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学位論文題目	Design of an Integrated MSW Management System Considering Energy Recovery in St.Petersburg, Russia （ロシアのサンクトペテルブルグにおける一般廃棄物のエネルギー利用に関する研究）
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論文内容要旨

The management of solid waste has become a significant problem that includes technical, economic, environmental and social issues. Technical and economic problems emerge in part because of rising demand due to income and population growth, a rising level of urbanization, and a decline of suitable disposal sites. The environment has a limited capacity for waste assimilation. In case too much waste enters the environment rather than being recycled or reused, the assimilative capacity of the environment is put under too much stress to be able to handle the total quantity of waste generated. These problems challenge researchers to find for more efficient solid waste management methods. Environmental and social issues emerge as people become increasingly concerned about the risks associated with living close to solid waste facilities. MSW can be treated in several ways. It can be composted, incinerated, recycled or landfilled. Landfilling is the least environmentally friendly waste treatment option.

However, until several decades ago, landfilling of MSW was very popular in Russian Federation (Russia). Currently, Russia is the world's third largest emitter of greenhouse gases (GHGs), with roughly 1,700 million tons of carbon dioxide emissions a year and a steady projected annual growth rate, follows the United States and China, thereby significantly contributing to climate change.

This research effort will focus only on municipal solid wastes typically found at urban are of Russia. Since this research focuses on municipal solid wastes, the disposal of medical and industrial wastes, as well as nuclear wastes will not be addressed. It is necessary to mention that, the target area of present research is limited to the St. Petersburg city, the second largest city in Russia after Moscow, located in North-West federal district. The regional differences and changes in climatic conditions consequences are outside the scope of this study. The overall objective of this research is to design of an integrated municipal solid waste (MSW) management system

considering energy recovery from waste treatment processes in St. Petersburg city, Russia. In this thesis, a linear programming model has been developed to analyze the waste management problem, as well as to evaluate the interactions between the waste treatment sector and several demand sectors, such as energy, industrial and agricultural sectors. Incorporation of policy instruments has been also implemented.

The waste treatment technologies considered in this research include landfilling of all types of waste with landfill gas (LFG) extraction, incineration of all waste fractions with energy recovery, recycling of all types of waste except organic, anaerobic digestion and large scale composting of organic and paper waste. The anaerobic digestion is assumed combined with composting facilities to increase the quality of composting product by including the digestate. Each technology is characterized by several specific parameters, such as costs (capital investments, operating and maintenance), emissions coefficients, and types of generated by-product. The energy produced from incineration, and the biogas produced from landfilling and anaerobic digestion, are assumed to be used either for heating and/or for electricity generation. Electricity or heat produced from waste treatment processes is assumed to be supplied to the existing electrical grid or to the district heating system (DHS).

The application of the model clearly showed the benefit in terms of CO_2 emissions reduction and increasing the types of by-products from the waste treatment activities. Among the scenarios considered, the increasing of alternative MSW treatment options gives positive energy, and economical and environmental benefits compared with the present MSWMS. According to the calculation results, transportation costs consume the largest portions of the total cost of the proposed MSW utilization system. From the sensitivity analysis of the best scenario (Low cost), it can be seen that changes in waste transportation distance have a significant effect on the cost of the proposed MSW system. The achieved results demonstrate that the presence of LFG recovery system as WTE treatment options has a significant influence on the modeling results.

The results of the model application clearly indicated the effectiveness of the landfill tax and subsidies as a waste policy instrument, in terms of promotion of other waste treatment technologies. Based on the results of the present analysis, it was found that introduction of landfill taxes has a significant effect on GHG emissions and promotion of other alternative technologies. However, the optimal value of landfill taxes is strongly depending on existence of other waste treatment facilities, recycling market and type of waste materials. In addition, the existence of LFG recovery systems has a significant impact on the configuration of MSWMS designed for the target area. Compare with landfilling tax, the introduction of subsidy for anaerobic digestion technology seems to be not effective in the present system.

Currently, most of MSW in Russia is disposed of in landfills, burnt, or illegally dumped, as there is no special government regulation on MSW treatment. Therefore the optimal waste utilization system with energy recovery designed at this research could have good prospects for diffusion throughout Russia (applied in all cities and areas).

According to the result of the St.Petersburg case studies, the energy generated from MSW may substitute fossil fuels and reduce GHG emissions resulting from energy activities. Emissions of other air pollutants, i.e. NO_x, CO, SO_x and also particulates can also be reduced. Energy production from WTE facilities can be in the form of electricity and/ or heat for district heating. In Russia, given the good infrastructure for DHS at present, not only electricity generation but the heat generation would be a reasonable option. However, based on the results of the present analysis, from the economical point of view, only heat generated from the MSW seems to be more appropriate than electricity production. At presence, due strong price control and existence of cross subsidies inside Russia, the price of energy (0.02 USD/kWh) is much lower compared to international standards (0.05-0.10 USD/kWh). Due to the current low prices of energy from fossil fuels, the high production cost (0.13 USD/kWh) of energy from waste represents the main barrier to expand waste to energy technologies in Russia. However, it should be kept it mind that WTE facilities serve a dual role of waste disposal and conversion of MSW to a much smaller volume of inorganic ash, as well as of energy and by-product (compost, recycled materials) production. Although the energy production cost may be more expensive for WTE than from convention sources, the benefits of waste management, energy and materials recovery, and reduction of GHG emissions need to be factored in. In addition, if industrial facilities were to be developed near WTE plant, it could make use of the by-product steam/heat for manufacturing processes, thus improving the efficiency of energy production from a WTE plant.

As demonstrated in this research, the restrictions regarding to landfill site, such as fixed landfillig rate and landfill tax introduction, have a strong influence to the choice of the optimal waste treatment technologies and transportation distance, as well as a positive effect on decreasing of GHG emissions. In order to decrease the cost of waste transportation, as well as the cost of the MSW management, international cooperation related to the trade of MSW can also be considered as alternative options. Nevertheless, establishment of the suitable policy and well organized process of waste separation involving the population are the main requirements. In the near future, improvement of recycling market and introduction of waste separate collection has positive and realistic solution which can be applied in the target area.

The outcomes derived in this study can be successfully implemented in the regions (cities) in other terms than those in Saint-Petersburg. For instance, in remote and not sufficient in energy resources regions with a high cost of transportation of energy resources, the cost of energy produced from waste will be equal to or even lower that the energy from fossil fuels. In such regions implementation of the proposed system will be more efficient from energy perspective than from environmental point of view.

To summarize, besides improving the environment, the proposed MSW utilization system is feasible from economically and partially from energy points of view. In addition, if introduced the developed MSW treatment system will provide many benefits, such as: a) Reduction of

environment pollution (ground cased by waste disposal and air pollution from open dumping and burning of waste); b) Overcoming social issues occurred from illegal waste disposal (open dumping); c) Conversion of non reusable waste into combustible gases for heat production, for better economic benefit; d) Utilization of municipal solid waste to reduce the use of fossil fuel for heat production; e) Reduction of GHG emissions; f) Cleaner environment for a better public health (odor, seeping of contaminated or polluted water, potential spreading of disease); g) Creation of job opportunities; h) Dissemination of a good MSW treatment technology to other regions in Russia.

Based on the findings of the present research and the existence of several limitations that constrained present analysis, to provide some directions for future research a number of recommendations have been formulated. The way in which MSW are treated is strongly related to many factors, which are differ from country to country. With regard to the choice of optimal MSW treatment options/technologies, to be appropriate to the local conditions of the target area consideration of several aspects is required. Such aspects may include the amount of the generated waste, waste composition and density, economic, energy and climatic conditions, urbanization rate and consumption patterns, existence of recycling market. In addition, several issues related to the social aspects, such as household size, occupation, income, willingness and ability to pay may also be included in the consideration.

The existence of well developed and competing market for recyclable materials has the strong relation to the choice of appropriate waste management strategy. To be able to move towards a more sustainable waste strategy, local governments in Russian federal districts need to introduce more socially acceptable waste policies. To achieve this, governmental institution must not only raise public awareness of the importance of waste policy, but also to improve present waste management system and public understanding of the benefits which exist on waste. For better promoting waste diversion, in addition to regulatory and economic tools, from a systematic perspective, the local government should also strive to improve the integration and cooperation of multiple agents, such as nongovernmental organization (NGO), research institutions, etc. Awareness of the effects that occur due to introduction of the MSWMS may affect the system in different ways. With awareness, the general public should know about risks related to the MSWMS and about the ways to protect themselves. Environmental education should be aimed to make people aware but at the same time understand their role in the MSWMS. There is a need to develop a sustained public education program on waste separation, prevention and reuse. If such education practiced in schools, offices and community centers located in St.Petersburg, in the future it could possibly be adopted into the community's way of life.

論文審査結果の要旨

開発途上国に低炭素社会及び循環型社会を実現させるためには、地域に散在する資源の利活用と、それを支援する地域社会のシステム設計が重要である。なかでも一般廃棄物は、高い発熱量を有するバイオマスの一種であり、その利活用に際しては地域の生活仕様や気候条件に密接に関係するので、廃棄物のマテリアルフローに加えてエネルギーシステムの詳細なモデル化とその特性評価に基づくシステム設計がきわめて重要となる。本論文は、地域熱供給のエネルギー源を化石燃料に依存してきた開発途上国(Russia)の州都サンクトペテルブルグを対象として、地域の特徴に合致するエネルギー利用システムを設計することを目的としている。ロシアの一般廃棄物処理システム向上やシステム性能について経済・環境・エネルギー評価の観点から初めて探求したものであり、全編6章から成る。

第1章は序論であり、本論文の目的、構成、背景について述べている。

第2章では、一般廃棄物を対象とするエネルギー変換と利用技術の先進事例を調査し、ロシアの現況と比較して総括している。廃棄物由来のエネルギー利用の効果を、廃棄物最終処分場の削減、再資源化率の向上及び廃棄物処理方法の改善など多様な観点から洞察している。

第3章では、一般廃棄物をエネルギー利用する一連のシステムを対象とした、数理モデルを構築している。線形最適化手法を用いて多様な目的に応じた解を導出する解析プログラムを作成して、システム性能を評価する手法を独自に考案している。

第4章では、対象都市の一般廃棄物由来のエネルギー生成量を、解析プログラムを用いて導出している。埋立による最終処分率の制約が、発電量と熱発生量に及ぼす影響を明らかにしている。多様な廃棄物組成やエネルギー変換機器の影響を詳細に解明し、経済性、エネルギーフロー等の各観点から最適なシステム構成を明示している。電力及び熱エネルギー生成に加えて、リサイクルに伴う有価物の需要に着目して解析することによって、エネルギー利用システム設計にきわめて重要な成果を得ている。

第5章では、以上で得られた知見をもとにして、開発途上国の廃棄物由来のエネルギー利用システムの設計指針をまとめていて、地域特性、技術性能を内生化した具体的な設計方策を明示している。

第6章は、結論である。

以上要するに本論文は、開発途上国の循環型社会実現とエネルギー利用向上に向けた一般廃棄物利活用のエネルギーシステムの設計指針を初めて明らかにし、廃棄物組成に応じたエネルギー変換の最適構成と地域社会への影響を明示したもので、熱工学およびエネルギーシステム工学の発展に寄与するところが少なくない。よって、本論文は博士（工学）の学位論文として合格と認める。