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Switching Coal-Fired Thermal Power Plant to Composite Fuel for Recovering Industrial and Municipal Waste: Combustion Characteristics, Emissions, and Economic Effect

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Received: 15 October 2019; Accepted: 2 January 2020; Published: 4 January 2020



Abstract: Combustion characteristics were studied experimentally for single droplets of fuel slurries based on wet coal processing waste with municipal solid waste components (cardboard, plastic, rubber, and wood) and used turbine oil. We established the ignition delay time for three various groups of fuel compositions in motionless air at 600–1000 °C. The minimum values are 3 s, and the maximum ones are 25 s. The maximum temperatures in the droplet vicinity reach 1300 °C during fuel combustion for compositions with 10% of used oil. The combustion temperatures of fuel compositions without oil are 200–300 °C lower. The concentrations of anthropogenic emissions in flue gases do not exceed those from dry coal combustion. Adding used oils to composite fuels reduces the concentrations of dioxins and furans in flue gases when municipal solid waste in the fuel burns out due to high combustion temperatures. Based on the experimental research findings, we have elaborated a strategy of combined industrial and municipal waste recovery by burning it as part of composite fuels, as illustrated by three neighboring regions of the Russian Federation with different industrial structures and levels of social development. This strategy suggests switching three typical coal-fired thermal power plants (one in each of the regions) to composite liquid fuel. It will reduce the hazard of waste to the environment and decrease the consumption of high-quality coals for power generation. Implementing the developed strategy for 25 years will save 145 Mt of coal and recover 190–260 Mt of waste. The positive economic effect, considering the modernization of fuel handling systems at thermal power plants and the construction of a fuel preparation plant, will make up 5.7 to 6.9 billion dollars, or 65–78%, respectively, of the main costs of three thermal power plants operating on coal within the identical period.

Keywords: coal waste; municipal solid waste; waste petroleum oil; co-combustion; thermal power plant; environmental and economic efficiency

1. Introduction

One of the most important global environmental problems nowadays is processing and recovery of various waste [1,2]. Vast areas are excluded from agricultural use due to the arrangement of landfill sites for industrial and municipal waste [1,3,4]. Apart from the above factors, each particular type of waste is characterized by a certain group of factors hazardous for the environment. For instance, typical coal mining and coal processing waste is fire-hazardous and contains heavy metals and acid-forming substances that become sources of integrated environmental pollution under severe exposure to natural factors [2]: solar energy, water, and air. Oil and petroleum waste are toxic. Storing such liquids under the conditions that do not comply with regulatory requirements leads to water pollution and acid

rains as well as enhances the greenhouse effect [5]. Landfill storage of untreated municipal solid waste (MSW) can be the cause of pollution ground waters and air by bacterial flora as well as a source of dioxins and furans (PCDD/Fs) in case uncontrollable local combustion occurs at a landfill [4,6].

There is an urgent need for an effective solution to the problem of waste treatment in the short term if the global environmental situation is to be preserved at the same level at least [4]. Experts estimate [7,8] that, despite the advances in waste management, the technologies now widely used for the treatment of waste (primarily and municipal) will not completely solve the issue of environmental pollution. Table 1 illustrates waste generation in 2018 and projections for the near future by country [4]. It is shown (Table 1) that waste generation all over the world grows rapidly. Therefore, the problem of waste recovery calls for the development of drastic solutions.

Nowadays, countries that stockpile their waste mainly at landfill sites (75–95%) take considerable efforts to develop waste management (regarding MSW). However, a low dynamics of waste management system transformation does not lead to a substantial improvement of the environmental situation. These countries are [4] the Russian Federation (MSW dumping at landfill sites is 95.0% of the total amount of annual waste generation), Turkey (98.0%), Ukraine (94.1%), Chile (93.7%), Mongolia (93.5%), Belarus (84.0%), Thailand (80.5%), Greece (80.0%), and India (77.0%).

The Russian Federation can be used as an example to provide the following typical statistical data that characterize quite a low level of waste management and common waste treatment technology development. As reported by the Russian Federal State Statistics Service, 6220.6 Mt of municipal and industrial waste were accumulated in Russia during 2017, which is 14.32% more than the statistical data for 2016 [9]. About 50% of such waste is recovered, while the rest is buried in the soil (about 13%) and stored at open-air disposal sites (about 37%). So far, more than 94 billion t of industrial waste have been collected in Russia; more than a half of it comes from the extraction and processing of solid and liquid hydrocarbons. Due to a low level of recycling and decontamination of industrial waste, a great amount of it (28.4 billion t) is stockpiled at open sites of industrial enterprises, which take up about 1 Mha of land.

Table 1. Waste generation and projections by country [4].

Country	2018 Year		2030 Year Projected		2050 Year Projected	
	MSW *, Mt	Population, mln.	MSW, Mt	Population, mln.	MSW, Mt	Population, mln.
Argentina	17.91	42.98	23.74	49.323	31.09	55.229
Australia	13.35	8.63	16.97	28.24	21.38	33.19
Brazil	79.89	205.96	96.69	225.47	114.3	232.69
Canada	25.1	35.54	30.38	40.62	36.17	44.95
China	220.4	1403.5	295.04	1441.18	335.79	1364.46
France	33.4	66.62	36.02	67.89	40.86	70.61
Germany	51.05	81.69	54.4	82.19	57.05	79.24
India	168.4	1071.48	387.77	1512.99	543.28	1658.98
Indonesia	65.2	261.12	87.96	295.6	118.55	321.55
Japan	43.98	127.14	45.02	121.58	43.32	108.79
Korea, Rep.	18.22	50.75	22.44	52.7	24.62	50.46
Mexico	53.1	125.89	69.64	147.54	90.44	164.28
Nigeria	27.61	154.4	54.81	264.07	107.08	410.64
Pakistan	30.76	193.2	42.43	244.25	66.38	306.94
Russian Federation	60	143.2	67	140.54	71.57	132.73
Saudi Arabia	16.13	31.56	20.97	39.48	25.18	45.06
South Africa	18.46	51.73	27.09	64.47	36.77	72.76
Turkey	31.28	78.27	39.98	88.42	48.78	95.63
UK	31.57	65.13	36.72	70.58	42.82	75.38
USA	258	318.56	311.04	354.71	359.89	389.59
World	2020	7380	2590	8550	3400	9770

* Municipal solid waste.

The situation is much more critical with MSW. The level of its processing in Russia does not exceed 5%. The main method of treatment is sorting and separation of recyclables. The rest of the waste is usually stored at open-air disposal sites [10,11]. Although the share of MSW in the total volume of Russia's waste is about 1% (or 57 Mt in 2017), it is this type of waste that poses the greatest threat to the population, as large disposal sites of MSW are located close to where most of the population resides

(in the suburbs of large cities and megalopolises). The low level of MSW recovery is explained by the undeveloped waste management infrastructure. In Russia, it is represented by about 240 MSW treatment facilities; about 50 sorting complexes; and 3 incineration plants with annual capacities of 75, 200, and 750 t of MSW recovery by burning.

Thus, the share of recoverable waste is less than 50% on average, which is only provided by the industrial use of bulk waste to fill up mined-out spaces in the natural raw material extraction and to rehabilitate disturbed lands. In Russia, the level of manufacturing waste recovery does not exceed 30–60%, whereas that of MSW recovery is just about 5%. The experience of countries with a high level of MSW management development [12] (Germany's MSW recovery is 67.6% of the total amount of annual waste generation, that of South Korea is 59.0%, that of Slovenia is 57.8%, that of Austria is 57.7%, that of the Netherlands is 54.2%, that of Belgium is 53.7%, and that of Switzerland is 52.5%) shows that the rational organization of waste recycling can boost these indicators to 50–70% [13,14].

Modernizing waste management and giving up the accumulation and burial of waste in favor of its processing and reuse requires an intermediate stage of waste treatment in the next 20–30 years. Within this period, the technologies of industrial recovery of waste by burning it for the production of electricity and heat will be in high demand [15–18]. Implementing such technologies will reduce the growing amount of waste at landfills. This will preserve the boundaries of landfill sites or, in some cases, even shrink them due to the combustion of waste that is unsuitable for recycling.

Therefore, it is a relevant task to develop industrial technologies to recover large amounts of MSW. The most efficient solution to this task is combustion of waste to produce power [16,17,19,20], e.g., at trash incineration plants. However, the construction and operation of technically sophisticated industrial facilities using MSW direct combustion are commercially unviable [21]. Moreover, electricity generation also requires extra investments in the development of new modifications of steam turbines, designed for relatively low parameters of water vapor [22,23]. Another technical problem, involving large investments, is strict flue gas cleaning requirements. Nowadays, there are rather tough legal restrictions [10,24,25] on the content of harmful substances in the flue gases of MSW incineration plants (EU 94/67/EEC), which will entail additional installation and maintenance expenses for costly gas filtration systems.

One of the alternative approaches to solving this problem is adding fine particles of MSW to composite liquid fuel based on a mixture of wet coal with a combustible liquid. Typical components are coal processing waste and used oils (engine, turbine, transformer, and other). According to a theoretical analysis [26], burning composite fuels containing 10–20% of MSW make it possible to decrease the area of territories for MSW disposal by 20–30%. The above approach is economically efficient because free combustible waste will replace costly fossil fuels to produce electrical and thermal energy.

The design, development, and implementation of promising technologies require an in-depth study of technical, environmental, and economic aspects of a new approach to waste disposal. Therefore, the purpose of this study is to experimentally investigate the mechanism, conditions, and characteristics of composite liquid fuel combustion; to investigate the concentration of anthropogenic emissions in flue gases; as well as to analyze the economic effect of switching coal-fired thermal power plants (TPPs) to composite fuel based on industrial and municipal waste, when three neighboring industrialized regions of the Russian Federation employ the strategy to recover various combustible waste.

2. Experimental Research

2.1. Fuel Preparation and Fuel Characteristics

Three groups of fuel compositions were prepared in the present work. One of the main components is filter cake (FC) of coking coal (the Severnaya coal washing plant, Kemerovo region, Russian Federation). Such coal slurry is a combustible by-product of coal processing. It can be widely used as fuel in TPPs [27]. FC is a mixture of coal dust (particle size about 100 μm) with water (mass fraction about 50%). The first and second groups of fuel compositions consisted of FC and typical MSW (cardboard, wood, rubber, and plastic). The concentrations of the latter are 10 and 20%

for groups I and II of fuel compositions, respectively. The last (third) group of fuel compositions included 10% of used turbine oil in addition to FC and MSW, which was intended to increase the temperature and thermal effect of combustion. The fuel compositions, their main characteristics, and the characteristics of separate components are presented in Tables 2–4. The heat of combustion for various fuel compositions was calculated analytically [28] using a method based on the mass fractions of fuel components and their higher heating values determined from the proximate analysis. Proximate and ultimate analyses were performed using standard methods of International Organization for Standardization (ISO 17246:2010 and ISO 17247:2013): ash, volatile, and moisture content were determined by ISO 1171, ISO 562, and ISO 11722, respectively; higher heating value was determined by ISO 1928; the fractions of carbon, hydrogen, nitrogen, and sulfur in fuel components were determined by ISO 17246, ISO 625, ISO 333, and ISO 351, respectively; the fraction of oxygen was calculated using the equation $O^{daf} = 100 - (W^a + A^d + C^{daf} + H^{daf} + N^{daf} + S^{daf})$ according to ISO 17247:2013.

Table 2. Fuel compositions.

Number	FC *	Oil	Rubber	Cardboard	Wood	Plastic	Heat of Combustion ** (MJ/kg)
Group I of fuel compositions							
1	100%	–	–	–	–	–	10.78
2	90%	–	10%	–	–	–	13.05
3	90%	–	–	10%	–	–	11.43
4	90%	–	–	–	10%	–	11.29
5	90%	–	–	–	–	10%	11.88
Group II of fuel compositions							
6	80%	–	20%	–	–	–	15.31
7	80%	–	–	20%	–	–	12.07
8	80%	–	–	–	20%	–	11.80
9	80%	–	–	–	–	20%	12.98
Group III of fuel compositions							
10	90%	10%	–	–	–	–	14.11
11	70%	10%	20%	–	–	–	18.64
12	70%	10%	–	20%	–	–	15.40
13	70%	10%	–	–	20%	–	15.12
14	70%	10%	–	–	–	20%	16.30

* Filter cake (FC) in initial wet state (moisture content 50%); ** calculated analytically [28].

Table 3. Characteristics of fuel components: Proximate analysis [16,29].

Component	W ^a (%)	A ^d (%)	V ^{daf} (%)	Q ^a _{s,v} (MJ/kg)
FC *	–	26.5	23.1	24.83
Wood	20.0	2.0	–	16.45
Rubber	2.0	1.8	–	33.50
Plastic	2.0	0.2	–	22.00
Cardboard	5.0	3.0	–	17.50
Oil	0.3	0.8	100.0	44.02

* FC in dry state (before the analysis, it was dried at about 105 °C until full evaporation of moisture); A^d, V^{daf}, and W^a are ash, volatile, and moisture content; Q^a_{s,v} is higher heating value.

Table 4. Ultimate analysis of fuel components [16,29].

Component	C ^{daf} (%)	H ^{daf} (%)	N ^{daf} (%)	S ^{daf} (%)	O ^{daf} (%)
FC	87.2	5.1	2.1	1.1	4.5
Wood	50.3	6.0	0.2	0.1	43.4
Rubber	97.9	1.2	0.3	0.6	–
Plastic	66.7	7.9	–	–	25.4
Cardboard	46.3	6.3	0.3	0.2	46.9

C^{daf}, H^{daf}, N^{daf}, O^{daf}, and S^{daf} are fractions of carbon, hydrogen, nitrogen, oxygen, and sulfur in the fuel component converted to a dry ash-free state.

2.2. Experimental Techniques

A well-tested technique was used to prepare fuel slurries [30]. MSW (cardboard, wood, rubber, and plastic) was ground separately and sieved through a sifter (mesh size of 140 μm according to ISO 3310:2000). Different compositions were obtained by mixing wet FC, MSW, and oil (Figure 1) with the component concentration presented in Table 2. A DC-600RM mixer (HT Machinery, Japan-Taiwan) and a steel vessel (volume of 0.2 L) were used. The basic compositions (Table 2) were also burned: No. 1—wet FC without any additives; No. 10—wet FC mixed with used turbine oil.

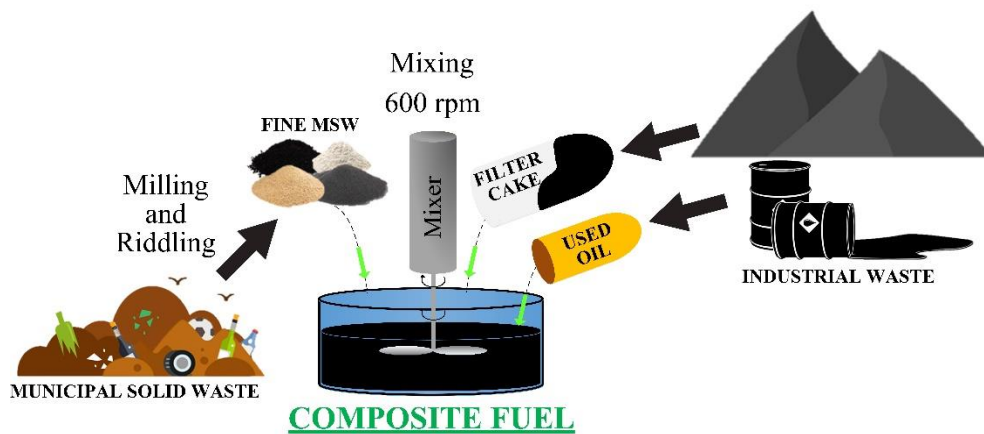


Figure 1. Scheme of fuel slurry preparation.

The fuel ignition and combustion characteristics were investigated using an experimental setup (Figure 2) [30], featuring a Loiplf50/500–1200 (Laboratory Equipment&Instruments, Russia) tube muffle furnace with diameter and length of the tube at 50 mm and 500 mm, respectively, and the temperature variation range at 20–1200 $^{\circ}\text{C}$. In each set of experiments, the furnace was preheated to a given temperature. After temperature stabilization, a fuel droplet ($D_d = 2$ mm) was introduced into the furnace along the symmetry axis of the ceramic tube. The processes were recorded by a Phantom V411 (Vision Research, USA) high-speed color video camera with a maximum filming rate of 4200 fps at resolution 1280 \times 800 pixels. The values of ignition delay times (t_d) were calculated by Tema Automotive software (Image Systems AB, Sweden) that analyze the evolution of the droplet luminance over time [29,30]. The systematic error when calculating t_d did not exceed 3%. Random errors for sets of 5–7 experiments under identical conditions were no more than 10%.

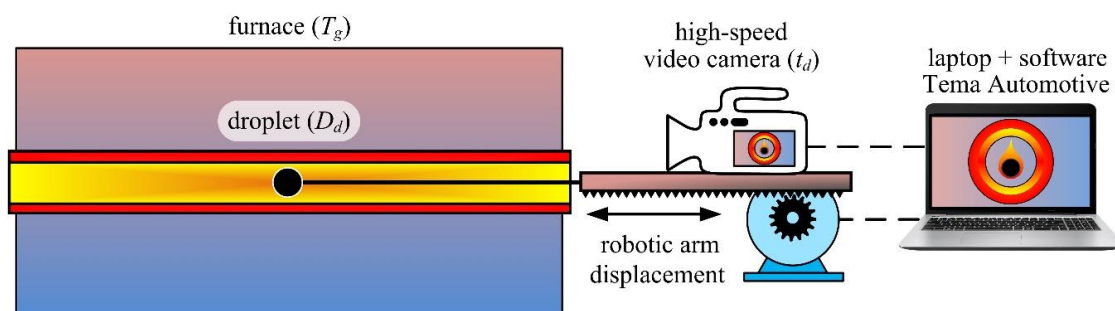


Figure 2. Scheme of experimental setup.

A Testo 340 (Testo, Germany) gas analyzer was used to analyze the main anthropogenic emission concentrations (carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxide (NO_x), and sulfur oxide (SO_x)) from the fuel composition combustion at $T_g = 1000$ $^{\circ}\text{C}$, employing the methods from References [29,31]. It was put in place of the high-speed video camera. The fuel sample (with a mass of about 1 g) was introduced into the preheated furnace. A gas analyzer sensor was introduced into the

furnace together with the fuel sample to collect flue gases. Series of 3–5 experiments were conducted under identical initial conditions. The research findings were averaged. Random errors did not exceed 5% for the experiments conducted under identical initial conditions.

3. Results

3.1. Ignition Delay Time and Combustion Temperature

The three regions (highlighted in different colors) in Figure 3 correspond to three fuel compositions (Table 2). They illustrate the conditions (the ambient air temperatures) and characteristics (delay times) of guaranteed ignition of 2-mm droplets of composite fuels considered in this study (Table 5). The ambient air temperature at $T_g = 600$ °C is the minimum required for composite fuel ignition. The maximum difference in t_d for the three composition groups is no more than 25% at 600–1000 °C. The ignition delay times of fuel compositions differ insignificantly (by less than 5%) in the conditions of $T_g > 1000$ °C.

In Figure 3, the maximum ignition delay times (the curve demarcating the blue area above for group I of fuel compositions) correspond to t_d of composition No. 1 (wet FC). Fuel composition No. 12 (FC 70% + cardboard 20% + oil 10%) has the lowest ignition delay times in the range of $T_g = 600$ –1000 °C (the curve demarcating the red area below for group III of fuel compositions). For other compositions under study, the t_d values lie in between these two curves. The fuel compositions have been sorted in descending order in accordance with their ignition delay times: group I—FC 90% + MSW 10%; group II—FC 80% + MSW 20%; and group III—FC 70% + MSW 20% + oil 10%. Thus, the latter compositions have the lowest ignition delay times. Adding 10% of MSW to the FC, increasing MSW content to 20%, and adding 10% of used oil lead to a decrease in the ignition delay time (Figure 3). It can be explained by lower moisture concentration (chemically inert and heat-absorbing component at the initial stage of the induction period) in the fuel slurry containing MSW, as compared with composition No. 1. Another reason for enhanced ignition is the presence of combustible liquid (used oil) in the fuel slurry.

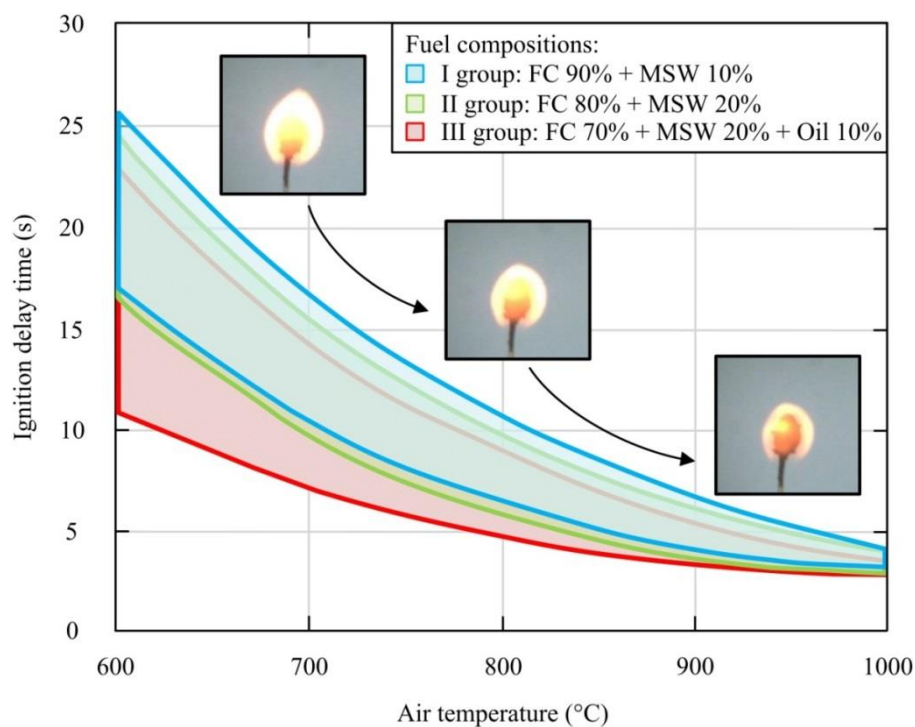


Figure 3. Regions of ignition delay times (highlighted in color) for composite fuels.

Table 5. Ignition delay times (s) of composite fuels.

Number of Fuel Composition	Temperature in Furnace				
	600 °C	700 °C	800 °C	900 °C	1000 °C
Group I of fuel compositions					
1	25.79	16.82	10.79	6.73	4.21
2	21.31	13.04	8.41	5.47	3.71
3	19.21	11.92	7.29	4.84	3.47
4	23.41	15.14	9.81	6.10	3.96
5	17.05	10.51	6.73	4.21	3.22
Group II of fuel compositions					
6	22.15	13.60	8.69	5.30	3.71
7	19.35	11.21	7.43	4.43	3.50
8	24.53	15.56	9.81	6.17	3.93
9	16.54	9.81	5.75	3.56	3.08
Group III of fuel compositions					
10	22.85	14.30	8.83	5.47	3.50
11	16.12	10.09	5.61	4.35	3.08
12	13.40	8.83	5.47	3.79	2.87
13	18.93	11.92	6.87	4.91	3.29
14	10.93	7.01	4.63	3.22	2.66

In addition to ignition delay times, another important characteristic of the fuel is combustion temperature, which influences not only the thermotechnical properties of energy-generating equipment but also the characteristics of gaseous product combustion. Figure 4 presents the curves of temperature change during the combustion of three various fuel compositions at $T_g = 800$ °C. T_1 is the droplet temperature (solid lines), and T_2 is the gas temperature (dashed lines) in the droplet vicinity at a distance D_d from T_1 (Figure 4), where the gas mixture burns out.

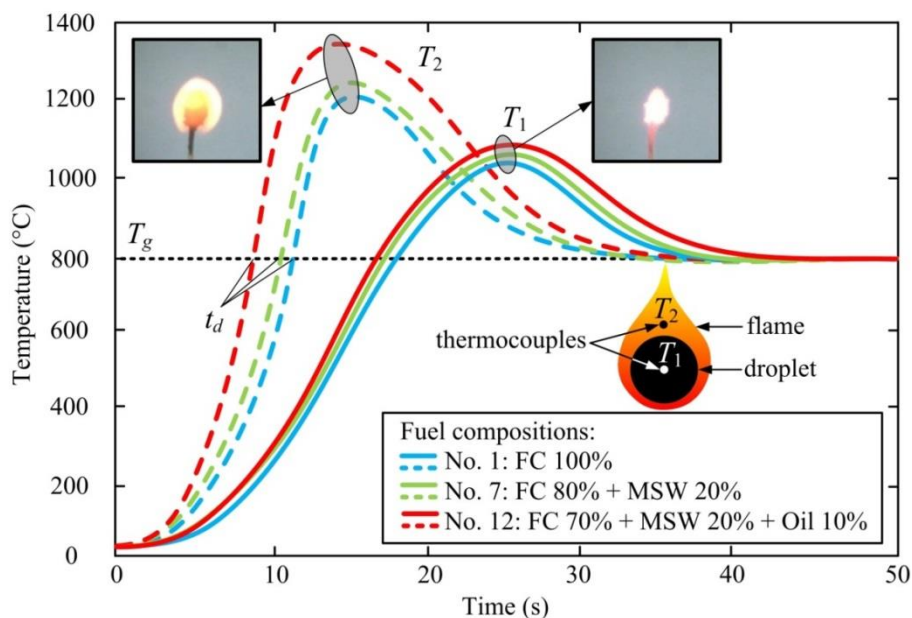


Figure 4. Temperature change of composite liquid fuel droplets of different compositions with initial diameter of 2 mm during the induction period at $T_g = 800$ °C.

In Figure 4, the points of intersection of the corresponding dashed curves with a line at $T_g = 800$ °C correspond to the ignition moment (t_d) of different fuel compositions. The heat input at $t = t_d$ in the area of rapid exothermic reaction (ignition zone) exceeds the heat outflow from this area into the environment. During the burnout of the gaseous mixture, the maximum values of T_2 reach 1300 °C for

group III of the fuel compositions with used oil. The maximum droplet temperatures T_1 for different fuel compositions have similar values and do not exceed 1150 °C (Figure 4). Under the heterogeneous combustion conditions, the droplet burns out layer by layer. The process duration from the gas-phase ignition moment up to the solid residue burnout at $T_g = 600\text{--}1000$ °C is 15–35 s (Figure 4) for droplets of 2 mm in diameter.

3.2. Environmental Emissions

According to Reference [10], when MSW is burned at 1300 °C and above, the harmful gases (PCDD/Fs) released break down into safe simple compounds that do not pose any threat to the environment. Adding carbamide into the boiler furnace and a mixture of activated carbon and alkaline sorbent $\text{Ca}(\text{OH})_2$ into the absorber also reduces the concentration of hazardous substances to regulatory limits in flue gases [10]. We can conclude that adding 10–20% of used oils to the fuel slurry (compositions with industrial waste and MSW), on the one hand, reduces the concentration of dioxins and furans in flue gases [10] due to an increase in the combustion temperature by 200–300 °C and, on the other hand, increases the concentration of the main anthropogenic emissions (carbon, nitrogen, and sulfur oxides) as compared with the same characteristics for burning fuel compositions without combustible liquids.

In this research, we analyzed the concentrations of anthropogenic emissions in flue gases for two main components (Figure 5): NO_x and SO_x . The concentrations of carbon oxides in composite fuel combustion products were not so different when the fuel with typical MSW was burned: CO_2 was 16–18%, and CO had no more than 370 ppm. These values do not exceed the identical characteristics of dry coal combustion. All the measurements were performed when fuel compositions were burned separately in the muffle furnace at $T_g = 1000$ °C. It is a typical operating temperature for steam boiler furnaces. Figure 5 shows the maximum concentrations of nitrogen and sulfur oxides in the flue gases of fuel slurries for combustion process occurring at air temperatures 600–1000 °C.

As for the significantly lower concentrations of NO_x and SO_x in the flue gases of composite liquid fuels as compared with those from dry coal combustion (Figure 5), they are explained by the following [27,29,31]. When dry coal is burned, the emissions of NO_x and SO_x are related to the nitrogen and sulfur content in the fuel. Adding water to the fuel slurry leads to a decrease in the total content of such components in the fuel composition. It positively affects a decrease in the concentrations of the corresponding oxides in flue gases. Moreover, during fuel combustion, the water in the slurry fuel (about 50%) is an oxidizer source, which enhances the process of coal burning. The rapid evaporation of water contributes to finer pulverization of the carbon component due to droplet microexplosions. As a result of these factors, the surface of oxidation reaction grows significantly for fuel components, which provides the 1.4- and 2.8-fold differences in the concentrations of nitrogen and sulfur oxides in the flue gases of dry coal and wet FC combustion (Figure 5a).

The MSW fuel components we added to the FC have been sorted in descending order (according to the NO_x and SO_x concentrations in combustion products (Figure 5)): rubber, cardboard, wood, and plastic. The content of nitrogen and sulfur in MSW is 2–10 times as low as that in the initial FC according to the element composition of the fuel components (Table 4). Thus, in the preparation of groups I and II of fuel compositions, the mass fraction of FC is reduced because a solid combustible component is added (cardboard, plastic, rubber, and wood) with lower nitrogen and sulfur content. Consequently, as a result of burning such fuel compositions in the conditions identical to the combustion conditions of composition No. 1 (wet FC 100%), the concentration of NO_x and SO_x decreases (Figure 5a,b). The concentrations of these anthropogenic emissions are 5–10% lower for the compositions with 20% of MSW (group II) than they are for the compositions with 10% of MSW (group I).

When we added used oil to the fuel slurry (group III), the concentrations of sulfur and nitrogen oxides were 18–22% and 10–12% higher, respectively (Figure 5c), than they were for the fuel compositions (Figure 5b) not containing oil (group II). The negative ecological effect of adding oil to composite fuel is explained by the chemical composition of the combustible liquid of petroleum origin: a relatively high

concentration of sulfur and nitrogen compounds. Moreover, an increase in the combustion temperature enhances the formation of sulfur and nitrogen oxides in the oxidation reactions. However, adding a liquid combustible component increases the combustion temperature. It is a positive factor for the reduction of PCDD/Fs concentration in flue gases as well as for the improvement of the characteristics of the ash residue.

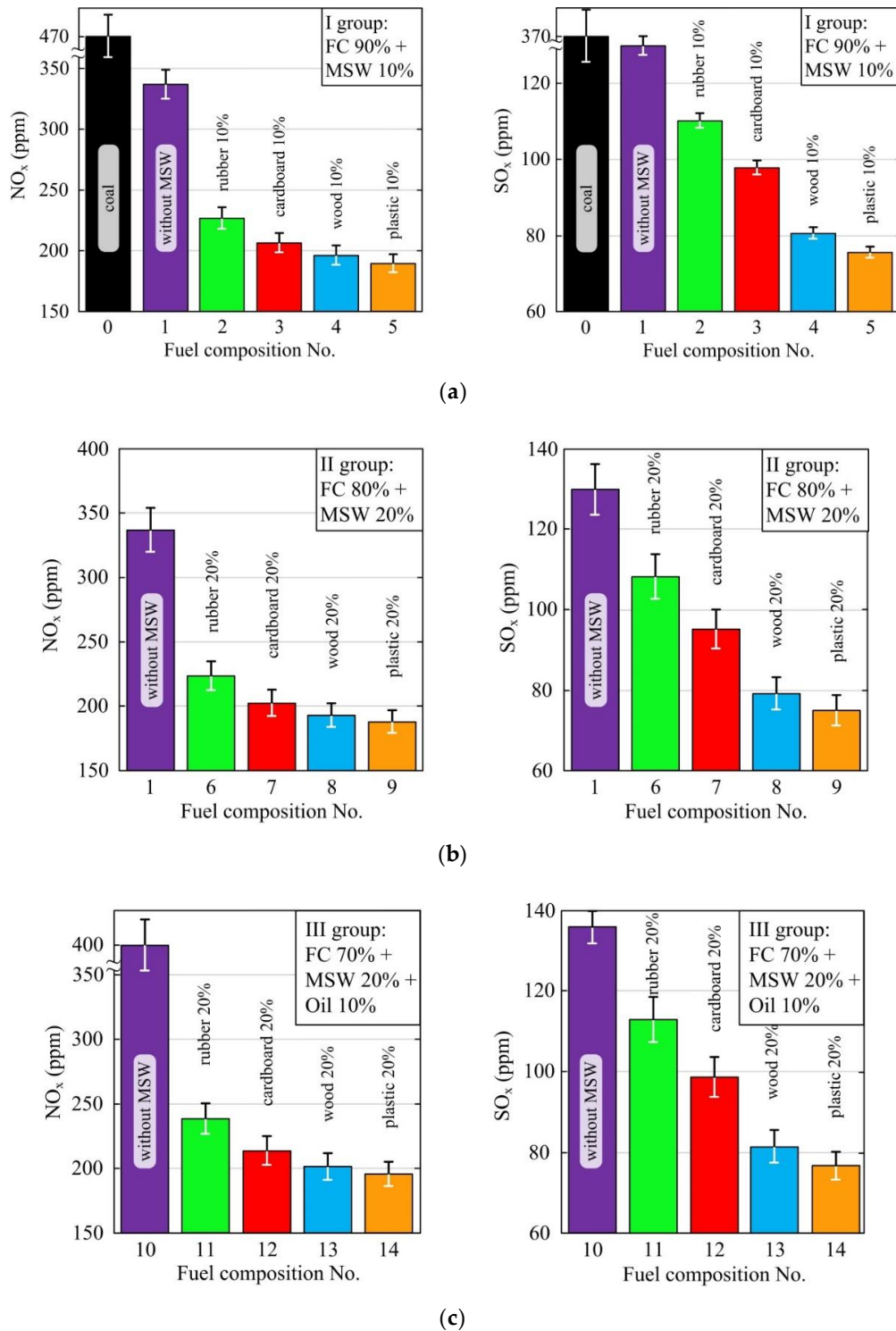


Figure 5. Concentrations of nitrogen and sulfur oxides in flue gases of dry coal and fuel slurries: (a) group I; (b) group II; and (c) group III (composition No. 0—data [31] for coking coal).

It can be concluded that adding a combustible liquid of petroleum origin (used oil) to the fuel slurry promotes the growth of NO_x and SO_x (sometimes by 30–40% as compared with fuels based on the coal and water composition). Even though the environmental characteristics of the composite fuel are worse after adding used oils, the increase in the nitrogen and sulfur oxide concentrations in flue gases is within the regulatory limits of the corresponding pollutants from dry fuel combustion (Figure 5 and Table 6). Therefore, composite liquid fuels are promising energy resources that can be used in thermal power engineering instead of solid fossil fuels.

Table 6. Emission limits for power plants [10] and research findings.

Emission	Power Plants for MSW Combustion (EU 94/67/EEC), Daily Average Values	Power Plants for Coal Combustion (the Russian Federation State Standard GOST ** 50831-95), Values at $\alpha = 1.4$	Research Findings *
Solid particles	10 mg/m ³	150–250 mg/m ³	not studied
CO	50 mg/m ³ (43 ppm)	300–400 mg/m ³ (258–344 ppm)	180–370 ppm
NO _x	200 mg/m ³ (160 ppm)	300–640 mg/m ³ (340–513 ppm)	190–400 ppm
SO _x	50 mg/m ³ (19 ppm)	1200–1400 mg/m ³ (450–526 ppm)	75–135 ppm

* The ranges correspond to the results in Figure 5. ** GOST (rus) or SUST (eng) is a State Standard of the Soviet Union.

4. Discussion

4.1. Combined Recovery of Industrial and Municipal Waste

This research offers a technological strategy to reduce the harmful effect of industrial waste and MSW on the environment and to cut down the consumption of high-grade coal for power generation. The strategy proposes combined waste (municipal and industrial) recovery by burning in fuel compositions at local coal-fired TPPs.

The main elements of the strategy were developed previously [16] for three neighboring regions of the Russian Federation located in Western Siberia. They are Kemerovo (No. 1), Novosibirsk (No. 2), and Tomsk (No. 3) regions. The strategy of co-combustion of industrial and municipal waste suggests switching three typical coal-fired TPPs (at least one in each of the regions) to composite liquid fuel. The preparation of fuel slurries and their transportation to consumers requires the construction of a corresponding plant and pipelines.

Below, we will consider the technical and economic aspects of implementing the designed strategy for three scenarios, each of them suggesting the combustion of one of three groups of fuel compositions under study by TPPs (Table 2): group I—FC 90% + MSW 10%; group II—FC 80% + MSW 20%; and group III—FC 70% + MSW 20% + oil 10%. The obtained results will be a basis for the development of waste management strategies in other regions of the world, with due regard to their peculiar characteristics (amount and structure of waste).

4.2. Structure and Amount of Industrial and Municipal Solid Waste

Table 7 presents statistics for the amount and structure of industrial and municipal waste produced as well as methods of their current treatment.

4.3. Need for Energy Resources of Coal-Fired Thermal Power Plants

The needs of regions No. 1–No. 3 for their own thermal and electrical energy are satisfied primarily by local thermal power plants. Combined heat and electricity in each of the three regions are generated by a group of TPPs, some of them operating on solid fossil fuel and others on natural gas. Table 8 presents the main characteristics of coal-fired TPPs typical of each of the regions.

Table 7. Characteristics of waste in each of three regions [16].

Characteristics	Region No. 1 (Kemerovo)	Region No. 2 (Novosibirsk)	Region No. 3 (Tomsk)
Total volume of waste, Mt/y	2801	3.9	1.3
Industrial waste, Mt/y	2800	2.6	0.9
Structure of industrial waste:			
- fossil fuel extraction waste	99.5%	43.8%	17.2%
- manufacturing industry waste	0.2%	8.1%	32.8%
- waste related to generation and distribution of power, gas, and water	0.1%	24.5%	7.2%
- construction and repair waste	<0.01%	0.1%	1.0%
- agricultural, forestry, fish-farming, and fishing waste	0.04%	16.0%	32.9%
- other waste	0.15%	7.5%	8.9%
Reuse/recovery, Mt/y	1876.0 (67.0%)	0.9 (34.1%)	0.3 (28.0%)
Burial/stockpiling at disposal sites, Mt/y	924.0 (33.0%)	1.7 (65.9%)	0.6 (72.0%)
MSW, Mt/y	0.9	1.3	0.4
Structure of MSW:			
- food waste	45%	35%	47%
- paper	29%	32%	19%
- plastic	13%	6%	6%
- metal	2%	4%	9%
- leather, rubber, and textiles	2%	6%	5%
- glass	1%	6%	8%
- wood	5%	2.5%	1%
- other	3%	8.5%	5%
Reuse/recovery, Mt/y	0.02 (1.9%)	0.3 (22%)	0.008 (2.0%)
Burial/stockpiling at disposal sites, Mt/y	0.88 (98.1%)	1.0 (78%)	0.392 (98.0%)

Table 8. Characteristics of typical coal-fired thermal power plants (TPPs) in each of three regions.

Plant *	Number of Boiler Units	Installed Capacity	Installed Heat Power	Electrical Energy Generation	Thermal Energy Generation	Specific Consumption of Fuel Equivalent per Electrical Energy Supply	Specific Consumption of Fuel Equivalent per Thermal Energy Supply	Produced Thermal Energy from Burning Coals in Boiler Furnace
	pcs.	MW	Gcal/h	GW·h	Tcal	g of Fuel Equivalent/(kW·h)	kg of Fuel Equivalent/Gcal	PJ
TPP 1	9	565	1449	1946	2911	370	160	35.0
TPP 2	6	1200	2730	7065	4652	292.9	138	79.0
TPP 3	10	331	815	1104	2154	249	159.6	9.0
Total	25	2096	4994	10,115	9717	911.9	457.6	123.0

* The indexing of TPPs corresponds to the numbers of the regions in Table 7.

Flame coal (the coal-bearing rock of Kuznetsk Basin, Russian Federation) was used as the main fuel at the TPPs under study. It has the following specifications: heat of combustion $Q_{s,v}^a = 21.4$ MJ/kg; moisture $W^a = 14.1\%$; ash $A^d = 13.1\%$; and volatile content $V^{daf} = 41.2\%$.

Analyzing the amount of thermal energy produced from burning coals in boiler furnaces (Table 8) and the thermotechnical properties of the solid fuel (heat of combustion $Q_{s,v}^a = 21.4$ MJ/kg) enabled us to determine the amount of coal consumed by three TPPs to produce electricity and heat. The consumption of high-quality solid fossil fuel [16] is 5.75 Mt (TPP 1—1.64 Mt, TPP 2—3.69 Mt, and TPP 3—0.42 Mt). About 123 PJ of heat (Table 8) is released from the combustion of said coal amount. The released energy is converted into heat and electricity with 70% efficiency of typical TPPs. The relatively low efficiency leads to irrecoverable conversion process losses of large amounts of thermal energy released in the boiler furnace from coal combustion. High-quality coal is used inefficiently. Using composite fuels from combustible solid and liquid waste rather than coals can significantly reduce the consumption of nonrenewable hydrocarbons.

4.4. Waste-to-Energy Strategy

It is believed that all the energy (about 123 PJ/y) released from the combustion of coal by three TPPs (Table 8) will be generated by the combustion of one of the three groups of fuel compositions (Table 2): group I—FC 90% + MSW 10%; group II—FC 80% + MSW 20%; and group III—FC 70% + MSW 20% + oil 10%. Due to differences in the characteristics of fuel compositions (Table 2), they will require different components if coal is to be replaced by fuel compositions with the equivalent energy yield. Table 9 presents the consumption of different groups of fuel compositions and their separate components within a year and within 25 years (the period of implementation of the proposed strategy) at average values of combustion heat for each group of fuel compositions, according to the data from Table 2: group I—11.91 MJ/kg; group II—13.04 MJ/kg; and group III—16.36 MJ/kg.

Table 9. Consumption of composite fuel and its components.

Period	1 Year				25 Years			
	TPP 1	TPP 2	TPP 3	Total	TPP 1	TPP 2	TPP 3	Total
Energy released from burning coals in boiler furnace *, PJ	35.0	79.0	9.0	123.0	875.0	1975.0	225.0	3075.0
Coal consumption **, Mt	1.64	3.69	0.42	5.75	40.89	92.29	10.51	143.69
Group I:	2.94	6.63	0.76	10.33	73.45	165.79	18.89	258.13
FC	2.65	5.97	0.68	9.30	66.10	149.21	17.00	232.31
MSW	0.29	0.66	0.08	1.03	7.35	16.58	1.89	25.82
Group II:	2.68	6.06	0.69	9.43	67.1	151.45	17.25	235.80
Fuel consumption ***, Mt	2.14	4.85	0.55	7.54	53.68	121.16	13.80	188.64
MSW	0.54	1.21	0.14	1.89	13.42	30.29	3.45	47.16
Group III:	2.14	4.83	0.55	7.52	53.47	120.69	13.75	187.91
FC	1.50	3.38	0.39	5.27	37.43	84.48	9.63	131.54
MSW	0.43	0.97	0.11	1.51	10.69	24.14	2.75	37.58
Oil	0.21	0.48	0.06	0.75	5.35	12.07	1.38	18.80

* Data from Table 8 for 1 year was multiplied by 25 for 25 years; ** deviation of energy released from burning coals in boiler furnace to heat of coal combustion $Q_{s,v}^a = 21.4$ MJ/kg; ***for groups I, II, and III, coal consumption was multiplied by deviation heat of coal combustion to heat of combustion for each group of fuel compositions; for fuel components: fuel consumption for groups I, II, and III was multiplied by component concentrations.

The 25-year implementation of a promising waste management strategy by three TPPs will allow for the total disposal (Table 9) of 130–260 Mt of FC, 25–38 Mt of MSW, and up to 19 Mt of used oils. The measures proposed for the three municipal regions in Western Siberia of the Russian Federation will completely solve the problem of recovering the accumulated waste petroleum oils and annually produced coal processing waste. Adding MSW to the fuel composition will eliminate the problem of

its industrial disposal until the transition affects a new system of waste management with a high share of MSW recycling and reuse [16].

4.5. Economic Effect

The economic effect of implementing the abovementioned strategy can be divided into two parts: (i) revenue—savings from the combustion of a cheap fuel based on industrial and municipal waste instead of costly high-quality coal—and (ii) expenditure—costs of constructing a central plant for fuel preparation and modernization of the process equipment of TPPs (fuel handling systems) when switching from solid fossil fuel to slurry composite fuel.

The economic effect has been evaluated using the algorithm from Reference [32], which was developed for the analysis of prospects of switching coal-fired TPPs to composite liquid fuels. The results of this research and of the previously conducted studies [16,29,30] make it possible to conclude that the combustion mechanisms and characteristics are similar for solid fossil fuels and composite fuels (mixture of industrial waste, MSW, and waste oil). Therefore, the latter can be burned using operating coal-fired boilers. Substantial modernization is mainly necessary for fuel feedstock storing, fuel preparation, and fuel handling systems. To cut down the modernization costs of these systems of operating coal-fired TPPs, we suggest building a central fuel preparation plant for the three TPPs located in the neighboring regions to transport fuel slurries through pipelines to the consumers [26]. This plant would be engineered to store sufficient reserves of initial fuel components, to prepare fuel compositions, and to distribute the ready-made fuel slurries between the three TPPs as required, including the conditions of supplying their 100% loads. Only tanks with homogenizers are to be located on the territory of TPPs to provide the required reserve of the fuel for 5 days and to maintain its performance characteristics when it is fed to the boiler furnace.

The analysis of performance characteristics using the algorithm from Reference [32], which takes into account the source data about the fuel composition, its energy performance indicators, consumption, and cost, suggests that it is economically viable to switch a coal-fired TPP to composite liquid fuel, comparing the following main costs:

(i) Fuel costs (S_1) are estimated by the cost of composite fuel components (assuming the prospective costs of transporting to the fuel preparation site). The comparative cost of different waste (FC, MSW, and used oils) may vary depending on the region and the supplier. In this study, we assume the following fuel costs [32]: 60 \$/t for coal; 8.11 \$/t for group I of composite fuel, 7.42 \$/t for group II of composite fuel; and 15.71 \$/t for group III of composite fuel. The equation for fuel cost calculation is as follows:

$$S_1 = C_{fuel} B_{fuel},$$

where C_{fuel} is the comparative cost of fuel, \$/t, and B_{fuel} is the amount of fuel burnt (Table 9), t.

(ii) The capital cost of constructing a central plant for fuel preparation (S_2) is one of the main nonrecurring costs when switching coal-fired TPPs to composite fuel. It takes into account the price of the process equipment necessary for putting the new fuel preparation system into operation [32]. This item of expenditure also includes the cost of storing the initial fuel components with due consideration of the necessary stock for 5 d [32] on the territory of the central fuel preparation plant. The main expenses of the process equipment acquisition and installation as well as the construction costs are presented in Table 10.

(iii) Modernization costs of fuel handling system of TPP (S_3): Based on the data (Table 8) about the number of boilers at each of the three TPPs (TPP 1—9 boilers, TPP 2—6 boilers, and TPP 3—10 boilers) and the design of typical fuel preparation systems (coal-fired TPPs normally use individual systems of fuel preparation with ball mills and an intermediate bin with coal dust for each boiler), we estimated the modernization costs for the corresponding process equipment [32]. The results (Table 11) were obtained with due consideration of the reuse of some auxiliary equipment (pipelines, valves, and pumps) in the new systems when switching boilers to composite liquid fuel as well as when storing the necessary stock of the prepared composite fuel on the territory of TPPs for 5 d [32].

Table 10. Construction costs of central fuel preparation plant.

Unit	Quantity	Unitary Cost, \$	Total, \$
Storage tank for FC	1	424,757	424,757
Storage tank for used oil *	1	849,515	849,515
Tank with homogenizer	3	379,248	1,137,744
Mill for MSW	1	33,000	33,000
Tank with a mixer	1	50,910	50,910
Building and assembly works	1	230,000	230,000
Total			2,725,926

*Taken into account for group III of composite fuel only (FC 70% + MSW 20% + oil 10%).

Table 11. Modernization costs of TPPs.

Unit	Quantity	Unitary Cost, \$	Total, \$
TPP 1			
Tank with homogenizer	9	45,510	409,590
Extended furnace	9	22,755	204,795
Fuel feeding device (burners, pump, and pipeline)	9	53,095	477,855
Total for TPP 1			1,092,240
TPP 2			
Tank with homogenizer	6	45,510	273,060
Extended furnace	6	22,755	136,530
Fuel feeding device (burners, pump, and pipeline)	6	53,095	318,570
Total for TPP 2			728,160
TPP 3			
Tank with homogenizer	10	45,510	455,100
Extended furnace	10	22,755	227,550
Fuel feeding device (burners, pump, and pipeline)	10	53,095	530,950
Total for TPP 3			1,213,600
Total for all TPPs			3,034,000

(iv) Operating costs (S_4) involve the cost of electricity consumed for fuel preparation system operation. They have been calculated on the basis of the average price [32] of electricity and its consumption per a unit of fuel ready to be combusted in the boiler furnace:

$$S_4 = S_{electricity} G_{electricity} B_{fuel}$$

where $C_{electricity}$ is the cost of electricity, 0.052 \$/(kW·h); $G_{electricity}$ is power consumed for fuel preparation, 38.58 (kW·h)/t for coal and 21.55 (kW·h)/t for composite fuel; and B_{fuel} is amount of fuel combusted (Table 9), t.

(v) Ash and slag waste storage and recovery costs (S_5): Based on the analysis results [32], the transition to composite fuel does not lead to increasing volumes of slag and ash waste. Therefore, these costs, S_5 , do not influence the analyzed economic effect. Ash removal costs make up 0.5% of the total operating costs of coal-fired TPPs. When switching them to composite liquid fuel of one of the three suggested compositions, the ash and slag removal costs will increase due to a higher ash content of the fuel, though for the most promising composition (group III), they will not exceed 1.9% of the total operating costs of TPPs.

(vi) Environmental costs and payment of fines (S_6): The research findings (Figure 5) and the results from Reference [26] show that the main anthropogenic emission concentrations from composite fuel combustion do not exceed the corresponding regulatory characteristics for the flue gases of coal-fired boilers (Table 6). Therefore, these costs do not influence the analyzed economic effect.

The summary results of the calculations made are presented in Table 12. The economic effect (for 25 years) was estimated as a difference between the total costs over 25 years, when all the three

existing coal-fired TPPs are operated, and the total costs within the same period, when those are switched to composite liquid fuel from industrial and municipal waste.

Table 12. Economic effect of switching coal-fired TPPs to composite liquid fuel.

Costs	List of Expenses, mln. \$			
	Coal	Group I of Fuel Compositions	Group II of Fuel Compositions	Group III of Fuel Compositions
Fuel costs (S_1) for 1 year/25 years:	344/8600	84/2100	70/1750	119/2975
TPP 1	98/2450	24/600	20/500	34/850
TPP 2	221/5525	54/1350	45/1125	76/1900
TPP 3	25/625	6/150	5/125	9/225
Nonrecurring capital costs of constructing a central plant for fuel preparation (S_2)	–	1.876	1.876	2.726
Nonrecurring modernization costs of fuel handling system of TPP (S_3):	–	3.034	3.034	3.034
TPP 1	–	1.092	1.092	1.092
TPP 2	–	0.728	0.728	0.728
TPP 3	–	1.214	1.214	1.214
Operating costs (S_4) for 1 year/25 years:	11.5/288	11.5/288	10.6/265	8.4/210
TPP 1	3.3/83	3.3/83	3.0/75	2.4/60
TPP 2	7.4/185	7.4/185	6.8/170	5.4/135
TPP 3	0.8/20	0.8/20	0.8/20	0.6/15
Total costs for 25 years	8888	2393	2020	3191
Savings for 25 years	–	6495	6868	5697

The data from Table 12 clearly demonstrate a decisive impact (85–95%) of the fuel constituent in the typical structure of total costs for 25 years. The total costs of constructing an advanced central plant for fuel preparation and of modernizing the fuel feeding systems for three TPPs are incomparably smaller than the costs of energy resource acquisition to generate heat and electricity. Thus, switching coal-fired TPPs to composite liquid fuel is known to have a positive economic effect even in the short term, as the cost of energy resources (coal and waste-based composite fuel) differs 2.5–3.5 times on average (in terms of a unit of energy released during fuel combustion). During the 25-year realization of the developed strategy of industrial and municipal waste recovery, the economic effect will make up from 5.7 to 6.9 billion dollars, depending on the composite fuel composition (Table 12). The economic effect vs. operating costs of coal-fired TPPs will be from 65% to 78%, respectively. It makes sense to invest the money saved into the development of thermal power engineering to carry out R&D activities for the development of advanced technologies and modernization of TPPs to boost their efficiency. Enhancing the performance of TPPs will make it possible to rationally use nonrenewable hydrocarbons to generate heat and electricity.

5. Conclusions

This paper suggests switching three typical coal-fired TPPs to composite liquid fuel, as illustrated by three neighboring regions of the Russian Federation to implement the developed strategy of industrial and municipal waste recovery. Thermal and electrical energy will be produced by these TPPs on a full scale from the composite liquid fuel combustion. Fuel slurries will be produced and transported to consumers through pipelines from the central fuel preparation plant.

Over 25 years of putting the suggested strategy into practice, 145 Mt of high-quality coal is to be saved. About 10.1 TW·h of electricity and 9.7 Pcal of heat will be generated by the recovery of 190–260 Mt of industrial and municipal waste: 130–260 Mt of FC, 25–38 Mt of MSW, and up to 19 Mt of used oils. The measures proposed for the three municipal regions will solve the problems of recovering used oils and coal processing waste. Burning MSW as a composite fuel component will solve the

problem of its landfill disposal until the waste management system has been transferred to MSW recovery and reuse.

The positive economic effect with due consideration of modernizing the fuel feeding systems of the three TPPs and of constructing a central fuel preparation plant will make up 5.7 to 6.9 billion dollars, or 65–78%, respectively, of the main costs of TPPs operating on coal for 25 years. This is attributed to a decisive impact (85–95%) of the fuel constituent (energy resource acquisition) in a typical structure of total costs and to the cost of energy resources, which differs 2.5–3.5 times for coals and waste-based composite fuel (in terms of a unit of energy released during fuel combustion).

The maximum concentrations of the main anthropogenic emissions (CO₂ at 16–18%; CO at 180–370 ppm; NO_x at 190–400 ppm; and SO_x at 75–135 ppm) in the flue gases of composite fuel do not exceed those from dry coal combustion (CO₂ at 16–18%; CO at 258–344 ppm; NO_x at 340–513 ppm; and SO_x at 450–526 ppm).

Author Contributions: Conceptualization, D.G.; funding acquisition, G.K.; investigation, D.G. and K.P.; methodology, D.G. and G.K.; software, K.P.; visualization, K.P.; writing—original draft, D.G.; writing—review and editing, G.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Russian Foundation for Basic Research, grant number [18-43-700001].

Conflicts of Interest: The authors declare no conflict of interest.

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