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Proposing a renewable heat incentive scheme for GSHP in Japan, a techno-economic analysis

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Abstract

Ground source heat pumps (GSHPs) provide efficient technology to meet the heating and cooling demands of buildings. However, their deployment is limited in Japan, mainly due to high drilling costs. Application of GSHP systems in Japanese residential buildings as substitutes for kerosene heaters and even air source heat pump (ASHP) systems, especially in northern Japan, would help to achieve the country's emission reduction goals in upcoming decades.
This study conducted a techno-economic analysis and investigated a renewable heat incentive (RHI) scheme for GSHP system installation in Japan's cold climates. The heating load for a sample residential single-family building in Sapporo City in northern Japan was calculated over one heating season. The required ground heat exchanger (GHE) length for a GSHP system was estimated to meet the heating demand of the building, and the total cost of the GSHP system was calculated. The payback period of the investment was calculated in various renewable heat incentive schemes. Results of the analysis showed that the renewable heat incentive could be a strong tool for accelerating the GSHP system deployment in residential buildings in Japan if suitable RHI tariffs and payment period were available.

Keywords: Ground source heat pump, renewable heat incentive, techno-economic analysis, Japan, market-based policies

1. Introduction

The transition to clean and renewable energy technologies requires adequate planning and government intervention in the energy market in developing supportive policies, mainly due to the higher capital cost of these technologies compared to that of conventional energy technologies. In recent years, feed-in tariff (FIT) and similar schemes have accelerated the installation of renewable power generation technologies [1]. Nevertheless, achieving the deep-decarbonization targets will be difficult without the contribution of low-carbon and renewable heating and cooling technologies [2].

Renewable heat incentive (RHI) schemes provide financial benefits for the owners of renewable heating systems. RHI schemes can cover technologies such as solar water and space heaters, biomass-fired heaters, heat pumps (air source and ground source), and the like. The owners of these systems receive specific financial benefits per unit of thermal energy that they derive from renewable resources [3]. So far, however, RHI schemes have received less attention than FIT plans in various countries.

The United Kingdom (UK) is one of the few countries to have put RHI schemes into practice. These programs began in 2011 and 2014 for non-residential and residential buildings, respectively. Table 1 shows the covered renewable technologies and tariffs of the RHI scheme in the UK [4]. This scheme has increased the renewable heating technology uptake in the UK, but the number of approved applications

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for receiving the RHI benefit has been lower than predicted [4,5]. The main reasons behind this issue have been investigated and discussed in existing literature.

Lowes et al. (2019) investigated the policy change, power, and development of Great Britain's RHI scheme. They looked at this topic from a socio-political power prospective using Lukes's dimension of power approach, aiming to identify the key actors in influencing RHI policy. Identifying the crucial impact of niche actors in developing RHI policy, they emphasized how these factors have provided more intensive support for specific types of renewable heating systems and have also slowed the introduction of this scheme for residential buildings [5].

Table 1. Levels of support within phase 2 (residential) RHI in UK

Technology	Air source heat pump	Biomass-only boilers and biomass pellet stoves with back boilers	Ground (and water) source heat pumps	Solar thermal panels (flat plate and evacuated tube for hot water only)
Tariff (p/kWh)	7.3	12.2	18.8	19.2

Connor et al. (2015) reviewed the development of renewable heating policy in the UK. They discussed the challenges related to adopting the RHI scheme, including the RHI tariff and period of financial support, along with protecting public funds [4]. Using an agent-based modeling approach, Snape et al. (2015) studied the adoption of RHI schemes in residential buildings in the UK, trying to explain the lower than expected uptake of RHI. They found that RHI uptake was not only sensitive to financial factors but also to non-financial parameters such as *hassle factor* [6].

Focusing on solar thermal systems, Abu-bakar et al. (2013 and 2014), conducted an economic analysis of the RHI scheme for solar water heaters in both residential and non-residential buildings in the UK. This study included sensitivity analysis of factors such as solar radiation, RHI tariff, and payment period to evaluate the payback period of investment on a solar water heater. They concluded that the RHI for solar water heating systems would be profitable for potential installers if the heat tariff increased to 32 p/kWh, or if the payment period increased to 17 years [7,8].

Donaldson and Lord (2015) introduced a case study for installation of ground source heat pump (GSHP) systems for school building in Glasgow. The total heating demand of the building was estimated to be 400 kW, and the location of building appeared to be a promising area for the installation of ground heat exchangers (GHEs) for GSHP systems. The latter resulted from the presence of strong groundwater flow and high thermal conductivity (75% higher than thermal conductivity for sandstone and shale). Eighteen vertical GHEs 110 m in length were installed in the car parking area and in the school's playground to meet the heating demand. They also installed a small CHP unit for injecting warm water inside the boreholes on harsh winter days to prevent freezing inside the GHEs and to increase the efficiency of the heat pump unit. However, heat injected by the CHP unit into the ground is not a renewable source of heat. As the result, the injected heat was measured and deducted from the total amount of heat derived from the ground by GHEs to calculate the RHI revenue. This study demonstrated the risks associated with an RHI scheme in the UK for the system owners, since the application for RHI is possible only after installation of the systems [9].

In this study, we conducted a techno-economic analysis to evaluate the feasibility of an RHI scheme for GSHP system installation in the cold climates of Japan. Information regarding the current status of GSHP in Japan is presented. The heating load of a sample residential building in Sapporo City was estimated, and the required GHE length to meet these loads was calculated. An economic analysis was conducted to calculate the payback period of the investment in the GSHP system in various RHI scenarios and compared to a conventional kerosene-fired heating system. A list of nomenclatures and acronyms is presented in Table 2.

Table 2. Nomenclature and acronym list

Nomenclature		
Parameter	Description	Unit
Q_H	Building heating load	kWh
Q_C	Renewable heat derived from ground	kWh
A_e	Building envelope area	m^2
A_f	Building floor area	m^2
T_i	Room temperature	˚C

T_o	Ambient temperature	˚C
I	Solar radiation	W/m^2
U	Overall heat transfer coefficient	$W/m^2/K$
η	Average solar heat acquisition rate	W/m^2
$\dot{m}$	Mass flow rate of working fluid	Kg/sec
C_p	Specific heat capacity of working fluid	J/kg/˚C
n	Year (in the life of project)	year
N	Total lifetime of the project	year
CF_0	Initial investment	Yen
CF_n	Cash flow in year n	Yen
r	Discount rate	
C_{Keros}	Annual cost of kerosene heating system	Yen
C_{GSHP}	Annual cost of GSHP system	Yen
R_{RHI}	Annual revenue of RHI system	Yen
R_{tot}	Total annual saving	Yen
u	RHI tariff	Yen/kWh
Acronyms		
RHI	Renewable heat incentive	
GSHP	Ground source heat pump	
GHE	Ground heat exchanger	
NPV	Net present value	Yen

2. GSHP in Japan

In Japan, 27.3% of the total energy expended in 2015 was consumed in buildings. Between 1990 and 2015, the energy-related CO2 emission change in buildings was around 44%, much higher than in other sectors (-10.3% and 6.5% for industry and transportation, respectively) [10]. As shown in Fig. 1, kerosene provides 61% of space heating energy for residential buildings. Using kerosene for space heating in Japanese houses comes with difficulties and risks for the consumer, including a high CO2 emission rate. Fig. 2 shows the unit prices for imported kerosene (JPY/L) and electricity (JPY/kWh) for 1990–2015 in Japan [11].

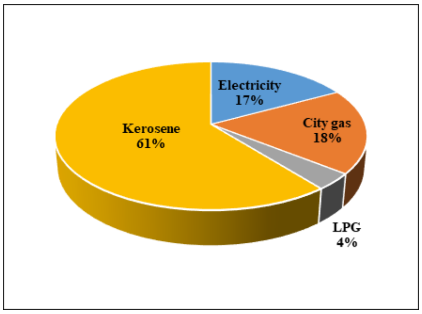

Fig. 1. Household space heating energy source, 2015.

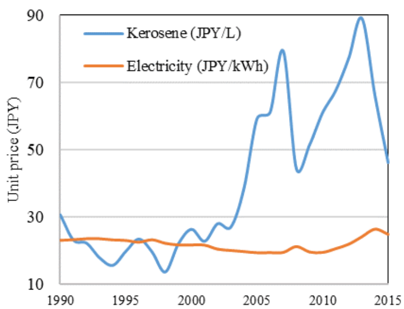

Fig. 2. Electricity and imported kerosene unit price in Japan.

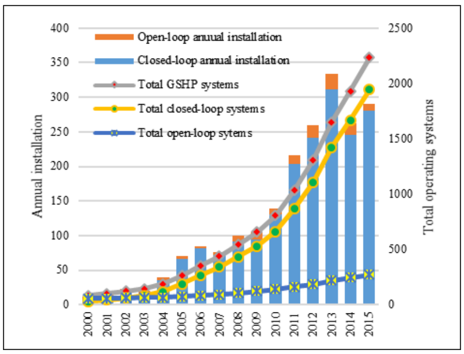

Fig. 3. Annual and total installation of the GSHP systems.

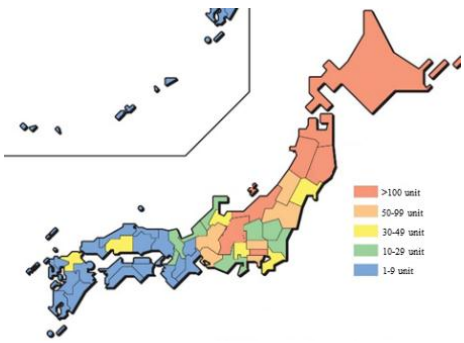

Fig. 4. Map of GSHP systems installation.

Fig. 3 shows the annual total installation number of GSHP systems in Japan from 2000–2015. The 2015 installations had doubled since 2010, and the total number of GSHP units in 2015 had reached 2,230 units. Closed-loop systems are the most popular GSHP systems in Japan, comprising 87% share of the total systems. In contrast, open-loop and hybrid systems comprise 12% and 1%, respectively, of total GSHP systems in Japan. Fig. 4 shows the map of GSHP installation in Japan [12].

3. GSHP for a Sample Residential Building in Sapporo City

The heating load calculations were performed based on the Japan Energy Saving Standard method [13]. The dimensions of the sample building are shown in Table 3 [14]. The building heating load was calculated using Eq. 1.

$$Q_H = \frac{U \times A_e \times (T_i - T_o)}{A_f} - \frac{I \times \eta}{A_f} \quad (1)$$

The values for U (overall heat transfer coefficient) and η (average solar heat acquisition rate) in Eq. 1 were reported for 8 different regions in Japan [13], and in the case of Sapporo City were 0.46 and 0, respectively. The heating period was considered to extend from the middle of October 2016 to the middle of March 2017, from 17:00 in the evening to 8:00 the next morning, with T_i equal to 20 ˚C. The hourly data for T_o was recorded from Japan Metrological Agency [15], and the Q_H was calculated (Fig. 5). The calculated total Q_H was 4,817 kWh.

Table 3. Sample building dimensions.

Floor area, A_f [m^2]	
Section	**Area (m^2)**
Main room	29.8
Other rooms	51.3
Non-residence	38.9
Total floor area	**120.1**
Building envelope area Ae [m^2]	
Section	**Area (m^2)**
Ceiling area	67.2
Floor area	65.4
Total area of wall and opening	177.0
Perimeter of earth floor (outside air)	3.2
Perimeter of earth floor (others)	3.2
Total building envelope area	**312.8**

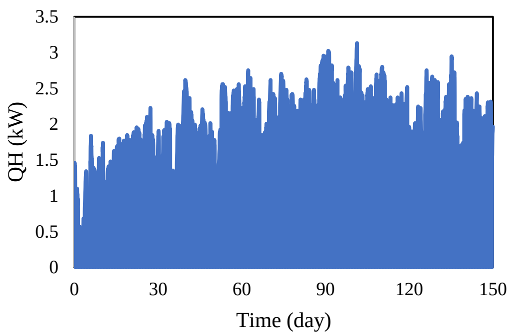

Fig. 5. Building heating load (kW).

In order to calculate the required GHE length for a GSHP system, we used the GshpCalc software [16]. The temperature of the water entering the heat pump was set to 7.2 ℃, with a design water loop flow rate of 3.23 L of working fluid per min per kW of heat pump capacity. The Sunpot Heat Pump model GSTR-

4601BX-K was selected as the heat pump unit for this study [17]. The undisturbed ground temperature was set to 15.1 ℃, with geological formation of silt, sand, and gravel, resulting in an average thermal conductivity and thermal diffusivity of 1.6 W/m/K and 0.07 m^2/day [18].

A double U-tube vertical GHE was considered in this study. The U-tube was made from high-density polyethylene (HDPE) with a thermal conductivity of 0.38 W/m/K and an inner dimeter of 27 mm. The U-tube was 3.5 mm thick, filled with a mixture of water and 20% ethylene glycol as a working fluid [19]. The working fluid flow inside of the GHE was in a turbulent condition to maximize the heat transfer. The borehole dimeter was 15 cm, and it was filled with cement with an average thermal conductivity of 1.5 W/m/K. The pump motor efficiency was 85% with a water head of 18 m.

The calculated GHE length based on infinite line source theory in GshpCal was 54 m, considering minimal groundwater movement in the domain. It is helpful to notice that there is a tradeoff between GHE length and the performance of the heat pump unit. With longer GHEs, the inlet temperature of the heat pump unit was higher in the cold season, and heat pump efficiency would also be higher. The rate of extracted renewable heat from the ground was calculated using Eq. 2.

$$\dot{Q}_c = \dot{m} \times C_p \times \Delta T \tag{2}$$

Here $\dot{m}$ and C_p are the mass flow rate and the specific heat capacity of the working fluid, respectively. ΔT in Eq. 2 is the temperature difference between the inlet and outlet temperatures of the GHE. In the real-world application of RHI for GSHP systems, a measuring unit would record the inlet and outlet temperatures of the GHE during the working hours of the heat pump unit to report the extracted renewable heat from ground. The calculated renewable heat for one heating season was 3,461 kWh. The power consumption of the GSHP system for one heating season, which includes the power consumption of the Sunpot hat pump unit, circulating pumps, and two fan coil units, is 1,355 kWh.

4. Economic Analysis

We used the investment appraisal methods to calculate the payback period of the investment on the GSHP system in various RHI scenarios [20]. The net present value (NPV) of the investment was calculated using Eq. 3.

$$NPV = -CF_0 + \sum_{n=1}^{N} \frac{CF_n}{(1+r)^n} \tag{3}$$

In this equation, CF_0 is the initial investment, which was the difference between investment in GHSP and that in kerosene-fired heating systems in this case study. CF_n in Eq. 3 is the cash flow in year n and N in the total lifetime of the systems, which was assigned as 20 years for the GSHP and 10 years for the kerosene heating system [21]. We used the World Bank data for real interest rate (averaged for 2004–2014) as an indicator for discount rate (r) in Eq. 3, which resulted in 2.57% [22].

The initial investment in the GSHP system consisted of three parts:

1. GHE drilling and installation cost: 15,000 Yen (JPY) per meter of GHE [23]
2. Heat pump unit and installation cost: 1,420,000 JPY [17]
3. Heat distribution system and installation costs: 40,000 JPY [24]

The initial investment in the kerosene heating system included the cost of an outdoor storage unit and two kerosene-fired fan heaters, which was estimated at 150,000 JPY. The lifetime of the kerosene heating system assigned was 10 years, which meant an additional investment in replacing the system at the 11th year.

To calculate the running costs of the systems, we considered 20 JPY per kWh for the GSHP system's electricity consumption. The unit price of kerosene was calculated from monthly average cost data for 2018's heating season in Hokkaido, which was 105 JPY per L [25]. In order to calculate the required volume of kerosene to meet the heating demand of this building, it was assumed that the heater would be converting 90% of the energy content of kerosene to thermal energy in the combustion process. The heating value (HV) of kerosene was considered as the average of the reported high and low HVs, which was 44.6 MJ/kg [26]. The calculated required kerosene was 432.1 kg (526.9 L). In our calculations, the annual increase in the price of electricity was averaged using the values for 1990–2015, which were 1% and 3% for electricity and kerosene, respectively (see Fig. 2). The maintenance costs of the heating systems were considered negligible [27].

The annual savings of the GSHP system were calculated in Eq. 4, where C_{GSHP} and C_{kros} are annual fuel costs of GSHP and kerosene heating systems, respectively.

$$R_{tot} = C_{Keros} - C_{GSHP} + R_{RHI} \tag{4}$$

R_{RHI} in equation 4 is the annual revenue from renewable heat incentive scheme, calculated by Eq. 5, where u is the RHI tariff in the unit of JPY per kWh of renewable heat extracted from ground.

$$R_{RHI} = Q_c \times u \tag{5}$$

Table 4 shows an example of cash flow. In this case, the RHI rate and payment period were set to be equal to the current RHI scheme for GSHP systems in the UK as the initial guess, which was 29.8 JPY/kWh for seven years [3]. In addition, we added the revenue resulting from avoiding the kerosene-fired heater replacement to the 11th year's annual savings.

The results of the cash flow calculation in Table 4 revealed that the assigned RHI tariff and payment periods did not make the investment feasible in this case study. As the result, either the RIH rate or payment period would need to be increased to make the RHI scheme attractive to potential investors. Fig. 6 shows the NPV for various RHI tariffs, maintaining a payment period of 7 years. The results displayed the minimum RHI tariff to make the investment feasible as 61.5 JPY/kWh.

Table 4. An example of a cash flow diagram (JPY).

Year	GSHP cost	Kerosene cost	RHI revenue	Annual saving	Cumulative cash flow	Discounted annual saving	NPV
0					-2120000		-2120000
1	27100	55325	103138	131362	-1988638	128071	-1991929
2	27371	56984	103138	132751	-1855887	126182	-1865747
3	27645	58694	103138	134187	-1721700	124351	-1741396
4	27921	60455	103138	135671	-1586029	122576	-1618820
5	28200	62268	103138	137206	-1448823	120857	-1497963
6	28482	64136	103138	138792	-1310031	119190	-1378773
7	28767	66060	103138	140431	-1169600	117576	-1261197
8	29055	68042	0	38987	-1130613	31824	-1229372
9	29345	70083	0	40738	-1089875	32420	-1196952
10	29639	72186	0	42547	-1047328	33012	-1163940
11	29935	74352	0	194416	-852912	147065	-1016876
12	30235	76582	0	46347	-806564	34181	-982695
13	30537	78880	0	48343	-758222	34759	-947936
14	30842	81246	0	50404	-707818	35333	-912603
15	31151	83683	0	52533	-655286	35902	-876701
16	31462	86194	0	54732	-600554	36468	-840233
17	31777	88780	0	57003	-543551	37030	-803203
18	32095	91443	0	59348	-484203	37587	-765616
19	32416	94186	0	61771	-422432	38141	-727475
20	32740	97012	0	64272	-358160	38691	-688783

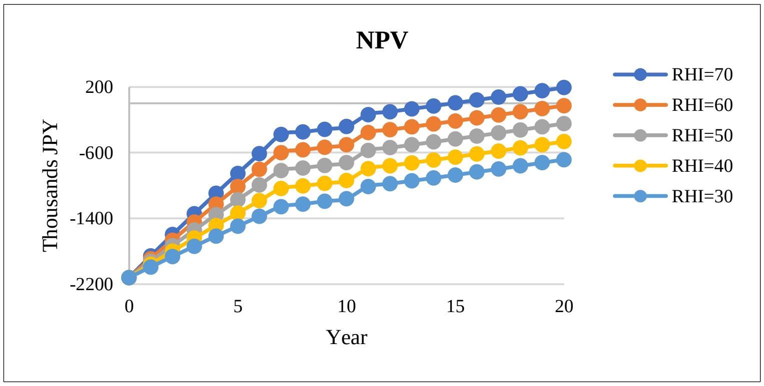

Fig. 6. Net present value in various RHI tariffs (JPY/kWh); payment period = 7 years.

Considering the constant RHI rate as 30 JPY/kWh, the payment period should be higher than 7 years to achieve a feasible investment. Fig. 7 shows the NPV for various RIH payment periods, when the RHI rate was 30 JPY/kWh. Results of these calculations displayed a minimum acceptable payment period in this case of 16 years. Taking a moderate approach, if the RHI period were set to 10 years, the minimum RHI rate for a feasible investment would be 48.8 JPY/kWh.

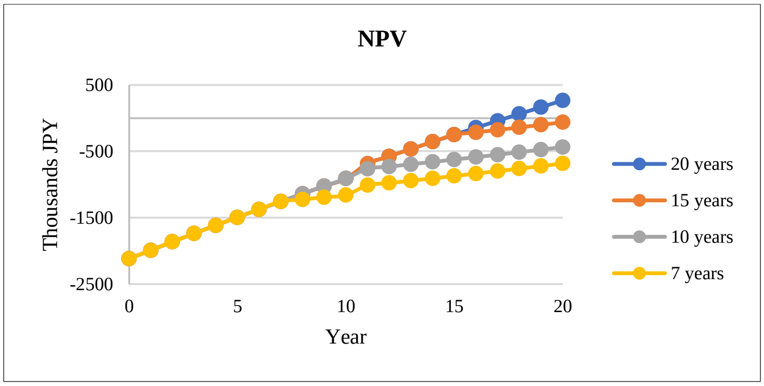

Fig. 7. Net present value for various payment periods (7–20 years); RHI = 30 JPY/kWh.

5. Conclusion

A renewable heat incentive (RHI) can be an effective market-based policy to expand the uptake of clean and renewable heating and cooling technologies. However, the success of such a policy requires adequate tariff calculation and implementation to make this investment feasible for potential investors. In this study, we proposed an RHI scheme for installing a ground source heat pump (GSHP) in the cold climates of Japan using a techno-economic approach. We calculated the required heat exchanger length to meet the heating demands of a sample residential building in Sapporo City, northern Japan. The initial investment and fuel costs of the designed GSHP system and a kerosene-fired heating system were calculated.

Using the investment appraisal method, we calculated the net present value (NPV) of the investment in various RHI payment scenarios. Results of the analyses showed that the RHI tariff of 29.8 JPY/kWh for renewable heat extracted from the ground for seven years, equal to the current RHI scheme in the UK for GSHP systems, would not make the investment feasible. When setting the RHI payment over seven years, the RHI tariff should increase to 61.5 JPY/kWh. Employing the same RHI tariff as in the UK scheme, the payment period should increase to 16 years. In a moderate scenario, we suggested a 48.8 JPY/kWh RHI tariff for 10 years.

One of the main reasons that we chose the residential buildings in our case study was the high share of kerosene as the current heating fuel in Japanese residential buildings. Burning kerosene for heating comes with extra issues and safety concerns. These issues might increase in upcoming years in Japan's aging society. A transition to an electricity-based heating system in the country's residential buildings would reduce emissions from this sector and would improve the energy self-sufficiency rate of Japan by increasing the future renewable share of the power generation sector.

Therefore, the current framework could be improved as time passes. Even though our case study occurred in a heating-dominated area, GSHP systems can work in cooling mode as well. The heat injected into the ground by GHEs in warm seasons, which prevents the heat island phenomenon in big cities, could be considered renewable heat and could receive revenue to make GSHP systems more attractive for investors. Adding a carbon tax for to the price of heating fuels and electricity in economic analysis has a potential to reduce the payback period of investment in GSHP systems. In this study, however, we didn't consider the effect of groundwater flow on heat transfer rate of the heat exchanger. Considering this effect could result in shorter GHEs and lower initial investment.

Along with economic parameters, non-economic factors could play an important part in achieving a successful RHI scheme. The easy, straightforward application process, as well as the possibility for submitting the application before installing the heating system, could improve the uptake rate in heterogeneous societies. On the other hand, assigning a cap for annual produced renewable heat per household, based on the building's heating load and minimum acceptable efficiency for heating technology, would be helpful in preserving public funds in RHI schemes. Expanding the district heating systems in cities and connecting RHI-supported renewable heating systems is a promising option for cutting emissions from the building sector in the future.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

H. Farabi-Asl developed the framework and analysed the data. A. Chapman, F. Taghizadeh-Hesary and S. Mohammadzadeh Bina contributed in literature review, discussions, and improving the manuscripts. All authors had approved the final version.

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