sewage sludge utilization

We considered seven alternative options for WWS disposal based on both new nontraditional technologies developed through practical experience in Europe and Russia and complete turnkey technologies.

Russian technologies of burning in a cyclone furnace:

I. Burning in a cyclone furnace based on existing but not utilized drum boilers of driers at wastewater purification plants («Tekhenerogokhimprom»);

II. Burning in a cyclone furnace based on existing but not utilized drum boilers at wastewater purification plants («Sibtekhenergo», Novosibirsk and «Biiskenergomash»);
Table 4. The chemical compound of ashes, %.

| Fraction | Novosibirsk WWS | Novosibirsk region | Coal Anthracite (lignite) | Kuzbass region1 | Kuzbass region 2 |
|----------|-----------------|--------------------|--------------------------|-----------------|------------------|
| SiO₂     | 56.2            | 58.0               | 66.9                     | 60.7            | 47.0             |
| Al₂O₃    | 12.4            | 27.4               | 23.0                     | 22.5            | 31.5             |
| Fe₂O₃    | 6.0             | 7.2                | 4.1                      | 9.7             | 15.2             |
| TiO₂     | 1.8             | –                  | –                        | –               | –                |
| CaO      | 6.4             | 2.1                | 0.8                      | 2.2             | 1.5              |
| MgO      | 4.5             | 1.8                | 1.0                      | 0.6             | 0.6              |
| SO₃      | 2.7             | 2.9                | 3.1                      | –               | –                |
| Na₂O     | –               | 0.3                | 0.9                      | 0.6             | 0.4              |
| K₂O      | –               | 2.0                | 2.7                      | 2.1             | 1.7              |
| P₂O₅     | 4.5             | –                  | –                        | –               | –                |
| MnO      | 0.3             | –                  | –                        | –               | –                |

European technologies of separate burning:
III. Separate burning in a new type multistage furnace (NESA, Belgium);
IV. Separate burning in a new type boiling bed furnace (Segher, Belgium);
V. Separate burning in a new cyclone furnace (Steinmuller, Germany);
Combined burning and other:
VI. Combined burning at the coal fuel power plant (CFPP) (Novosibirsk, Russia);
VII. Storage of dried waste sludge in a depositary located near the municipal WWTP.

4. Analysis and economic evaluation of various options for WWS disposals (as exemplified by the city of Novosibirsk, Russia)

4.1. Economic estimation of the options considered
Different options are compared with regards to technological and economic feasibility, energy generation potential, and environmental impact. The applied method is based on the net present value, internal rate of return, and payback period, which are calculated using cash flow sheets. This method allows for multivariate factor analysis [18].

The analysis was based on data from environmental and economic accountings of 2005 as well as personal communications with WWTP staff. The life span of buildings and machinery was estimated to be 50 and 20 years, respectively. In calculations, we have used the average tariffs on heat energy and electric power for 2005 approved by the Novosibirsk regional power commission.

The fulfillment of energy-saving projects is hardly possible without credit financing. Currently, the Russian economy is only operating in an attempt to prevent economic depression while not proactively to encourage economic growth. The basic legislative decisions forming a legal field of investment activity have been made. However, central issues such as improvement of an investment climate, and the maintenance of guarantees to the investor have not been solved. In this sense, investment in the energy-saving sector is in a preferable position, because authorities in regions have both the legal rights, and a practical opportunity to give corresponding guarantees to investors. They can also take advantage of the assistance and help from federal executive authorities in ensuring these guarantees, if necessary since they are authorized by the Russian government to act at the federal level as guarantors of energy-saving investments.

For the calculations, we assumed that a combination of various ways of financing, partially due to the state sources, joint-stock investments, and credit financing would be used. Considering the complexities in making loans on ecological-energy projects, we have assumed that for all options only
12% of investments for the purchase of the equipment and carrying out reconstruction would be financed. Russian banks give loans in convertible currency, at approximately 2-3 times higher interest rates than the European banks because of the deficiency of financial means and high risk.

We also took into account the tax system of the Russian Federation and Novosibirsk region:
- Profit tax (Pt): 1Pt option – 35%, 2Pt option – 13% for energy-saving actions;
- Interest Rate (IR): 1IR option – 8%, 2IR option – 18%, 3IR option – 35 %;
- Inflation rate (I): 1I option (maximal) – 10% within the first 7 years; 2I – (minimal) – 10% within 4 years with the subsequent decrease every 3 years on 2%;
- Discount rate changes within the limits of 8–20 %;
- The size of the loan capital from commercial banks makes 12 % of investments for the purchase of the equipment;
- The predicted period – 20 years (average life span of the equipment).

The basic assumptions used in calculations and results of an economic estimation by minimal option are given in Table 5.

**Table 5.** The basic economic parameters of WWS utilization options under the minimal scenario.

| Parameter                        | Option |         |         |         |         |         |
|----------------------------------|--------|---------|---------|---------|---------|---------|
|                                  | 1st    | 2nd     | 3rd     | 4th     | 5th     | 6th     |
| Investments, mln RUB             | 64.5   | 45.5    | 85.7    | 79.6    | 171.0   | 47.0    | 41.0    |
| Capital investment, mln RUB/year | 7.5    | 5.3     | 10.0    | 9.3     | 20.0    | 5.5     | 4.8     |
| Operational expenses, mln RUB/year | 10.5   | 4.2     | 11.2    | 19.0    | 34.9    | 10.2    | 14.3    |
| Internal rate of return (IRR), % | 2.52   | 10.63   | -1.42   | 2.05    | ...     | 23.08   | 6.07    |
| Discounted payback period, (PBP), years | 15.0   | 9.0     | ...     | 15.5    | ...     | 5.0     | 12.0    |
| Saving fossil fuel:              |        |         |         |         |         |         |
| natural gas, 1000 m³/year        | 9.928  | 9.269   | 9.512   | –       | –       | –       | –       |
| coal, 1000 tons/year             | –      | –       | –       | 129.6   | 130.0   | 77.4    | –       |
| WWS, 1000 tons/year              | 129.6  | 129.6   | 129.6   | 129.6   | 130.0   | 131.4   | -       |

Options are compared concerning technological and economic feasibility, energy generation potential, and environmental impact. The results show that the most efficient WWS utilization option is the 6th variant, namely, combined burning of WWS with coal at the CFPP:
- maximum NPV is around 63.03 million RUB, IRR equals to 23.08%, PBP – 5 years;
- 77,000 tons of coal is replaced by 131,400 tons of WWS, equivalent to a net annual power income of 67 GW/year;
use of stored municipal WWS (1 million tons) allows producing about 1,090 GW of energy.

Increasing only profit tax from 13 to 38%, at the preservation of the minimal scenario on other parameters, is accompanied by a decrease in NPV for all options by 20-50%, IRR – by 1-5 %, while the greatest growth in a payback time only by 1.5 years is noted for the 1-st option (figure 5).

**Figure 5.** Dependence of NPV on the profit tax (6th option, discount rate – 8%).

The use of the highest raised interest rate of 35% in comparison with 10%, makes only small changes in NPV, IRR, and PBP parameters. This is due to the low share of loan capital, just 12%, in the total amount of investments (figure 6).
Figure 6. Dependence of NPV on the interest rate (6th option, discount rate – 8%).

With an increase of discount rate from 8 to 20% (assuming the maximal scenario) all considered options have a small or negative value of NPV, and become inefficient (figure 7).

Figure 7. Dependence of NPV on the discount rate (6th option, interest rate – 8%).
Conclusions
The results show that the most efficient option of WWS utilization involves the burning of WWS with coal at coal fuel power plants.

Fulfillment of this project will allow achieving:
- maximum NPV around 63.03 million RUB (equivalent to one million USA dollars), IRR equal to 23.08%, PBP – 5 years;
- replacement of 77,000 tons of coal by WWS, equivalent to a net annual power output of 67 GW/year;
- potential total energy production of about 1090 GW;
- solutions to the socio-economic problems of waste storage;
- lower environmental impact;
- creation of new jobs.

Methodical and applied results of this research were used in the preparation of a socio-economic development strategy for the Novosibirsk Region. The suggested approach can also be used to design socio-economic development strategies in various countries at the federal, regional, and corporate levels of management.

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