STUDY ON THE INTRODUCTION OF ROAD HEATING SYSTEMS USING RENEWABLE ENERGY IN HOKKAIDO

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ABSTRACT

After the 1990 studded tire use ban in Japan, extremely icy road surfaces emerged in Hokkaido, the northernmost island of Japan, probably as a result of the phenomenon whereby studless tires buff the road surface. To counter the slippery road surfaces that emerged, road heating systems were rapidly introduced. However, in order for a road heating system to melt road snow by gas or electric power in a severely cold, snowy environment like that of Hokkaido, the system requires high snow melting performance, which is quite costly. The intensive introduction of high-performance snow-melting systems has resulted in financial difficulties for local governments. These governments face the additional issues of increases in the maintenance costs of old road heating systems and limitations in electrical power supply due to the shutdown of all nuclear power plants in Japan after the 2011 nuclear accident in Fukushima. To investigate solutions to such issues, this study discusses the feasibility of several types of road heating systems that use renewable energy and their practicability for Hokkaido.

1. INTRODUCTION

Cold, snowy regions account for roughly 60% of Japan’s land area, and approx. 20% of the nation’s population lives in these regions (Figure 1). After the 1990 ban on the use of studded tires in Japan, extremely icy road surfaces emerged in Hokkaido, the northernmost island of Japan, probably because of the prevailing use of studless tires, which buff icy roads. To counter such slippery road surfaces, road heating systems were rapidly introduced.

In Sapporo, the capital of Hokkaido and a city of 1.9 million residents, the annual cumulative snowfall is approximately 600 cm and the average temperature in January is -3.6°C. Under such severe winter weather conditions, icy road surfaces are likely to emerge. As a measure against such road surfaces, which became more common after 1990, electric road heating systems were intensively installed around the city to secure smooth traffic.

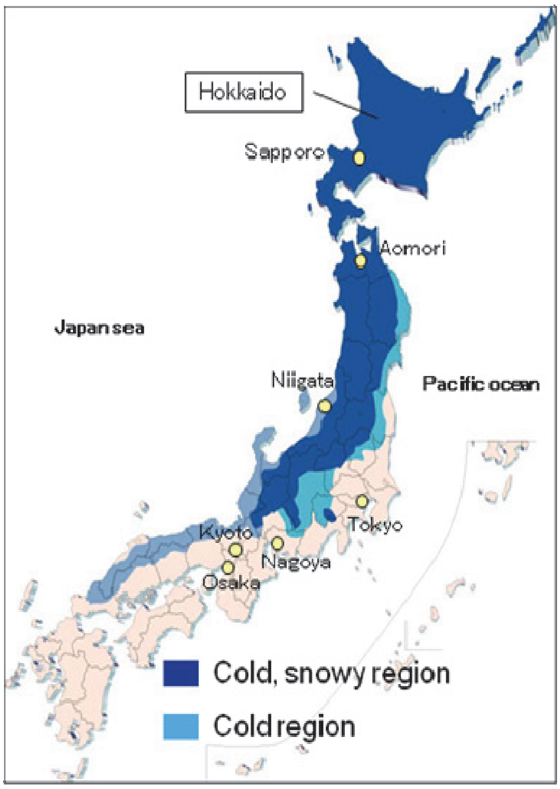


Figure 1. The cold, snowy regions of Japan

However, the intensive introduction of high-performance electric snow-melting systems has resulted in financial difficulties for the City of Sapporo, because of their high operating cost. Other municipalities in Hokkaido have been suffering from the same problem. Furthermore, electric power shortages due to the shutdown of all nuclear power plants in Japan after the 2011 nuclear incident in Fukushima have presented difficulties in using electric road heating systems. In the 2012-2013 winter, a 7% reduction in electrical power consumption was called for in Hokkaido.

In light of this, ways of reducing the operating costs of road heating systems are being sought. Based on analyses of recent climatic trends associated with global warming, such as increases in average temperature, this study discusses the potential for introducing renewable-energy-based road heating systems to Sapporo as an alternative to electric systems.

2. CHANGES IN WINTER WEATHER IN NORTHERN JAPAN, HOKKAIDO ISLAND AND SAPPORO CITY

Probably because of global warming, average temperatures in Japan have been tending to increase. Figure 1 shows Japan’s cold, snowy regions, including northern Tohoku and Hokkaido. Figure 2 shows the average temperature in February and cumulative snowfall observed at 22 weather monitoring stations for 50 years in those regions. The average temperature in February is 0.8°C higher for the second half of the 50-year period than for the first half of that period (an increase to -0.3°C from -1.1°C), and the annual cumulative snowfall is more than 80cm less for the second half of the 50-year period than for the first half of that period (a decrease to 326.0cm from 409.6cm).

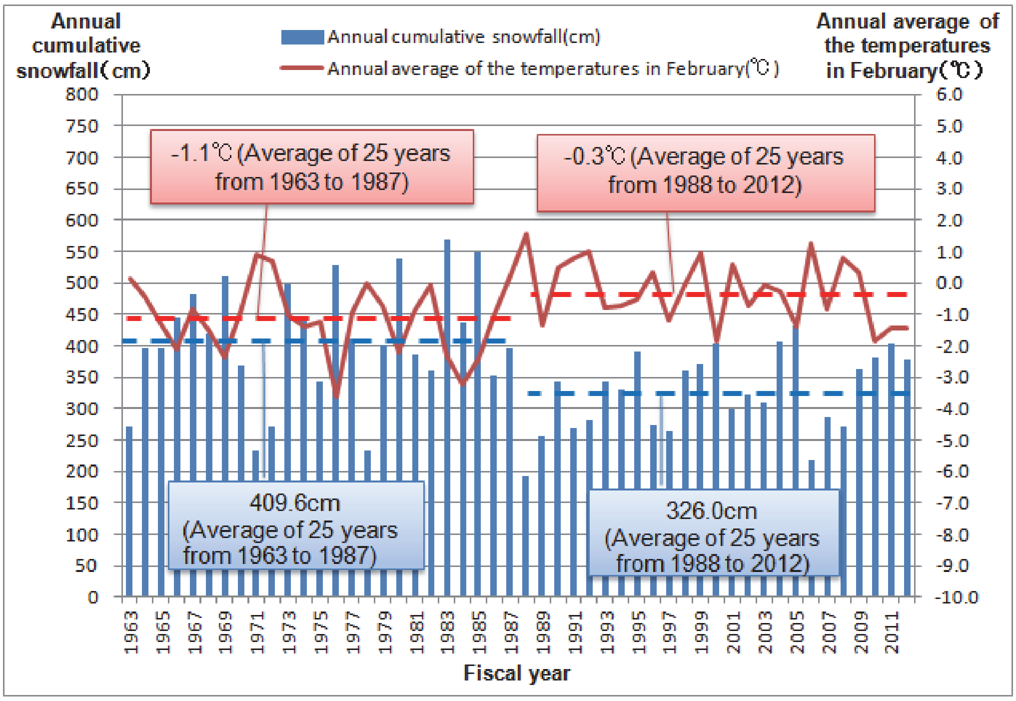


Figure 2. Changes in average temperature in February and cumulative snowfall in Japan’s cold, snowy regions

Figure 3 shows the average temperature in February and the annual cumulative snowfall observed at 22 weather monitoring stations in Hokkaido for 50 years. The average temperature in February is 1.0°C higher for the second half of the 50-year period than for the first half of that period (an increase to -5.2°C from -4.2°C), and the annual cumulative snowfall is more than 7cm less for the second half of the 50-year period than for the first half of that period (a decrease to 390.2cm from 397.2cm). This suggests that global warming has had greater effects on temperature than on cumulative snowfall.

Figure 4 lists the average temperature in February and the annual cumulative snowfall in Sapporo for 50 years. The average temperature in February is 1.3°C higher for the second half of the 50-year period than for the first half of that period (an increase to -4.6°C from -3.3°C), and the annual cumulative snowfall is more than 4cm less for the second half of the 50-year period than for the first half of that period (a decrease to 496.3cm from 492.3cm).

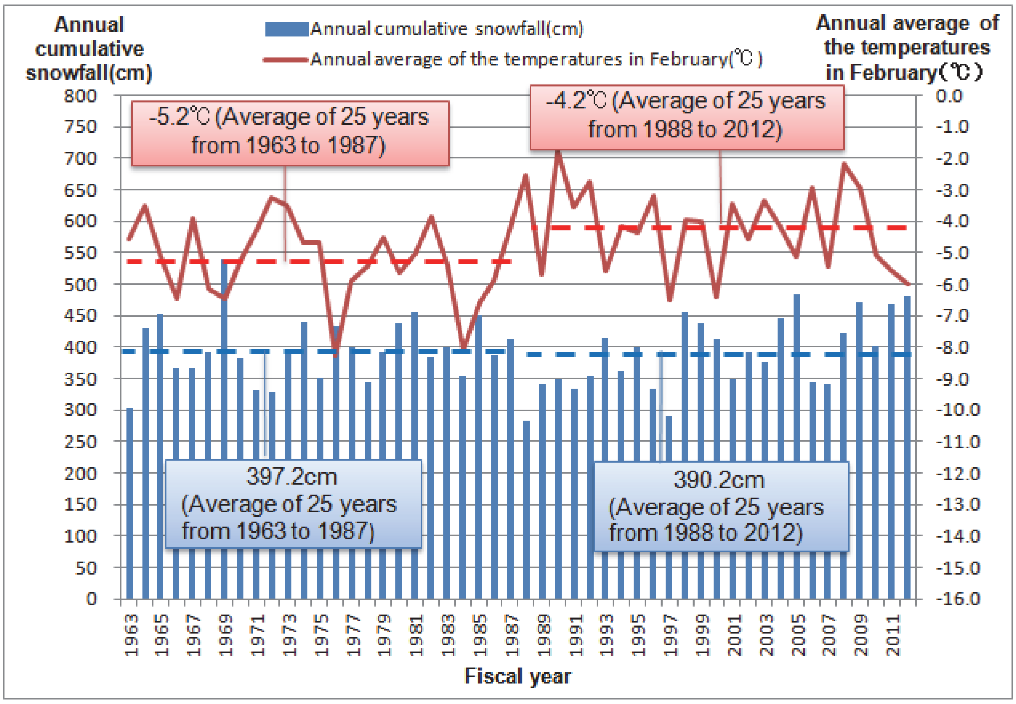


Figure 3. Changes in average temperature in February and cumulative snowfall in Hokkaido

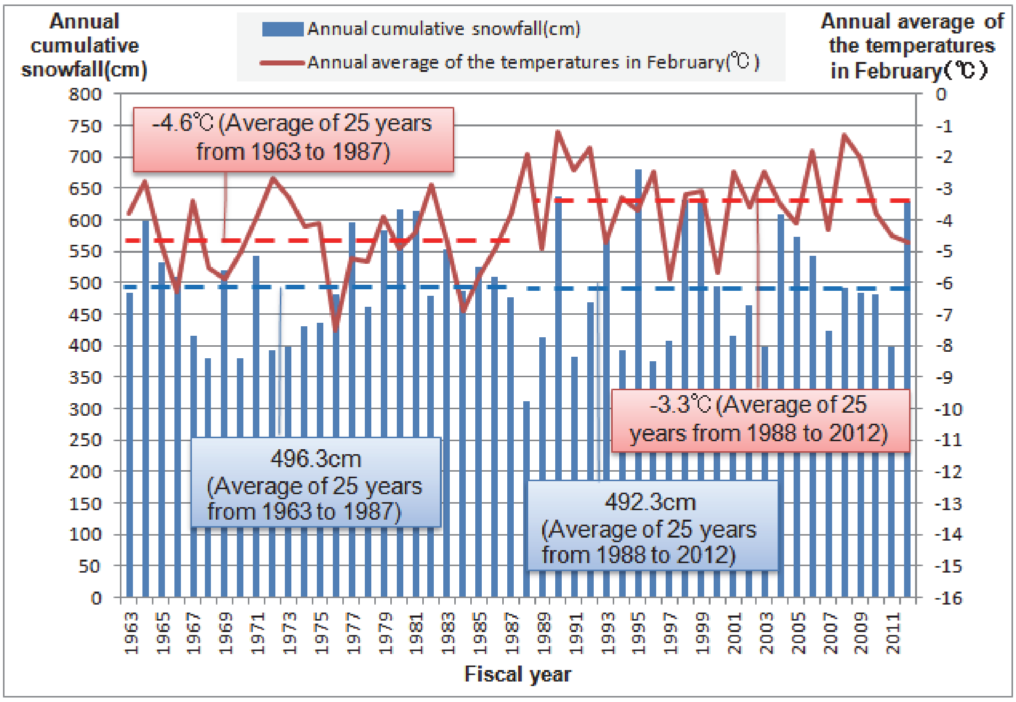


Figure 4. Changes in average temperature in February and cumulative snowfall in Sapporo

The above comparisons of average temperature in February and annual cumulative snowfall for 50 years show that the changes in the most recent 25 years from those in the previous 25 years are greater for temperature than for annual cumulative snowfall. This study examines how the temperature changes for those 50 years may affect the feasibility of road heating systems using renewable energy sources.

3. HEAT REQUIRED FOR A ROAD HEATING SYSTEM TO EFFECTIVELY PERFORM IN SAPPORO

To determine the heat (calories) required for road heating systems to effectively operate, the heat necessary for snow melting and that necessary to prevent road surface freezing are calculated. The larger of these two values is adopted in the design of road heating systems.

3.1 The heat required for a road heating system to melt snow is calculated by Equations 1 to 4. [2] [3]

$q_1=1/\eta\cdot(q_s+q_n)$……………………………..Equation 1

q_1 : Heat required to melt snow (W/m^2)

q_s : Sensible heat (W/m^2)

q_n : Sensible heat of melting (W/m^2)

η: Heat efficiency (0.65~0.9)

$q_s=2.78\times(C\cdot\triangleleft\theta\cdot h_s\cdot\rho_s)$………………………..Equation 2

$q_n=2.78\times(J\cdot h_s\cdot\rho_s)$……………………………Equation 3

C : Specific heat of snow (2.1J/g/°C)

$\triangleleft\theta$: Heat required to increase the snow temperature to 0°C

h_s : Expected hourly snowfall (cm/h)

ρ_s : Snow density (g/cm^3)

J : Sensible heat of snow (334J/g)

$hs = 0.32Hs^{0.7}$ Equation 4. [1]

Table 1 Average of the max. daily cumulative snowfall of 80% relative frequency

Period of time (FY)	1982-1991	1991-2001	2002-2011
Max. daily cumulative snowfall of 80% relative frequency	12 cm	11 cm	9 cm

3.1 Details of the factors that are used in Sapporo to calculate the heat required for road heating systems to melt snow.

- Snow density (ρ_s): 0.05 g/cm^3, obtained from records of the Japan Meteorological Agency in Sapporo
- Snow temperature: regarded as the same as the air temperature
- Expected hourly snowfall (hs): Daily cumulative snowfall of 80% relative frequency is substituted into Hs in Equation 4.
- Average of the max. daily cumulative snowfall of 80% relative frequency: 10 cm

Table 1 lists the average of the max. daily cumulative snowfall of 80% relative frequency for every ten years in Sapporo since 1982. The average value gradually decreases from 12 cm for the 1982-1991 period to 9 cm for the 2002-2011 period.

Equation 4 is an approximation equation for deriving expected hourly snowfall (hs). The correlation coefficient 0.32 is obtained through liner regression analysis by setting the daily snowfall and expected hourly snowfall as variables. In Sapporo, 10 cm, the average of the max. daily cumulative snowfall of 80% relative frequency from 1992 to 2011, is used in designing road heating systems. Table 2 shows the heat required to melt snow, derived by applying the coefficient to Equation 4.

Table 2 Heat required to melt snow

	Period of time (FY)	1982-1991	1991-2001	2002-2011
Heat required for snow melting	$hs = 0.32Hs^{0.7}$	110.6 w/m^2	103.6 w/m^2	89.8 w/m^2

3.2.2 Calculation of the heat required for a road heating system to prevent road surface freezing.

To calculate the heat required to prevent road surface freezing, the temperatures and wind speeds need to be specified. In designing road heating systems, the latest 10-year average of the lowest temperatures for the coldest month of the year is used. For wind speed, a faster speed is used by comparing 10-year average of wind speed for the coldest month and 3m/s. February is annually the coldest month in Sapporo. Table 3 lists the average of the lowest temperatures and the average wind speeds in January for every 10-year period from 1982 to 2011. For the decade from 1982 to 1991, the average lowest temperature in January is -7.5°C. For the period from 2002 to 2011, it has increased to -6.5°C. The average wind speed, which is 2.0 m/s for the period from 1982 to 1991, tends increase: It was 3.3 m/s for the period from 2002 to 2011.

Table 3 Changes in 10-Year-Period Average Lowest Temperatures and Average Wind Speeds in January in Sapporo (1982-2011)

		Year		
		1982-1991	1991-2001	2002-2011
Avg. lowest temp. in Jan.		-7.5 °C	-7.0 °C	-6.2 °C
Avg. wind speeds in Jan.	Observed	2.0 m/s	2.6 m/s	3.3 m/s
	Applied	3.0 m/s	3.3 m/s	3.0 m/s

Heat required to prevent road surface freezing[2] [3]

$$q_2=1/\eta \cdot Ar \cdot (q_e+q_i) \quad \cdots\cdots \text{Equation 5}$$

q_2 : Heat required to prevent road surface freezing (W/m^2)

q_e : Heat of evaporation (W/m^2)

q_n : Convective radiant heat (W/m^2)

η: Heat efficiency (0.65~0.9)

Ar : Ratio of road surface without snow to total road surface area

Under the condition without snowfall, the road surface temperature needs to be kept at least 0°C to prevent road surface freezing, and usually 1°C is applied to achieve an Ar of 1. At low temperatures, the heat of evaporation becomes small enough to ignore; thus, q_e is regarded as 0.

$$q_2=1/\eta \cdot q_i \ \ldots\ldots\ldots\ldots\ldots\ldots \text{Equation 6}$$

$$q_i=(\alpha_c+\alpha_r)\cdot(T_m-T_a) \ \ldots\ldots\ldots\ldots \text{Equation 7}$$

α_c : Surface convection heat conductivity ($W/m^2/°C$)

$$\alpha_c = 5.8+4.0u \text{ (wind speed : } u \leqq 5m/s) \ \ldots\ldots\ldots \text{Equation 8}$$

$\alpha_c = 7.14u^{0.78}$ (wind speed : u<5 m/s)………… Equation 9

α_r : Surface radiation heat conductivity (W/m^2/°C)

$$\alpha_r = \frac{5.41}{T_m - T_a}\left\{\left(\frac{273+T_m}{100}\right)^4 - \left(\frac{273+T_a}{100}\right)^4\right\} \quad \text{………Equation 10}$$

T_m : Road surface temperature (°C) T_a : Air temperature (°C)

In Sapporo, -6.6 °C for the temperature and 3.0 m/s for the wind speed are used to calculate the heat for a road heating system to prevent road surface freezing. -6.6 °C is the 20-year-average of the lowest temperatures in January from 1992 to 2011, and 3.0 m/s is adopted for the wind speed because, as previously mentioned, the 20-year-average wind speed, 2.9 m/s, is less than 3.0 m/s.

Table 4 shows the changes from 1982 to 2011 by 10-year period in the average heat required for road heating systems in Sapporo to prevent road surface freezing.

Table 4 Heat required for road heating systems to prevent road surface freezing in Sapporo

	Period		
	1982～1991	1992～2001	2002～2011
Heat required for road heating systems to prevent road surface freezing in Sapporo	234.3 w/m^2	220.6 w/m^2	209.5 w/m^2

Much more heat is needed for the system to prevent road freezing (Table 2) than for it to melt snow (Table 4). That is because, at low temperatures, after snow is melted by road heating, the meltwater is likely to refreeze, and more heat is necessary to prevent that than to melt snow.

Therefore, as the heat required for road heating systems to work effectively in Sapporo, the heat to prevent road surface freezing is applied.

4. POTENTIAL RENEWABLE ENERGY SOURCES FOR ROAD HEATING SYSTEMS

Various energy sources have been used for road heating systems (Table 5). When the total costs, including those for facility installation and operating costs, for road heating systems whose heat source is either electricity, gas or kerosene are compared with the costs for renewable-energy-source systems, those of the latter tend to be cheaper than those of the former. With respect to operating costs, systems that use renewable energy sources are cheaper than systems that do not, and renewable energy use contributes to the reduction of CO_2 emissions. In Japan, the main renewable energy sources for road heating systems are groundwater, ground heat and thermal energy of the air. Table 6 compares the heat available by road heating systems that use different renewable energy sources. Except when the heat for road heating is directly supplied by heat sources with high temperatures, such as by hot springs, road heating systems that require 200 W/m^2 or more of heat cannot rely on renewable heat sources, because most of such sources have heat output levels under 200 W/m^2.

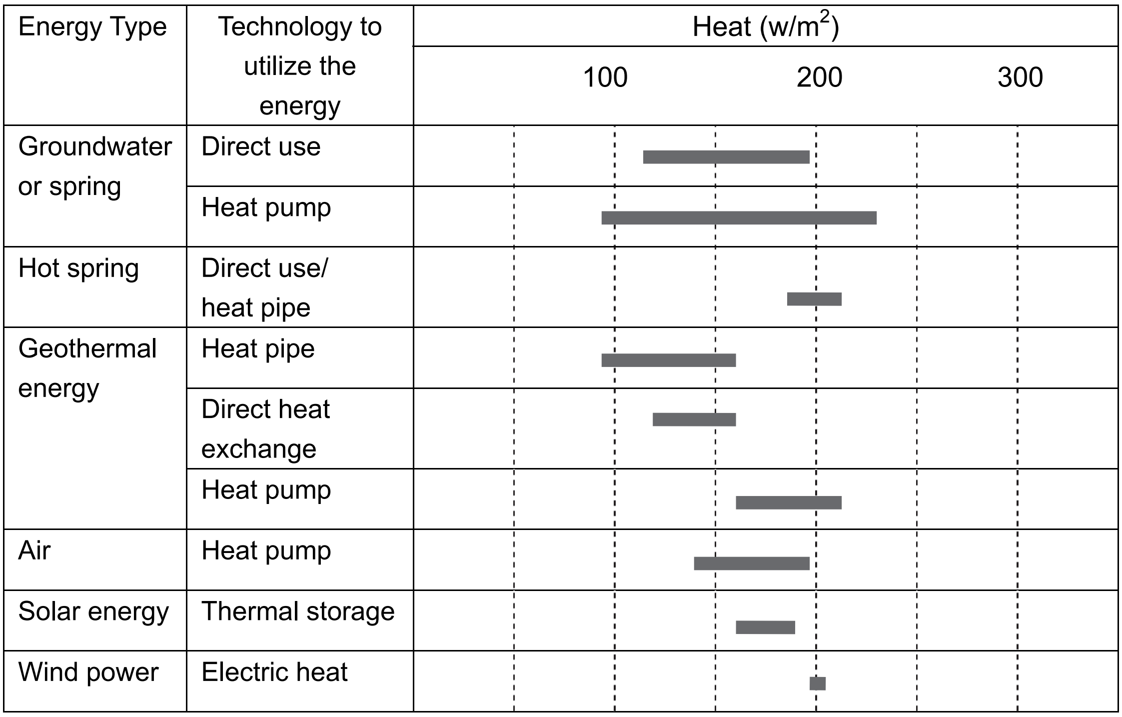
However, the use of heat pumps may increase the heat outputs of road heating systems using renewable energy sources to about 200 W/m^2 or higher, which can expand the feasibility of renewable energy to be used for road heating systems in cold places like Sapporo. As shown in Table 4, the average heat required for road heating systems to operate in Sapporo during the 2002 - 2011 period was about 210 W/m^2, down from about 235 W/m^2 for the 1982 -1991 period. This change indicates that road heating systems using renewable energy sources with a min. heat output about 200 w/m^2 or higher could be used even in Sapporo.

Table 5　Heat sources for snow melting facilities

Heat source			Technology that uses the heat source
Renewable energy	Wind power		Electrical coil heating, and power supply for various pumps
	Water	Groundwater	Direct piping, heat pipe, heat pump
		Spring water from tunnel	Direct piping, heat pump
		Lake water	Heat pump
		Hot spring water	Direct piping, heat pipe
	Ground		Direct piping (heat exchanger), heat pipe, heat pump
	Air		Heat pump
	Solar		Storage in groundwater or underground
Waste energy	Exhaust heat from urban facilities		Direct ducting
Fuel energy	Electricity		Electrical coil heating
	Gas and kerosene		Boiler

(Source: Green Winter Road Management, Japan 2010)

Table 6 Heat required by road heating systems using renewable energy sources



Energy Type	Technology to utilize the energy
Groundwater or spring	Direct use
	Heat pump
Hot spring	Direct use/ heat pipe
Geothermal energy	Heat pipe
	Direct heat exchange
	Heat pump
Air	Heat pump
Solar energy	Thermal storage
Wind power	Electric heat

5. ISSUES TO OVERCOME TOWARDS APPLYING RENEWABLE ENERGY SOURCES TO ROAD HEATING SYSTEMS

As shown in Table 4, the min. heat required for road heating systems in Sapporo is decreasing because of increases in winter temperatures. The average heat required for a road heating system to operate in Sapporo during the 2002-2011 period was about 210 W/m^2. If renewable energy sources such as groundwater heat, geothermal heat and air heat are used in combination with heat pumps, then road heating systems that rely on renewable energy made be practicable in Sapporo. To examine more specifically the feasibility of road heating systems using renewable energy sources in Sapporo, we compared the costs of using conventional road heating systems which are designed to have a max. output heat of 234.3 W/m^2 and those of road heating systems using renewable energy sources whose max. output heat is 210 W/m^2 (Figure 7, Figure 8). The comparison was made between an electric road heating system and each of the three types of road heating systems using renewable energy (groundwater heat, geothermal heat or heat of ambient air) as energy sources, all of them used in combination with a heat pump. They are all road heating systems of the same size: 1.5 m in width, 200 m in length and 300 m^2 in area.

As shown in Figure 7, the operating costs of road heating systems that use either groundwater heat or geothermal heat in combination with a heat pump are lower than those of the other two types. Their operating costs are about 60% those of the conventional electric road heating system. The operating costs compared here include maintenance costs. In a comparison that focuses only on the only energy costs of the target road heating systems, we find that systems that use renewable energy have energy costs of only about 30% those of electric systems. In contrast, in a comparison of the total costs (installation costs plus operating costs) for 25 years, road heating systems using renewable energy sources have slightly higher costs conventional road heating systems (Figure 8). However, the difference is gradually decreasing, due to performance improvements in road heating systems using renewable energy sources. In light of the advantages of road heating systems using renewable energy sources, such as reduced carbon emissions and lower running costs than conventional systems, road heating systems using renewable energy sources could be introduced in Sapporo as environmentally friendly and cost-effective systems to replace conventional systems. By lowering the installation costs, selecting facility installation locations that optimize renewable energy use and improving facility designs to increase the heat output, it will become more feasible to introduce road heating systems using renewable energy sources.

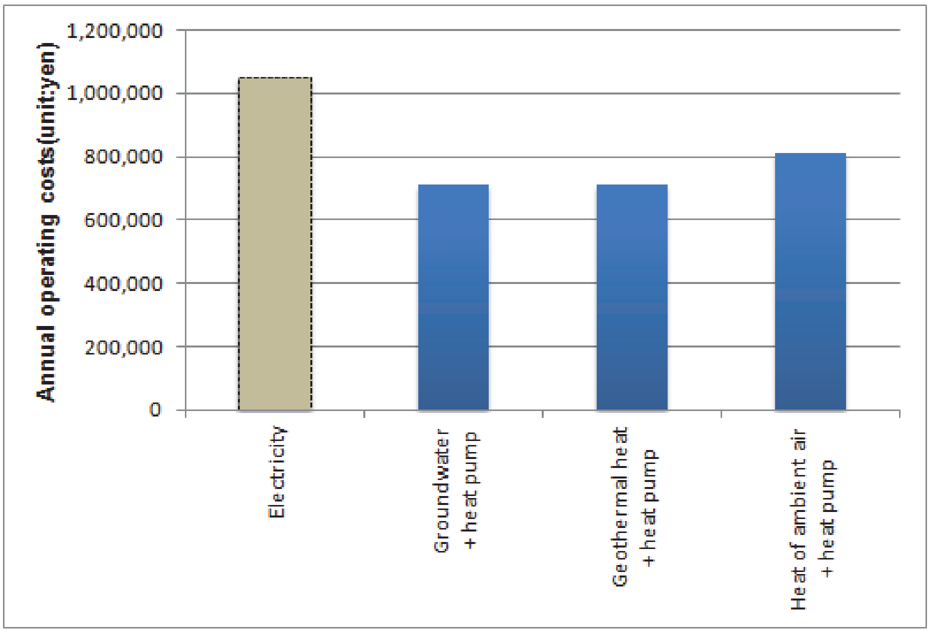


Figure 7 Operating costs of road heating systems by energy source

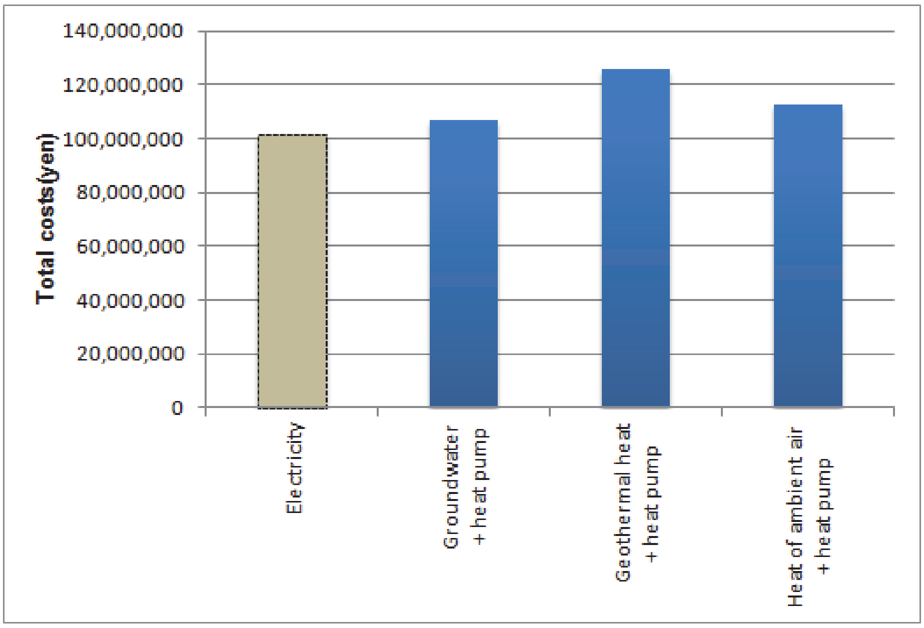


Figure 8 Total costs of road heating systems by energy source for 25 years

6. CONCLUSION

After the 1990 use ban on studded tires in Japan, extremely icy road surfaces emerged in Hokkaido, probably because of the prevailing use of studless tires, which buff icy roads. As measures against such slippery road surfaces, road heating systems were rapidly introduced. However, to melt road snow by gas or electric road heating systems in a severely cold, snowy environment like that of Hokkaido, the systems require high snow melting performance, which is quite costly.

Probably because of global warming, average temperatures tend to be increasing and average cumulative snowfall tends to be decreasing all over Japan. This study examined how such climatic changes in winter might affect the amount of heat required for road heating systems to effectively operate in Sapporo. Climatic data show that the scale of increase in average temperatures in winter in Sapporo is greater than that in all of Hokkaido or all of Northern Japan. The average temperature increase in Sapporo suggests that the max. heat of the road heating systems that were designed on the basis of the average temperatures in winter before global warming may be set too high at present. If road heating systems are able to work with a lower max. heat than that of the present electric or gas-sourced systems, then renewable-energy-source road heating systems whose max. heat outputs are lower than those of electric or gas systems might be useable in Sapporo.

Based on climate data for about the 30 years from 1982 to 2011, the heat required for road heating systems in Sapporo to effectively operate was calculated for every ten-year period. As a result, compared with the average heat required for road heating systems from 1982 to 1991, the required heat fell to about 210 W/m^2 on average in the period from 1992 to 2011, a 25 W/m^2 drop from the former value of 235 W/m^2. In some cold, snowy parts of Honshu, where the winter temperatures are higher than in Hokkaido, road heating systems have been able to work with a heat output of about 210 W/m^2. This suggests that road heating systems using renewable energy sources may be feasible in Sapporo. If such systems can be used in Sapporo, it will contribute to the reduction of CO_2 emissions and operating costs. A remaining issue is how to lower the installation costs of road heating systems using renewable energy sources, which are higher than those of conventional systems. If the facility designs and materials are improved and if decreases in facility installation costs can be achieved, it may enable greater use of renewable-energy-source road heating systems in Sapporo.

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