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Energy potential of anaerobic digestion of wastes produced in Russia via biogas and microbial fuel cell technologies*

Sergey Kalyuzhnyi‡

Department of Chemical Enzymology, Chemistry Faculty, Moscow State University, 119992 Moscow, Russia

Abstract: The well-known use of the microbiological process of anaerobic digestion (AD) to generate biogas (mixture of methane and CO_2) is now widely implemented for the production of renewable energy worldwide. In Russia, however, this is not the case despite huge amounts of organic wastes (OW) suitable for AD. This paper firstly inventories major flows of OW from various sectors of the national economy (agriculture, industry, households, etc.) and estimates their biogas potential. Special attention is paid to existing bottlenecks and barriers to implementation of biogas technology given the Russian socioeconomic conditions. The second part of the paper is devoted to a new emerging technology based on AD—microbial fuel cells (MFCs). The current status of research in this field in Russia is reviewed in comparison with worldwide developments. The possible niches for implementation of MFC technology in Russia (e.g., wastewater treatment) are pointed out, including its complements to conventional biogas processes.

Keywords: anaerobic digestion; biogas; microbial fuel cells; energy potential; waste.

INTRODUCTION

At the dawn of the third millennium, humankind encountered a number of global problems related, first of all, to the quickly increasing population and the resulting steady growth in energy demand. Since conventional energy sources are, to a significant extent, becoming exhausted, renewable energy sources, including those derived from biomass (i.e., biofuels) will play an important role in the near future [1]. The second factor critically influencing the structure of global energy production is the increased demand of public opinion to minimize the so-called "ecological footprint" of energy-generating technologies, especially with regard to climate changes and dangerous emissions to the environment. In this respect, bioenergetics represents a practically ideal case as compared to the combustion of fossil fuels, because combustion of biofuels does not disturb the planet-wide CO_2 balance.

The microbiological process of anaerobic digestion (AD) is well known for its biogas (mixture of methane, 50–70 %, and carbon dioxide, 30–50 %) generating capability and has been widely implemented for production of renewable energy worldwide. However, this technology has not seen widespread use in Russia in spite of huge amounts of organic wastes (OW) suitable for AD. The objective of this paper is to inventory the major flows of OW from various sectors of the national economy (agriculture, industry, households, etc.) and estimate their biogas potential. In particular, special attention is

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‡E-mail: svk@enz.chem.msu.ru

paid to existing bottlenecks and implementation barriers to biogas technology within Russian socio-economic conditions. The second part of the paper is devoted to a new emerging technology based on AD—microbial fuel cells (MFCs). The current national status of research in this field is reviewed in comparison to worldwide developments. The possible niches for implementation of MFC technology in Russia (e.g., wastewater treatment) are pointed out, including its complements to conventional biogas processes.

BIOGAS POTENTIAL OF WASTES PRODUCED IN RUSSIA

Brief history of biogas developments in the former USSR

In the former USSR, interest in biogas technologies fluctuated between periods of activity and neglect. The first full-scale implementation of this technology occurred in the 1950s, when the largest anaerobic digesters in the world (for that time) were constructed at a Moscow wastewater treatment plant (WWTP) for treatment of a mixture of primary and secondary sludge [2]. The biogas produced was used for heating digesters, and other internal needs of the WWTP and the excess in summer was just burned in a flare. It should be noted that the Soviet scientists and engineers were pioneers in implementation of thermophilic AD (53–55 °C), as only mesophilic AD (30–35 °C) had been applied in other parts of the world at that time. The choice to operate in the thermophilic regime was made due to the better hygienic quality of digested sludge in that range. The system implemented in Moscow quickly became a technological standard in the field of wastewater sludge management in the former USSR. Besides sludge treatment, similar continuous stirred tank reactor (CSTR)-based systems were applied in the 1960s to the treatment of high-strength industrial wastewater such as the acetone–butanol-producing plants in Efremov and Groznyi, etc.

In spite of huge reserves of oil and natural gas, the oil crisis of the early 1970s obliged the USSR to focus attention not only on treatment but also on the energetic function of AD. An additional motivation was that industrial livestock production began to be intensely developed at that time, generating an enormous quantity of waste. After a decade of intensive research and development, the industrial production of biogas installations for manure treatment was organized in Kurgan in the second half of the 1980s.

Unfortunately, economic transformations started in 1992 led to a severe crisis in this field of bioenergetics in Russia, which currently only has around 100 working anaerobic digesters and reactors—sludge treatment in Moscow and Moscow province, local WWTPs of the food industry, a few animal farms using AD of manure, etc. At the same time, the potential for development of the domestic biogas industry is really huge (see below).

Biogas potential of wastes generated by the agro-industrial complex

The estimation, based on available statistics, of the number of agriculture animals [3] shows (Table 1) that, in Russia, around 520 million tons of animal wastes (67 million tons of dry matter, DM) are produced annually, the treatment of which may generate 20 billion m^3 of biogas (70 % CH_4).

Table 1 Livestock production in Russia [3], waste yield [4], and its biogas potential.

Animal	Heads, million	Waste yield[a], t/head/year (moisture, %) [4]	Total wastes (DM), million t/year	Biogas potential[b], billion m^3
Pigs	13.5	2.4 (87)	32.3 (4.2)	1.3
Cattle	21.4	20 (88)	428.9 (51.5)	15.4
Sheep/goats	18.2	2 (85)	36.4 (5.5)	1.6
Poultry	342.8	00.069 (75)	23.7 (5.9)	1.8
Total			**521.2 (67.0)**	**20.1**

[a]Feces + urine.
[b]Average biogas yield: 0.3 m^3 (70 % CH_4)/kg DM [4].

If we take into account all the wastes generated by the Russian agro-industrial complex (Table 2), their annual production accounts for 773 million tons (228 million tons DM). Applying AD for their processing, one may obtain 62.5 billion m^3 of biogas and 121 million tons of high-quality organo-mineral fertilizers. For convenience, theoretical recalculations of the energetic potential of biogas into other types of energy carriers have been listed: 1000 m^3 of biogas (70 % CH_4) = 25 GJ = 0.79 t of oil equivalent = 4.41 MWh ~ 500 L of gasoline/diesel. So, 62.5 billion m^3 of biogas are equivalent to 31 billion L of gasoline/diesel, or, using biogas for cogeneration (conversion efficiency to electricity: 38 %), one can obtain 106 GWh of electricity and 1 billion GJ of heat. For comparison, in 2005, Russian agriculture consumed 1.6 million tons of gasoline, 4.4 million tons of diesel, and 60 GWh of electricity [3]. Thus, the Russian agro-industrial complex may, in principle, become energetically autonomous through a rational utilization of its wastes. Moreover, the electroenergy generated will also be sufficient for supplying electricity to the entire rural population in the country (39 million inhabitants annually consuming 43 GWh of electricity [5]). A similar autonomy can be expected for fertilizers: 14 and 50 million tons of mineral and organic fertilizers, respectively, were introduced on the Russian agriculture fields in 2005 [3], or about two times less than can be produced through AD of wastes.

Table 2 Annual biogas and fertilizer potential of wastes generated by the Russian agro-industrial complex.

Branch	Total wastes, million t/year	DM, million t/year	Biogas potential (70 % CH_4), billion m^3	Fertilizer production (85 % DM), million t/year
Livestock	521.2	67.0	20.1[1]	31.5
Plant breeding	222.2[a]	147.0[a]	36.8[2]	86.5
Agro-processing industry	29.2[a]	14.0[a]	5.6[3]	3.3
Total	772.6	228.0	62.5	121.3

[a]Data from [5].
Biogas yield (m^3/kg DM): [1]0.3; [2]0.25; [3]0.4 [4].

It should be noted that this huge biogas potential has been practically unused until now by the Russian agro-industrial complex. The only exception is a growing application of AD for treatment of high-strength wastewater of food and other agro-processing industries [6]. The modern high-rate anaerobic reactors began to be implemented in Russia at the end of the previous century when the domestic food industry entered its boom phase. Until now, 20 such reactors were constructed, having a total reactor volume above 30 000 m^3 and treating over 61 000 m^3 wastewater per day. Biogas is usually used for the production of hot water or steam consumed internally within plants. Figure 1 gives a distribution of constructed installations with regard to reactor type. A prevalence of reactors with granular sludge [upflow anaerobic sludge blanket (UASB) and expanded granular sludge bed (EGSB) reactors] is clearly observed due to their superior performance compared to the other types of anaerobic reactors. With regard to wastewater origin, anaerobic treatment technologies are mostly widespread in the food industry, especially Russian breweries (Fig. 2). There is no doubt that the invasion of high-rate anaerobic technologies will continue as they are more economically profitable than conventional aerobic technologies.

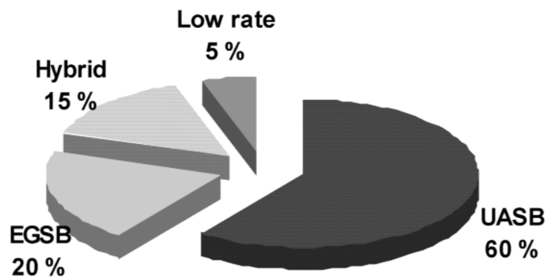

Fig. 1 Distribution of modern anaerobic WWTPs (total: 20) constructed in Russia during 1998–2007 with regard to reactor type (updated from [6]).

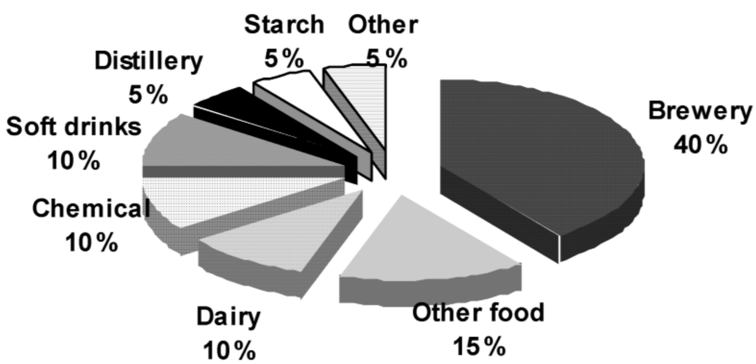

Fig. 2 Distribution of modern anaerobic WWTPs (total: 20) constructed in Russia during 1998–2007 with regard to wastewater treated (updated from [6]).

Biogas potential of municipal solid wastes, wastewater sludge, and landfills

Municipal solid wastes

The annual production of municipal solid waste (MSW) in Russia accounts for 35 million tons [7] or, taking into account the urban population (104 million inhabitants), 337 kg per capita, i.e., approximately 2 times less than in the United States and other western countries [8,9], however, we are quickly eliminating this gap (10 % increase/year [6]). Currently, >96 % of these wastes are disposed of via landfilling [8,9], while around 40 % of MSW consists of easily biodegradable food residues or biowastes (Table 3); annual generation of these in Russia accounts for 14 million tons (50 % DM). Under AD of biowastes, one can obtain 2.1 billion m^3 of biogas (70 % CH_4, biogas yield: 0.3 m^3/kg DM) and 2.3 million tons of high-quality organo-mineral fertilizers. Both products obtained can be easily utilized in the municipal economy but, of course, a separate collection of biowastes should be organized. Some other organic fractions of MSW can, in principle, be used for biogas production; however, primary attention should be focused on biowastes.

Table 3 Composition of MSW in Russia [7], % by mass (if not specified).

Parameter	Value	Parameter	Value
Food residues	32–49	Density, kg/m^3	190–200
Paper and cardboard	22–35	DM	40–65
Wood	1–5	Moisture	35–60
Metals	2.5–5.5	Volatile solids, % DM	68–80
Textile	3–6	Ash, % DM	20–32
Bones	1–2	Combustion energy, MJ/kg	5–8
Glass	2–6	Total nitrogen, % DM	0.8–1
Rubber and leather	0.5–3	Phosphorous (as P_2O_5), % DM	0.7–1.1
Stone and plaster	0.5–3	Potassium (as K_2O), % DM	0.5–0.7
Plastics	3–6	Calcium (as CaO), % DM	2.3–3.6
Other	1–4		
Siftings (<15 mm)	4–8		

Wastewater sludge

Over 80 million m^3 of a mixture of primary and secondary sludge (3 % DM) is generated annually in Russia from a very large domestic sewerage system and numerous municipal WWTPs [10]. The practice of disposal used in Russia of this nonstabilized sludge involves the use of so-called sludge beds for natural drying [10] or application as a fertilizer. Unfortunately, this is unsustainable and leads to the release of numerous, possibly dangerous, emissions into the environment. At the same time, wastewater sludge is a valuable resource especially with regard to its energetic value. As mentioned above, Russia has 60 years worth of unique experience in its thermophilic anaerobic treatment. However, this experience is currently used almost only at WWTPs in Moscow where 25 000–30 000 tons of sludge are daily treated in 44 digesters (total working volume: 277 600 m^3) [2]. Overall, the AD treatment of all the wastewater sludge generated in Russia would produce 0.6 billion m^3 of biogas (70 % CH_4) and only 4 million m^3 (70 % moisture) of stabilized sludge, whose disposal/utilization presents a significantly lesser problem.

Landfills

As mentioned above, landfilling is still a major route of disposal of MSW in Russia [9], and such a practice is far from sustainable. The exact number of landfills within Russia is unknown because of its huge territory, the lack of comprehensive statistics, and the existence of thousands of unsanctioned sites for waste disposal. However, the estimates show that, in total, Russian landfills occupy 0.8 million ha, i.e., an area equivalent to eight cities of the size of Moscow. These landfills not only occupy waste grounds, ravines, and quarries, but also fertile black soils. On a geographical scale, however, landfills do not occupy a great deal of space in Russia, for example, all the MSW which will be produced at current rates during the next 500 years can be disposed of in an area of 600 km^2 with a waste layer thickness of 25 m [8]. By the end of the 1980s, 88 % of landfill sites, according to the inspection of the USSR State Committee of Nature (1989), were in unsatisfactory sanitary condition, emitting many dangerous pollutants to the environment [8]. However, due to federal and provincial programs of MSW management accepted in the 1980s, there is an evident trend currently in Russia toward closure of old landfills and construction of large modern ones having reliable (bottom, walls, and top) insulation, as a result, the number of operating landfills is decreasing (e.g., by 50 % in Moscow province during the last five years). The other trend (especially for big cities) is toward a decreasing percentage of MSW or other OW being consigned to landfill. For example, Moscow is actively implementing incineration plants for MSW [9] while St. Petersburg intends to incinerate a majority of the wastewater sludge produced [11].

Spontaneous anaerobic microbial activity within a landfill also results in the generation of biogas (5–10 m^3/ton of waste per year with a composition similar to the biogas produced from other sources). Landfill gas, if not contained and extracted, percolates upwards through the landfill and is released to the atmosphere, resulting in atmospheric pollution, enhancement of global warming, and creation of the risk of on-site fires and explosions. Although modern landfill sites intend to practice biogas extraction, recovery, and use, Russia contains a historical legacy of closed or still operational, uncontrolled landfill sites. It will require at least 50 years of post-closure monitoring of new landfills in order to minimize their negative impact on the environment. The annual methane emission from landfills in Russia is estimated at 0.7–1.3 billion m^3 [12], i.e., comparable with the amount of biogas which can be obtained by AD of all the Russian municipal biowastes (see above). Several systems of biogas recovery and conversion into electricity have been developed and are now in different stages of implementation [9,13]. However, the extraction and use of landfill gas is hindered in Russia by the fact that the produced electricity is currently more expensive than the electricity generated from fossil fuels or by nuclear stations [13]. Most likely, some kind of state subsidy or tax preference will be required to facilitate recovery and usage of this type of biogas. The other option is to develop a trade of CO_2 quotas resulting from the Kyoto Protocol (this business is in initial stages in Russia).

Bottlenecks for development of biogas production in Russia

Russia has huge reserves of fossil fuels (oil, natural gas, coal, etc.) and is one of the biggest world exporters of energy carriers. This energetic richness has generally a detrimental effect on development of alternative sources of energy in the country, with the exception of nuclear energy. The other bottlenecks are financial weakness of Russian agriculture and municipal authorities, legislative imperfection in the field of waste treatment, and the almost complete absence (until now) of stimulating state policy with regard to renewable sources of energy. However, such a situation cannot last forever, because sooner or later, the existing fossil fuel reserves will be exhausted and the country will have to develop another energy strategy. The first steps are now being taken through the revision of the basic document "Energy strategy of Russia for a period till 2020" [14] where (as planned) substantial attention will be paid to the development of energy production from biomass.

MICROBIAL FUEL CELLS

Brief overview of current status of developments in the field

Besides conventional methane generation, AD also offers another way of harvesting energy from dissolved biomass—by using the so-called MFCs [15–17]. Though this technology is regarded in literature as an emerging one, the idea of employing microorganisms to generate electricity is not new—the first MFC was constructed almost a century ago [18]. However, for many years since that discovery, MFCs did not produce enough energy to be of much interest. But now technological advances are promising to move MFCs from the curious toy to real applications [15,17].

The basic principles of MFCs are similar to a battery or chemical fuel cell (CFC). A simple MFC is composed of two chambers, one containing an anode and the other a cathode (Fig. 3). Fuel (organic matter or biomass) is oxidized by microorganisms at the anaerobic anodic chamber, generating electrons and protons which are attracted to oxygen in the cathodic chamber. However, they move toward the cathode via two distinct ways. A selective membrane separating the two chambers allows the protons to pass through to the cathode while the electrons travel from the anode via an external circuit to the cathode, where they combine with the oxygen and the protons to form water. The stream of electrons passing through the external circuit generates a flow of electricity.

Microorganisms play a key role in an MFC, acting as biocatalysts in analogy to CFCs. First of all, they are responsible for charge-splitting (into electrons and protons) under bioconversion of initial substrate. Secondly, they are involved in electron transfer to the anode, which can be membrane-associated direct electron transfer [19–20] or mediator-associated (indirect) electron transfer [21] (Fig. 3).

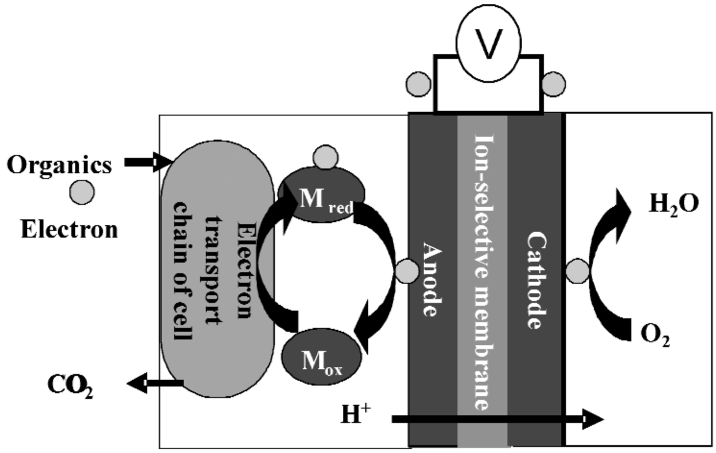

Fig. 3 Schematic representation of MFC.

The mediators in turn can be externally introduced, e.g., redox dyes [21], or internally produced by bacteria [22]. The possible mediation by so-called nanowires has also recently been proposed [23].

A variety of microorganisms [both axenic (pure) and mixed cultures] belonging to numerous genera of anaerobic or facultative species are currently used in MFCs as biocatalysts [15]. This fact implies that such "electrophilic" consortia are ubiquitous in nature. Mixed cultures have some important advantages compared to axenic ones, namely, a higher resistance against process disturbances, a larger substrate versatility, and a higher power output [15–17].

The maximum voltage which potentially can be generated by a single MFC is around 1 V (it follows from process thermodynamics), however, the real voltage achieved so far is 0.5–0.7 V. Until now, the current generated by MFCs has not exceeded 0.1 A, thus, the average power density of a single MFC is currently around 40 W/m^3. Recently, stacked configuration of several MFCs have reached power densities of 250 W/m^3 [24], implying that improvements of MFC performance are under way [15].

However, in spite of the boom observed over the past few years in this field of research, MFCs still face significant limitations with regard to full-scale implementations. The major hurdles are insufficient performance stemming from both anodic and cathodic electron transfer, upscale technical issues, and the as yet still high investment costs.

MFC research in Russia

To the best of our knowledge, research in this field in Russia started only in this century [16–17]. First of all, a nonconventional, so-called sulfate-reducing MFC should be briefly discussed [25]. Its working principle is based on peculiarities of respiration of sulfate-reducing bacteria transferring electrons from organic substrates to their specific acceptor—sulfate. The reduced product (sulfide) plays the role of internal mediator since it is easily oxidized on the anode transforming back to sulfate (assumed major route). The power density of this MFC was around 100 W/m^3 (i.e., 2.5 times higher compared to conventional types of MFC) but, during long-term exploitation, a steady accumulation of elementary sulfur was observed due to incomplete oxidation of sulfide into sulfate. As a result, both the concentration of internal shuttle-mediator and the power densities steadily decreased [25].

In the field of conventional MFCs, the recently proposed multi-electrode bioelectrochemical reactor for wastewater treatment and simultaneous generation of electricity should be mentioned [26]. Due to the original construction of anodic and cathodic chambers, continuous plug flow regime of operation, and better electrochemical properties of the metal-impregnated graphite anodes, this MFC showed enhanced power densities (up to 50 W/m^3) on a variety of fuels (saccharose, acetate, glycerol) used as well as an efficient removal of organic contaminants from a liquid phase [26]. Also, due to modular structure, this MFC can be relatively easily scaled up.

The other ongoing research includes the use of immobilized axenic cultures (e.g., *Gluconobacter oxydans*) with some external electron-transport mediators for development of new types of MFCs [27].

Possible niches for implementation of MFC technology in Russia

In spite of a short history of MFC research in Russia and the current absence of full-scale implementations worldwide, this technology is very attractive for the country. The major driving forces for MFC implementation are the following (many of them are actually for the other countries as well):

- due to the booming economy and steadily improving living standards, there is an increased demand for electricity as a high-grade energy carrier; moreover, currently the Russian economy has begun to feel some deficiency of electroenergy supply;
- due to the vast territory, nonuniform distribution of electricity producers around the country, and thus complex transport logistics, there is a strong need for development of a decentralized supply of electroenergy;
- an extremely broad versatility of fuels for MFCs: in fact, any biodegradable organics can be used for this purpose (e.g., wastes and wastewater); in other words, the fuel has low (if any) or even negative cost;
- a simultaneous solution of energetic and environmental problems; and
- an easy integration into existing systems of waste and/or wastewater treatment.

Because conventional biogas technologies are also focused on waste utilization, one can assume that MFCs are competitive with them. In fact, both technologies have different application niches and are, in some instances, even complementary to each other: the biogas-generating ones are most applicable for utilization of high-strength waste/wastewater, whereas MFCs are better suited for the treatment of low-strength (<1 g COD/l) and cold (<20 °C) wastewater [15].

Based on these features of MFCs, their clearly seen application niches are pretreatment of sewage and posttreatment of anaerobic effluents. For this, the MFC units can be put upfront of existing conventional activated sludge plants, decreasing their load and thus saving aeration costs. Thus, MFCs can be relatively easily integrated into the existing wastewater treatment infrastructure in Russia though the issue of biological oxygen demand (BOD) requirements for subsequent nutrient removal should be carefully considered.

The annual production of wastewater in our country accounted for 52 km^3 in 2006 [28], the average chemical oxygen demand (COD) concentrations may be assumed to be 200 g/m^3 [2]. Thus, the total contamination load can be roughly estimated as 10.4 billion tons COD/year. For treatment by conventional aerobic technologies (energy consumption for aeration is 1 kWh/t COD), Russian WWTPs annually spend around 10.4 billion kWh of electricity. Through implementation of MFC technologies (under their 30 % efficiency), one can directly obtain 13.8 billion kWh electroenergy (brutto). In addition, at least 3.1 billion kWh will be saved by WWTPs because of the elimination of aeration for minimally 30 % of load. Thus, the total gains will account for more than 16 billion kWh of useful electric energy, i.e., ~2 % of electricity production in Russia (991 billion kWh in 2006 [29]). Moreover, WWTPs may loose their image as strong consumers of electricity; possibly even becoming energetically autonomous (or even generating) units. But of course, significant financial, intellectual and political resources should be put into Russia to achieve such a prosperous future.

CONCLUDING REMARKS

The analysis presented above clearly shows a high potential for AD (both conventional biogas and emerging MFC technologies) in Russia. The Russian agro-industrial complex may become, in principle, self-sufficient with regard to energy and fertilizers through the proper utilization of its wastes, e.g., by conventional biogas technologies. However, until now, this potential has been largely overlooked except in the increasing application of high-rate anaerobic technologies for treatment of wastewater generated by processing industries. A similar situation is found in the field of municipal waste/wastewater management. The Russian cities (especially the larger ones) spend an enormous amount of money for its treatment/utilization and final disposal (e.g., incineration and landfilling) instead of applying the more resource conserving and cheaper technologies discussed above. Landfilling of OW is banned in many EU countries due to methane and other emissions; however, this is still a major practice (though with some recent improvements and protective measures) in the solid waste management industry in Russia. This creates (and will create) big problems for the fulfilment of our obligations under the Kyoto Protocol. However, since currently the Russian economy is demonstrating an accelerated growth inspired by high oil prices, now is the proper time to change the internal policy in the field of renewable sources of energies and waste management in order to direct the country to a more sustainable path of development.

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