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https://doi.org/10.15017/16593

出版情報：九州大学大学院総合理工学報告. 22 (2), pp.183-192, 2000-09. 九州大学大学院総合理工学府
バージョン：
権利関係：

九州大学大学院総合理工学報告
第22巻 第2号 183-192頁 平成12年9月

Engineering Sciences Reports, Kyushu University
(KYUSHU DAIGAKU SOGORIKOGAKU HOKOKU)
Vol. 22, No. 2 pp. 183-192 SEPT. 2000

Energy Infrastructures and Underground Space Utilization

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(Received May 30, 2000)

Energy infrastructures in the future urban areas need to manage various profiles of energy demand and supply required within the area through the year, also allowing long-term flexibility for utilizing new energy systems. To improve overall efficiency of energy use in the urban areas, satisfying the above requirements, underground space utilization for the urban energy infrastructures that enable a flexible network of distributed-type facilities could be one of appropriate options. In order to realize this underground network concept, a network planning approach to evaluate proper energy balance is essential. Also, categorizing and classifying transferred items and depth of underground space to be utilized will be valuable in establishing a set of data on the first tentative plan of the network. The discussed network routes covering a 700km length as a total, consists of a combination of a circulation-shaped network and a radiation-shaped network, assuming a typical urban area as the base for the study. This paper concludes that an appropriate planning with long-term flexibility for new energy systems enables the underground energy infrastructures that improve the energy efficiency and the environmental conditions in the urban areas.

1. Introduction

Although it is obviously significant issues for human beings to improve current efficiency of energy systems in urban areas, both reducing environmental influences caused by the energy use and maintaining flexibility of the energy systems for possible convert to new energy options in the future are also essential and rather challenging subjects. Utilization of underground spaces will be one of appropriate approaches to improve these issues. This paper discusses an approach to improve energy use efficiency and optimization, showing an appropriate planning of new energy infrastructures, introducing an underground network concept.

This paper proposes a concept of an underground network of energy systems that will be enabled by 1) highly efficient distributed-type energy facilities, 2) network systems and 3) energy flow management systems. In addition, 4) proper planning approach is also significant due to a long-term construction and operation period of the systems.

In order to provide an implementation approach of the concept, this paper discusses the current and the future energy systems, based on the evaluation data on an assumed metropolitan area as a typical study model to be studied in this paper, utilizing actual data set referring to the Tokyo metropolitan areas. In accordance with the result of the transfer load analysis, typical cross sections and network routes to cover the areas are shown to balance the energy demand and supply profiles in the area. Over 700km of the underground network systems that have five different routes are referred to for the discussions. Also, a conceptual model of the underground infrastructure network is shown.

As a result, this paper concludes that long-term flexibility, taking into account new energy options in the future, is one of the most significant features for the future energy infrastructures in underground spaces of the urban areas, in order to satisfy both the required energy use efficiency and the energy network optimization, in terms of economics and environmental influences.

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2. Approach to improving energy use efficiency in urban areas

For future urban areas, it is essential to establish an efficient energy supply system that covers the whole urban area and efficiently utilizes valuable energies, and reduces waste amount and emission influences, such as NO_X, SO_X, and CO_2, to improve a demand and supply balance of required energies in the areas [1)2)]. To meet the requirement, it is necessary to improve not only a performance of existing energy facilities but also energy flow conditions among the facilities. However, a careful study on current problems and a future goal of the area need to be conducted to obtain a satisfactory result by the modification of the energy flow conditions, taking into account renewable energy technologies, such as photovoltaic, as alternative energy options, from the standpoint of long term energy management. Otherwise, a large investment may result in only a small improvement, or even result in a negative effect in terms of urban-wide and long-term energy flow management [3)4)]. **Fig. 1** shows a planning flow to improve such energy use efficiency in an urban area, assuming a future introduction of the urban-wide energy flow management systems, where an energy network has significant functions of the introduced system. Since underground space would allow flexibility for networks among each facility, energy infrastructures utilizing underground spaces could significantly improve energy balances in the future urban area, when a proper plan is established based on a detailed, actual data analysis along with the improvement approach shown in **Fig. 1**.

3. Underground network of energy infrastructures

3.1 Concept of underground network

Fig. 2 show a concept of an underground network of energy infrastructures in future urban areas. The proposed concept interconnects a business office area, residence area, energy center, and industrial area by underground network. Each area has different energy profiles (demand and supply) that will be balanced by proper energy management. This network system consists of highly efficient distributed-type energy facilities and energy flow management systems.

3.2 Network plan

Here we discuss a network planning procedure. Although the final network plan should be determined after a detailed study on overall investment and profitability analysis obtained by the plan, we at first need to set up a tentative area that the network plan will cover. Based on the current conditions and quantitative data on the area regarding energy or material transfer situations [5)6)], observed environmental problems, or social and industrial functions of the area and their future plan, etc., we could

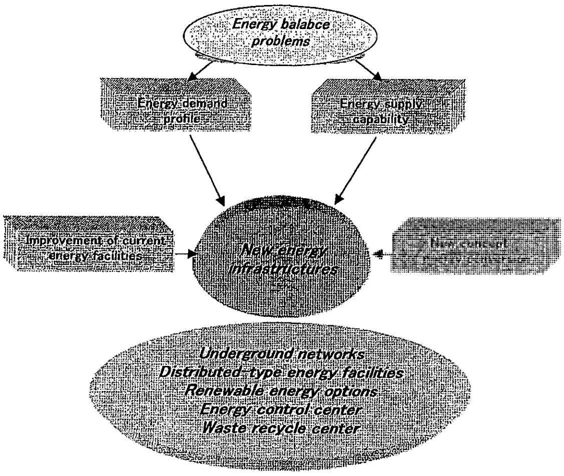

Fig. 1　Planning flow of energy infrastractures

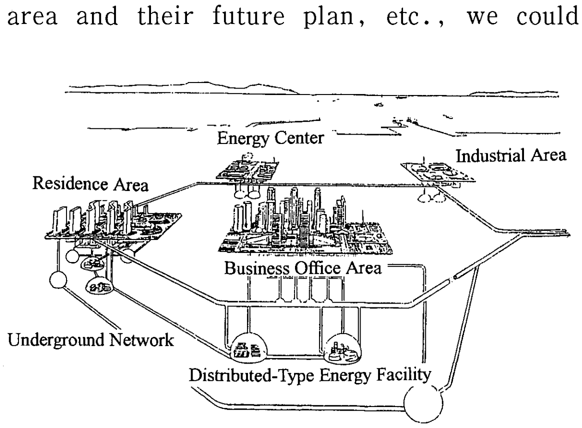

Fig. 2　Concept of underground network of energy infrastrucures

prepare a network plan for a further detailed analysis.

It should be noted that both existing infrastructures and new energy facilities will be reviewed, in accordance with the procedure described below:

(1) Identification of transfer items and future energy structures

The proposed network plan will cover transfer activities in urban areas including energy and fuels (electricity, gas, oils, thermal energy, hydrogen and methanol, etc.), compressed air (energy storage and air supply), water (drinking water, industrial water and sewage water), wastes (municipal waste and industrial waste), recycle energy and materials (thermal energy and recycled materials), packages and containers, transportation and information, etc.

(2) Depth leveling

Each transfer item could be categorized into different underground depths such as shallow, middle deep and deep underground, based on the local station of each item.

(3) Network plan category

Also, each item can be classified into five different categories based on current conditions and a future plan, as follows:

a. Currently existing on the ground, and will be moved to underground in the network plan
b. Already existing underground and will be included into this network plan
c. Expected to bring future network needs when the underground facility is constructed in the future
d. At present, not transferred either on the ground or underground, however future network needs and applicability will be expected when the urban, social and energy structures are changed in the future
e. Not included in a. through d. and excluded from this plan

Table 1 summarizes the above discussion items and shows an example of network planning review and classification, assuming a typical urban area in Japan.

Based on the discussion result of each transfer item as shown in **Table 1** and analysis data including current problems, improving needs, effects of underground network, technical subject and economical impact to realize the network plan, we need to establish long-term network planning for the area.

3.3 Network models

Assuming a typical metropolitan area, such as a metropolitan area including Tokyo in Japan, we discuss an underground network model of energy infrastructures. The purpose of this modeling is to provide underground network features based on a certain numerical data set, to discuss effects and subjects toward its realization.

(1) Assumptions of the model

a. Area : Metropolitan area with a population of approximately 10 million
b. Basic concept : Flexible underground network can be planned with interconnecting various energy related local stations that are also included in the network concept. Distributed-type energy facilities will play significant roles in the plan as local stations. New energy sources or new energy supply systems, such as photovoltaic, hydrogen supply, or compressed air energy storage, are assumed to be utilized in the plan.
c. Items to be transferred : Energy and fuels (electricity, gas, oils, thermal energy, hydrogen and methanol, etc.), compressed air (energy storage and air supply), water (drinking water, industrial water and sewage water), wastes (municipal waste and industrial waste), recycle energy and materials (thermal energy and recycled materials), packages and containers, transportation and information
d. Technologies : Technologies to realize the network plan are based on current available

Table 1 Summary of

Transfer Energy/Material	Study Items	Facilities in Network: Local Facility/Station	Shallow	Middle	Deep
Energy/Fuel	Electricity	Transformer Station	○	○	
		Underground Power Plant		○	○
		Underground Waste Incineration			○
		CAES-GT (Gas Turbine)			○
		CG (Compressed Gas) ES		○	○
		Fuel Cell		○	○
		SMES		○	○
		Electric Car			
	Gas	Gas Supply			○
		Underground Holder			○
		CGES		○	○
		Pipelines			
	Oil	Oil Supply		○	○
		Underground Factory		○	
	Heat	Co-Generation plant		○	○
		Thermal Energy Supply		○	○
	H2, MeOH	Production & Storage		○	○
Air	Air	CAES-GT (Gas Turbine)			○
		Supply to Underground Facilities	○	○	○
Water	Drinking Water	Water Supply Facility	○	○	○
	Industrial Water	Water Treatment Facility		○	○
	Sawage Water	Water Treatment Facility		○	○
Waste	Municipal Waste	Underground Incineration		○	○
		Waste Collection & Storage	○	○	○
	Industrial Waste	Treatment Facility			
		Excavated Soils			
Recovered Energy/Material	Recycled Thermal Energy	Thermal Energy Center		○	○
		Subways		○	
		Transforme Stations		○	
		Sewarage Treatment Facility		○	
		Water Routes		○	
		LNG Storage Tank		○	○
		Thermal Storage	○	○	
	Recycled Material	Recycling Facility	○	○	
Package		Handling Center		○	○
Iransportation		Underground Network (Parking)	○	○	○
		Station		○	○
Information		Information Technology Center			

Facility Planning

Cetegories				
a. Currently existing on the ground, and will be moved to underground in the network plan	b. Already existing underground and will be included into this network plan	c. Expected to bring future network needs when the underground facility is constructed in the future	d. At present, not transferred either on the ground, however future network needs and applicability well be expected when the urban, social and energy structures are changed in the future	e. Not included in a. through d. and excluded from this plan
Cable	Underground Cable	Underground Cable		Cables outside
		Generated Power		the targeted area
		Generated Power		
		Generated Power		SMES
		Generated Power		
			Underground Cable	
Pipeline	Pipeline			Low pressure
		Pipeline		Pipeline
			Pipeline	
Oil supply to Station		Supply to station		
Oil supply to Factory		Supply to station		
		Thermal line		
Thermal pipeline		Thermal line		
			Pipeline	
		Supply line		
		Supply line		
	Pipeline			
	Pipeline			
	Pipeline			
Waste collection		Secondary waste		
Capsule/pipe transfer				
		Transfer to surface		
		Underground transfer		
	Recovered thermal	Recovered thermal		
Capsule/pipe transfer		Valuable material		
Underground route				Mail/package
			Underground system	Underground parking
				Underground parking
		Underground IT center		

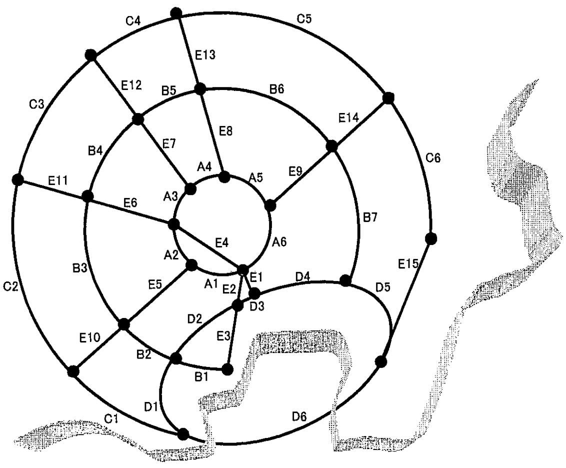

Fig. 3 Simplified schematic routes of underground network

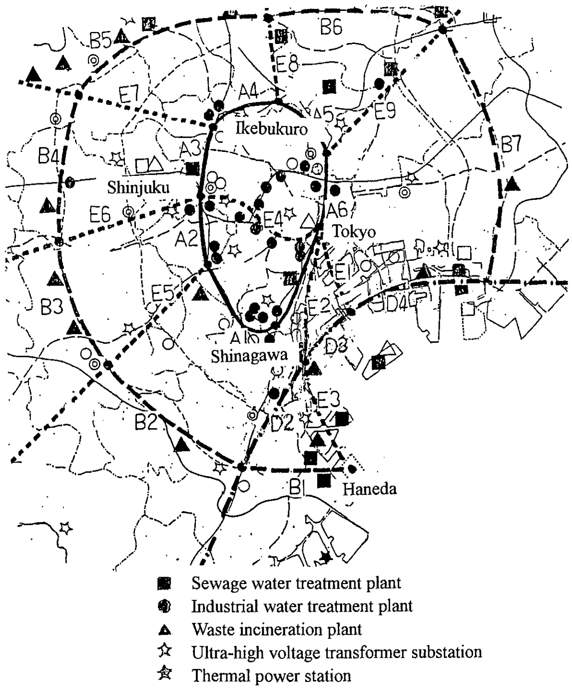

Fig. 4 Local facilities and assumed network cocept in Tokyo area

technologies and future possible technologies that are currently being developed for the energy supply system and underground network construction.

e. Time frame : 2005-2080

(2) Underground network

Fig. 3 shows an underground network model that was derived based on the above assumptions. Total length of this network is approximately 700km, with five typical route groups; four circular-shaped route groups A, B, C and D, and one straight-shaped route group E. They cover different areas with various transfer needs and energy demand. Crossing point of each route are shown as dotted marks that divide each route into subsections such as A1, A2. Because illustrated routes in **Fig. 3** are simplified schematic routes for the discussion, it should be noted that the actual routes are to be determined reflecting the actual site conditions, the transfer needs and load profiles, and the existing local energy facilities, when this planning is applied to the existing urban areas. Based on the transfer needs and energy demand profile, transfer pipeline and necessary space are evaluated. **Fig. 4** shows some local facilities of the Tokyo metropolitan area used for this modeling study as a representative data sample for route A, B, D and E. In **Table 2**, assumed transfer loads of individual routes of the network are shown. As a typical example, **Fig. 5** illustrates a cross section of route D3 that handles the largest transfer loads among the network plan of this study. The following are typical features of each route group:

Route A (A1−A6) :

Metropolitan circular route located at the center of the assumed metropolitan city. Total length of this route is estimated to be 31km. Within this route, 18 industrial water treatment facilities exist and one waste incineration plant is in operation. There are also four ultra high-voltage transformer substations, two drinking water supply stations and one sewage water treatment plant within this route. Introduction of this route improves energy balance and environmental problems currently observed at the center of the city. More green areas can be introduced after the plan is realized.

Route B (B1−B7) :

Metropolitan circular route located outside of Route A. Total length is estimated to be 66km. Between route A and route B, there assumed to be six sewage water treatment plants and eight industrial water treatment plants. Three waste incineration plants are treating

Table 2　Transfer Volume of Each Route

Route Name		Distance (km)		Typical Transfer Load		
Route	Name	Overall	Route	Recovered thermal energy	Waste	Commercial packages
A	A-1	31	11	2,000 Tcal/year	150K ton/year	26 million ton/year
	2		4			
	3		4			
	4		4			
	5		4			
	6		4			
B	B-1	66	6	5,100 Tcal/year	550K ton/year	12 million ton/year
	2		10			
	3		7			
	4		8			
	5		11			
	6		10			
	7		14			
C	C-1	200	34	6,000 Tcal/year	2,130K ton/year	28 million ton/year
	2		23			
	3		32			
	4		23			
	5		50			
	6		38			
D	D-1	138	37	1,100 Tcal/year	150K ton/year	56 million ton/year
	2		7			
	3		4			
	4		8			
	5		27			
	6		55			
E	E-1	272	5	Included in the above loads to interconnect networks		37 millfon ton/year
	2		8			
	3		7			
	4		8			
	5		8			
	6		8			
	7		8			
	8		5			
	9		9			
	10		32			
	11		29			
	12		26			
	13		35			
	14		52			
	15		32			

combustible wastes.　Also six ultra-high voltage transformer substations exist between route A and B.　The area covered by route B primarily represents residence area and newly planned integrated industrial parks that require efficient network needs to be the center of the metropolitan covered by route A.

Route C (C1－C6) :

This route covers outer area of route B.　The total length is assumed to be 200km. Almost areas interconnected by this route are satellite-type cities where clear needs for underground is not identified, however, in the 21st century, more materials are assumed to be transferred between the center of the metropolitan and these satellite-type cities.　In this case, an efficient transfer network not depending on surface truck transportation is desirable from both

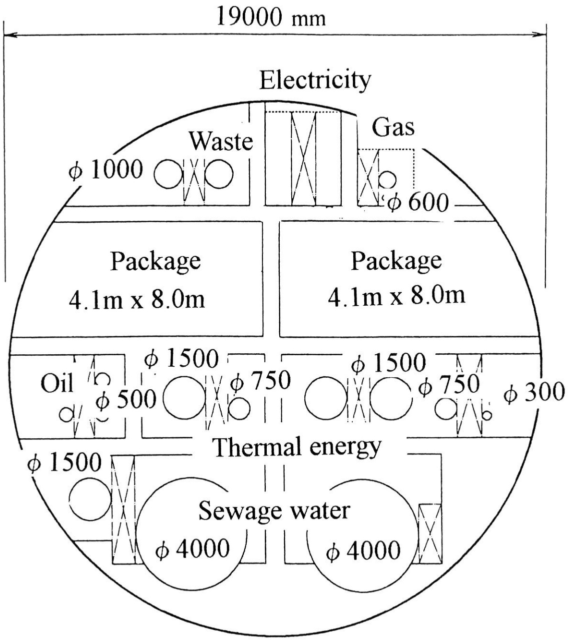

Fig. 5 Cross section of Route D3

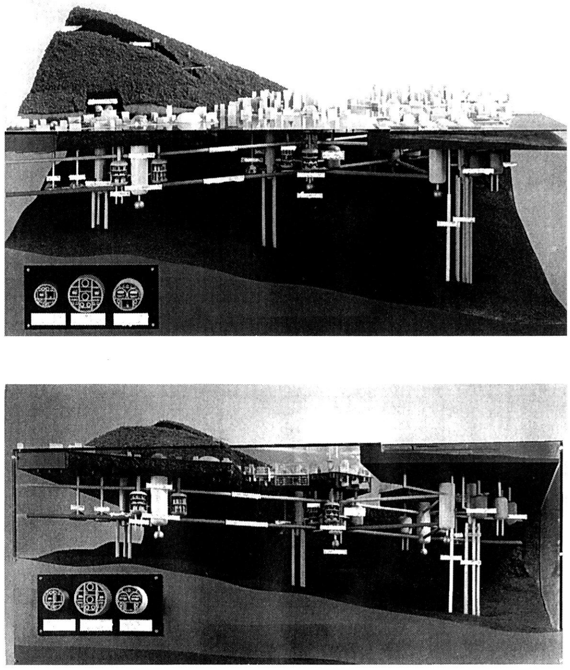

Fig. 6 Conceptual model of underground network

5energy saving and environmental point of views. In this model study, it has been assumed that the number of energy related facilities that should be included into the underground would be small, except material handling and transfer local stations.

Route D (D1－D6) :

This circular route covers a bay area of the assumed metropolitan, such as the Tokyo bay area. Along with this route that has an estimated length of 138km, it has been assumed that many energy related facilities, such as thermal power stations, natural gas stations or industrial facilities would exist, generating a large amount of excess thermal energies. Materials and fuels are to be transferred in large quantities among these facilities. Generated wastes also need to be transferred to their treatment facilities. This route is a very active route as well as route A of this model evaluation. Metropolitan side of this route covers five sewage water treatment plants, three waste incineration plants, two thermal power stations and one industrial water treatment plant along with only 19km of the route (D2－D4).

Route E (E1－E15) :

Route E represents straight networks from the center area (route A) toward outer areas, crossing route B or D, except E4 that ties inner side of route A. This route has a length of 272 km totally of E1 through E15. This radiation-shaped route will play a significant role in the 21st century connecting the center of the metropolitan and outer new functions surrounding the metropolitan. Also, this route has important functions of interconnecting route A through D, as only a radiation-shaped route in this plan.

3.4 Long-term flexibility and further optimization

Figs. 6-8 show several photograph views of the network conceptual model discussed in this paper covering a business area, industrial area and energy center, etc., showing underground local energy stations, such as waste treatment center, sewage water treatment center, recycle center, gas holder, compressed air energy storage systems or thermal energy storage systems. Transportation systems and energy related networks are sited in different underground levels. In **Figs. 7** and **8**, underground substations such as waste treatment facility or energy storage facility are shown.

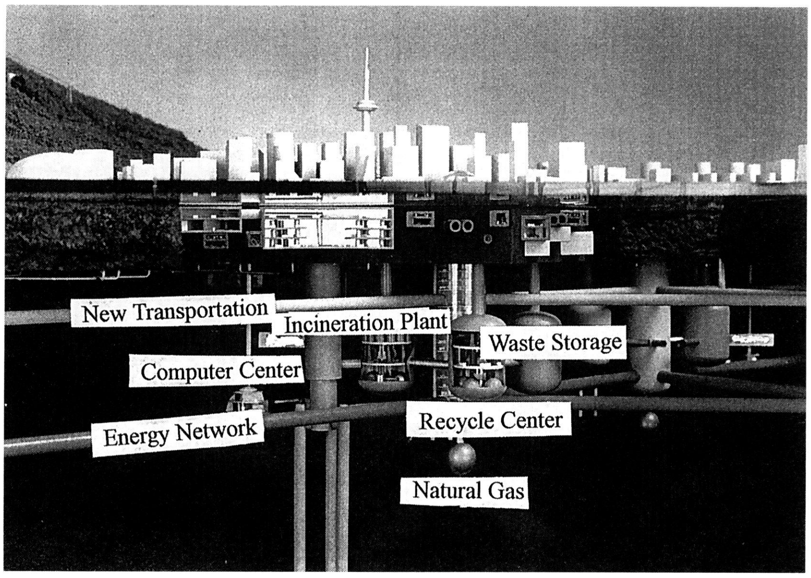

Fig. 7 Local substations (Waste treatment facilities)

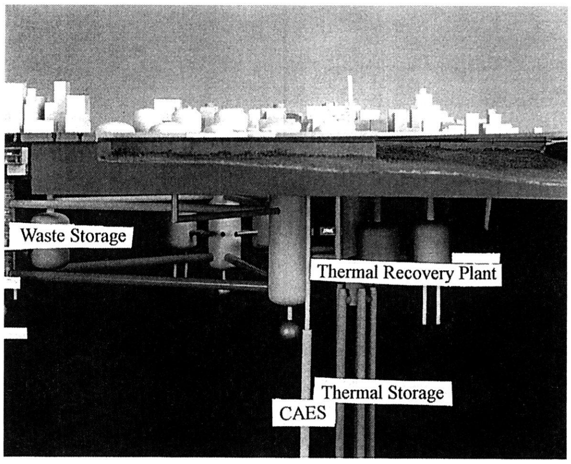

Fig. 8 Local substations (Energy recovery and storage facilities)

The importance shown in this conceptual model is that underground is flexible for original installation of various facilities, however, once they are constructed in underground spaces and interconnected, modification of them would require complicated work and investment, because access to the underground spaces will be so limited. In addition, a long time frame of the use of the underground network should have allowance to reflect future technology development or new innovations for the covering area's next energy options. This means that designs not only for station structures but also for network lines should take account of flexibilities for further optimization using new technologies. A quantitative analysis, therefore, is necessary to obtain a proper network plan. Also, because this construction plan requires a long term, we need to start the use of some parts of the network during construction work in other parts of the network. The appropriate long-term extension plan of the network is essential to optimize the underground network plan.

4. Conclusion

The energy network planning approach proposed in this paper will provide the urban areas that need improvement of energy supply and demand balance with appropriate solutions. Especially, categorizing and classifying approach of transferred items and depth of underground space to be utilized will be valuable in establishing a data set of the first tentative plan of the network. Base on the tentative plan, an energy flow analysis can be performed covering the targeted area. The proposed combination of a circulation-shaped network and a radiation-shaped network is an efficient approach to satisfying the required transfer amount, allowing future flexibility of new planning, such as introduction of new functions into surrounding areas of the existing metropolitan area, etc. Construction schedule and utilization schedule are to be discussed in detail to have the optimized network plan. Also, the size of the network needs to be discussed based on the required investment and the profitability of the network. In that analysis, some numerical simulations are necessary taking into account environmental influences or their compensate costs, such as NO_x, SO_x or CO_2 emissions for long time frames.

Based on the discussion of this paper, we conclude that the proposed network concept and the planning approach will bring the efficiency and the long-term flexibility of energy infrastructures, including new energy options in the future in the 21st century.

Acknowledgement

The authors acknowledge the support of the Engineering Advancement Association of Japan (ENAA), Kajima Corporation, Shimizu Corporation, Taisei Corporation, Obayashi Corporation, Kumagai Gumi Co., Ltd., Hazama Corporation, NKK Corporation, Kawasaki Steel Corporation, Tokyo Electric Power Company and Tokyo Gas Co., Ltd. for the data used in this study.

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