GRC Transactions, Vol. 45, 2021

Utilizing direct-use geothermal energy to improve roads during winter conditions in the Reno-Tahoe region, USA

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Keywords

Geothermal, Melt, Ice, Snow, Roads, Highways, Direct-use, Reno, Tahoe, Magnetotelluric (MT)

ABSTRACT

Geothermal energy from subterranean geothermal reservoirs along the eastern base of the Sierra Nevada in the Reno-Tahoe region of the western United States (USA) can potentially be used to melt ice and snow formed on Highway 50, Interstate 80, and other similar roads such as Mt. Rose Highway and Kingsbury Grade. This would save millions of dollars in snow plow and road maintenance costs over the years and have a positive environmental impact due to the reduced requirements for snow plows, road safety vehicles and checkpoints, and construction vehicles and equipment. Geothermal reservoir temperatures at the base of the Sierra Nevada mountains in this region range from <50°C (122°F) to >160°C (320°F) depending on well location and geometry of reservoir substructure. Examples of areas with successfully functioning road ice and snow melting geothermal systems include Japan, Argentina, Poland, and in the USA, New Jersey, Wyoming, Colorado, and Oregon. From these examples, in combination with other engineering considerations, a reasonable custom design can be constructed in the Reno-Tahoe region. An ideal design would be a geothermal closed-loop circuit that transfers heat via a plate heat exchanger house to a closed-loop ground circuit which runs 2 inches underneath the road surface and along the road. The general order of operations for this project are: running heat loss calculations along pipelines based on estimated temperature ranges, conducting geophysical surveys in target well areas (considering real estate and permitting, etc.), designing the geothermal binary closed-loop pipe system and all its peripheral components, and finally constructing and maintaining the system. The purpose of this report is to list in a comprehensive and succinct format the necessary components and their feasibility, thus initiating the beginning phases of designing and installing such a system.

1. Introduction

The Reno-Tahoe region surrounds the area of the California-Nevada border where the state line runs through Lake Tahoe. Winter storm activity in this region can heavily impact local, tourist, and commercial traffic resulting in high costs maintaining road safety and subsequent repairs (Chebot et al., 2015; Shi, 2018). Highway 50 acts as a major thoroughfare from Reno, NV and Carson City, NV in the region's valleys heading to Lake Tahoe in the adjacent mountains, and Interstate 80 from Reno to the north of Lake Tahoe across Donner Summit and beyond to Sacramento, CA, the latter being an extremely important commercial route for large semitrucks.

Geothermal energy from local geothermal reservoirs along the eastern base of the Sierra Nevada in the Reno-Tahoe region can potentially be used to melt snow as it falls over the roads and prevent ice buildup on the roads. This will greatly reduce requirements for snow plows, road safety vehicles, checkpoints, and construction vehicles and equipment, and therefore save millions of dollars. Examples of successful snow and ice melting geothermal systems on roads and bridges are in certain areas of Japan, Switzerland, Argentina, Poland, and in the USA, New Jersey, Colorado, and Oregon (Eugster, 2007; Lund, 2005 and 2009). Little previous work has been documented regarding the use of geothermal for roads in the Reno city limits except for a few special cases (e.g. Shevenell et al. 2014 shows an attempt to determine the possibility of using geothermal energy to maintain Reno airport runways).

The N-S-trending Walker Lane lies at the western edge of the Great Basin, USA, an extensional geologic environment known for its virtually limitless geothermal potential (Coolbaugh et al., 2005; Faulds and Hinz, 2015). This region is classified by the International Geothermal Association (IGA) as a CV2 geothermal play type (Hervey et al., 2014). Thermal waters heated from deep magmatic sources upflow along normal faults and their related fractured structures before mixing with meteoric drainage flows. These fracture zones generally trend north-south mostly along the base of the mountain ranges and are primary targets for geothermal wells, typically 1-3 km depth (Faulds and Hinz, 2015). In areas between faults, thermal waters have been observed to flow in lateral aquifers with no visible surface indicators (a.k.a. "blind" geothermal systems) (Faulds and Hinz, 2015). Geothermal temperatures recorded in the area range from <50°C (122°F) in areas such as near Lawton hot springs in northwest Reno and Minden, NV in the Carson Valley at a depth of 1-2 km (NBMG, 2021) to >160°C (320°F) at Steamboat Power Plant in south Reno at a depth of 3-5 km, with increasing temperatures deeper towards the source, the highest measured at 260°C (500°F) (Bjornsson et al., 2014; Ormat, 2018). Figure 1 shows the recent Nevada Bureau of Mines and Geology (NBMG) map with geothermal data overlaid, with the darker colored areas representing higher measured temperatures (NBMG, 2021). Geothermal waters are typically slightly mineralized and have an electrical resistivity of 3-10 ohm-m, and sharply contrast the surrounding rock (Muñoz, 2013). Geophysical surveys, primarily broadband Magnetotelluric (MT) soundings which are used to generate 3-D electrical resistivity models, reveal hydrothermal substructures and thus provide invaluable information delineating geothermal well targets (Muñoz, 2013).

The nature of this investigation is three-fold. First, we detail a description of the known geothermal areas of interest to this project and the procedure in which to delineate well targets via geophysical surveying. Secondly, suggestions on design and construction of the closed-loop pipe system carrying geothermal energy up the highways based off of known examples will be given. Thirdly, we will provide a section on estimated economic and environmental impact resulting from the reduction of ice and snow, road safety, and construction vehicle and maintenance costs based on recent reports from local agencies.

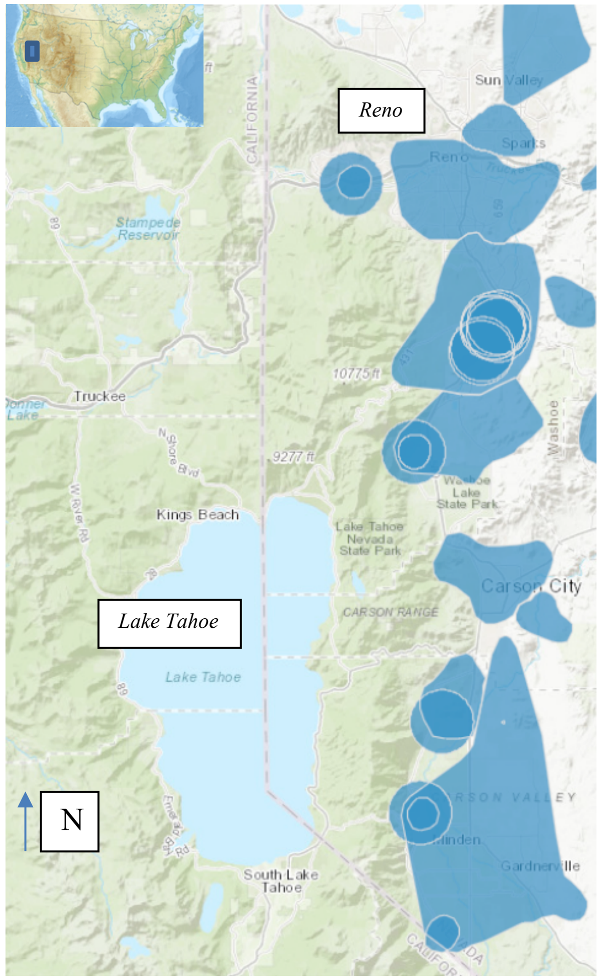

Figure 1. Map of the Reno-Tahoe region, USA showing geothermal cluster data, with the darker colored areas representing higher measured geothermal well temperatures (average range 45°C to 120°C, 113°F to 248°F). Highway 50 runs into the center of Lake Tahoe directly from Carson City to the east, and Interstate 80 (I-80) runs from Reno southwest through Truckee to the north of Lake Tahoe (Nevada Bureau of Mines and Geology, 2021).

2. Delineation of geothermal source targets

At the base of the Carson Range (a short N-S branch of the Sierra Nevada) to the east of Lake Tahoe, Highway 50 runs through Carson City, NV in the region's valleys heading up to Lake Tahoe in the adjacent mountains to the west. Here deep below the ground geothermal waters upflow along fractured normal fault planes (Coolbaugh et al., 2005; Faulds and Hinz, 2015). When the geothermal heat energy is extracted via binary fluid closed-loop system and pumped into pipes running along the highway, it can melt ice and snow on the road. To access these the energy in these thermal waters, a well must be drilled into a fractured zone along the fault plane - the more fractured the better in general - and preferably from a zone where the mixing with meteoric waters is at a minimum (Faulds and Hinz, 2015). A minimum temperature is required in order maintain de-winterization along the entire length of pipe (>0°C) while respecting the maximum temperature which the pipe can stand without melting (e.g. PEX pipe has a melting temperature of 120 - 130°C (248 - 266°F) depending on grade) (Lund, 2005; Warmup, 2016). It is crucial to locate proper geothermal well drill targets to achieve maximum possible geothermal temperature available. To delineate specific drill targets that have a high probability of heat production, we must follow an order of operations. Geologic mapping, as well as any known well logs which have temperature data, are first considered when choosing a temperature test site, preferably within close proximity to a fault since the drill target is a fractured fault contact zone (Faulds and Hinz, 2015; Heliasz, 2001; NBMG, 2021). Geochemical data should be considered if available from well logs or any present surficial as it will help understand the reservoir properties (Neupane, et al., 2015).

The next phase is to narrow down the wellsite selection by conducting geophysical surveys at the chosen landsite. Although regional assessments of structural controls in the Great Basin have shown that N - NE-striking faults (N0°E - N60°E) are the primary control for ~75% of the fields, many show no signs of geothermal activity. Thus, it is imperative to determine which faults or which segments of individual faults are most likely to host geothermal activity, especially in a region where the majority of the geothermal resources are likely blind or hidden (Faulds and Hinz, 2015). Most of the land along the mountain base close to where Highway 50 runs through Carson City, NV is in non-urban/suburban areas is either forest land or is managed by the Bureau of Land Management (BLM) and is open to the public and easier to conduct geophysical surveys on as opposed to less accessible more urbanized areas (BLM, 2021). Land availability requires current market research as well as local drilling permits, water and geothermal. An area surrounding primary available land purchases must be chosen for initial geophysical surveys - primarily broadband MT soundings - which will help to reveal the geothermal substructure via a 3-D electrical resistivity model (Muñoz, 2013). Seismic and gravity surveys may compliment the subsurface model by constraining local structural controls. BLM land is typically open for surveying but may require prior permission. Purchase of land and associated geothermal and water leases should immediately follow positive survey results.

For melting ice and snow Highway 80 from Verdi, NV just west of Reno, NV up to Truckee, CA utilizing geothermal energy is a bit more challenging, considering the source target's low temperature ranges (documented thus far) and distance from the source to the summit. In Figure 1, the geothermal target area would be the small area that protrudes out the most in the west relative to the north-south trending geothermal areas, which is in the northern section along Highway 80. Historic Lawton Hot Springs in Mogul measured temperatures <50°C in 2016 of wells less than a km deep (NBMG, 2021). Recent reports suggest a possible high-temperature geothermal reservoir fueled by deep magmatic injections beneath the Verdi-Mogul area, extending to Sierraville, CA north of Truckee, CA as well as to the south in the north Lake Tahoe area, associated with a tectonically active area deep in the subsurface (Ruhl et al., 2016 (a + b); Smith, 2013). In order to tap into the geothermal energy in any of these areas, further study is required, primarily by means of literary review, geologic mapping, geochemical testing, and geophysical surveys to image hydrothermal substructures, all combined prior to temperature testing via slimhole wells.

Besides these two areas and their respective major highways, there are other areas which have accessible geothermal energy to utilize for highway snow and ice melting (see Figure 1). At the base of Kingsbury Grade in Gardnerville, NV there are geothermal areas similar to the ones to the north near Carson City (NBMG, 2021; Coolbaugh et al., 2005). If the goal is to simply utilize geothermal energy for the Stateline area of South Lake Tahoe to the east, geothermal energy in the form of hot water (or steam if a source >100°C (212°F) is located) can be piped up ~16 km from the base of the grade along Daggett Creek over Daggett Pass and come down Edgewood Creek for example, generally following along Kingsbury Grade. Most of the land at the mountain base in Minden, NV is private and so the land purchase and surveying may be more of a challenge (BLM, 2021). Constructing a pipeline on the Kingsbury Grade road itself is also a challenge since it is more narrow and windy compared to the highways. Other examples of geothermal areas of interest are north and even in and around Lake Tahoe (Smith et al., 2004; Smith, 2013; Squaw, 2015). Similarly with the same challenges of road style and property availability, it is also possible to utilize the geothermal steam from the Steamboat area up Mt. Rose Highway towards north Lake Tahoe (Ormat, 2018; NBMG, 2021). No known work has been done for the Reno area except a report on the feasibility of constructing a geothermal heat pipe system on the Reno International Airport runways, which was apparently abandoned due to the inability to locate a feasible resource on the property (Shevenell, 2014). The area of Squaw and Olympic valleys in north Lake Tahoe have expressed interest in using geothermal steam for melting ice and snow (Squaw, 2015). There is a bit of geothermal activity deep in the subsurface below the area around Kings Beach, NV that could potentially be used (Smith et al., 2004).

In any geothermal project, both for power production and for direct-use such as with this project, using the allotted budget properly inherently means to conduct proper research before drilling and construction begin. It is important to emphasize the requirement for literary review as well as geophysical surveys before any temperature testing via slimhole wells in order to reduce the risk of missing desired targets. This is true especially considering the cost of drilling can be one of the most expensive components of any geothermal project, generally increasing exponentially with depth. A modern design of a geothermal closed-loop system with detailed directional drilling such as the one shown in Figure 2 will be of course be even more expensive. Once a well target is chosen, environmental impact assessment, real estate, drilling permits, water and geothermal leases must be obtained before drilling. Estimated costs of most required components for this project are listed below in the appendix.

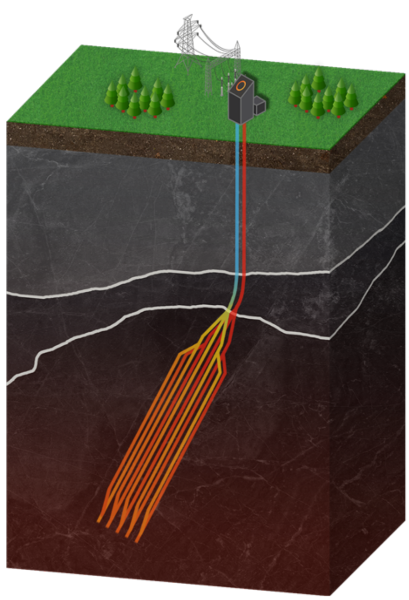

Figure 2. Example of a modern closed loop system (Eavor, 2021).

3. Design and Construction

Once the proper surveys have been conducted and well targets have been chosen, and the land and proper permits have been acquired, the design and construction phases may begin. The design, construction, and maintenance plan requirements of this project include but are not limited to these main components: closed-loop geothermal well installation, plate heat exchanger house, closed-loop ground pipe circuit and pump system.

The first and perhaps most important question that arises (next to "is there geothermal energy available locally?") is can we keep the highways free of ice and snow with the geothermal temperatures available for the distance along the highway required. Essentially this question asks an answer that requires calculation of heat loss along a geothermal steam pipe system using a virtually limitless supply of heat from a geothermal well. The goal is to determine if a closed-loop geothermal well system can provide the required heat to melt snow and ice on the road via a plate heat exchanger house to a closed-loop pipe circuit that runs 2 inches underneath and along the road surface. One report that helps to answer this is Lund (2005). According to this report, Chapman (1952) derives and explains equations for the heating requirement of a snow-melting system. Chapman and Katunich (1956) derive the general equation for the required pavement heat output (q_o) in Btu/hr·ft^2 (modified):

$$q_0 = q_s + q_m + A_r\,(q_e + q_h) \qquad (1)$$

where

q_s = sensible heat transferred to the snow (Btu/hr·ft^2),

q_m = heat of fusion (Btu/hr·ft^2),

A_r = ratio of snow-free area to total area (dimensionless),

q_e = heat of evaporation (Btu/hr·ft^2), and

q_h = heat transfer by convection and radiation (Btu/hr·ft^2).

The details of each parameter of this equation are explained below.

The sensible heat q_s to bring the snow to 32°F (0°C) is:

$$q_s = S(cp)\,D_W(32-T_a)/c_1$$

where

S = rate of snowfall (inches of water equivalent per hour),

D_W = density of water equivalent of snow (62.4 lb/ft^3),

cp = specific heat of snow (0.5 Btu/lb·°F),

T_a = air temperature (°F). and

c_1 = conversion factor (12 in/ft).

For hot water (hydronic[(A)]) systems, the above reduces to:

$$q_s = 2.6\,S\,(32-T_a)$$

The heat of fusion q_m to melt the snow is:

$q_m = (S h_f D)/c_1$

h_f = enthalpy of fusion for water (143.5 Btu/lb).

For hot water (hydronic[A]) systems, the above reduces to:

$q_m = 746\ S$

The heat of evaporation q_e (mass transfer) is (for hydronic):

$q_e = h_{fg}\ (0.0201\ v + 0.055)\ (0.188 - p_{av})$

where

h_{fg} = heat of evaporation at the film temperature (Btu/lb),

v = wind speed (mph), and

p_{av} = vapor pressure of moist air (inches of Hg).

the heat transfer q_h (convection and radiation) is (for hydronic):

$q_h = 11.4\ (0.0201\ v + 0.055)\ (T_f - T_a)$

where

T_f = water film temperature (°F), usually taken as 33°F(0.56°C).

(A) hy·dron·ic - denoting a cooling or heating system in which heat is transported using circulating water.

The solution of the general equation for q_0 for the required pavement heat output requires the simultaneous consideration of all four climatic factors: wind speed, air temperature, relative humidity, and rate of snowfall (Lund, 2005). If we assume that the area is initially nearly snow-free at the beginning of a winter storm due to preheating of the road surface by a near-boiling temperature geothermal system and a low to moderate wind speed (~10–30 mph), and the heat of evaporation at the film temperature ~1000 Btu/lb, we can drop the $A_r\ (q_e + q_h)$ term since this would render the value relatively negligible (typically this term would be < 10% of the total heat output required), thus reducing the heat output equation to

$$q_0 = q_s + q_m = S\ [2.6\ (32 - T_a) + 746] \qquad (2)$$

Some calculated values based on regional averages (Weather Spark, 2021) are shown in Table 1.

Rate of Snowfall	Air Temperature	Heat Output Required To Melt	Heat Output Required To Melt
S (inches/hr)	T_A (°F)	q_0 (BTU/hr·ft²)	q_0 (W/ft²)
1	30	751.2	220.2
2	30	1502.4	440.3
3	30	2253.6	660.5
1	20	777.2	227.8
2	20	1554.4	455.5
3	20	2331.6	683.3
1	10	803.2	235.4
2	10	1606.4	470.8
3	10	2409.6	706.2
1	0	829.2	243.0
2	0	1658.4	486.0

Table 1. Sample calculations of required heat output for melting snow and ice on roads during winter conditions using equations modified from Chapman et al., 1952 and 1956 and Lund, 2005. Snowfall rates and air temperatures selected are standard values for the Reno-Tahoe region (Weather Spark, 2021).

Next, the geothermal heat output q_G is calculated. First this value is calculated at the initial point at the well location based on the temperature of the well, then it is calculated for a particular distance from the well by subtracting q_L, the heat loss per foot. The solution of the general equation for q_G and q_L, requires the simultaneous consideration of initial geothermal temperature, the distance from the well, flow rate, density (29.166 kg/ft^3) and specific heat (2.777 kJ/kg·°C) of the 50/50 ethylene glycol mix used in the ground circuit, and heat conductivity of the pipe material. The desired outcome is that the required heat output q_0 is met at every point in the circuit along the roads before the fluids return to the plate heat exchanger house for heat recharging.

The heat output in kJ at the well source q_G follows the equation

$$q_G = C_F V_G (T_G - T_g) \tag{3}$$

Where C_F is the specific heat of the fluid used in the closed-loop circuit in the geothermal well in kJ/kg·°C, and V_G is the volume of the fluid in ft^3/ft (converted to kg of fluid), which in this case can be the first foot of pipe coming from the plate heat exchanger (0.022 ft^3 or 0.642 kg), T_G is the geothermal well temperature in °C, T_g is the ground temperature (assumed to be equal to the air temperature) in °C assuming 100% heat transfer from the well to the exchanger to the ground circuit (Takahashi and Yoshida, 2013). Dividing this equation by 3.6 converts to W-hr/ft, which for every foot of 1-inch diameter pipe it is about 34.7 - 49.6 W-hr for a well temperature range of 70 – 100°C.

As a general rule of thumb, you can assume a minimum flow rate of about 2.5 to 3 GPM is required for every 12,000 BTU/hour (1 ton, 3.5 kW) of heating and cooling using a water source heat pump (though some units specify flows as low as 1.5 GPM/ton for open-loop systems and 3 GPM/ton for closed-loop systems) (Butts, 2018). With lower temperatures, higher flow rates are required to transfer the heat output required for melting ice and snow at greater distances. At these higher flow rates, the ground circuit can be treated as q_G since it performs as an extension of the geothermal well. The flow rates required for this setting depend on the geometry of the ground circuit design.

Present practice in the U.S. is to use plastic pipes made of a cross-linked polyethylene (PEX), that according to ASTM standard F 876, can handle 82.2°C (180°F) water at 100 psi or 93.3 °C (200°F) water at 80 psi with iron for the header pipe (Lund, 2005). This type of pipe is lightweight and easier to handle, can be bent around obstructions or for reverse bends with radii of as little as 12 inches (30.48 cm), is available in long sections, does not require expansion loops, and uses mechanical compression connections. Because it does not corrode, it has a utilization lifespan of over 50 years (Lund, 2005). PEX pipe has a high thermal conductivity of 0.41W/m·K (2.84 BTU·in/hr·ft²·°F) and has a temperature limit of about 120°C (248°F) (Warmup, 2016), whereas the more costly CPVC pipe has a high thermal conductivity of 0.136 W/m·K (0.943 BTU·in/hr·ft²·°F) and has a temperature limit of about 180°C (356°F) (C-Therm, 2020).

To calculate heat loss per feet per hour along the ground circuit q_L, we must consider the heat conductivity of the pipe, the temperature of the geothermal well, the ground temperature, the inner and outer pipe diameter ratio, and finally adding a 10% increase of power loss due to convective and radiant losses (Smith, 2018). This forms the equation

$$q_L = \{2\pi k\,(T_G - T_g) / 40.1\,[\ln(d_o/d_i)]\} \cdot 1.1 \qquad (4)$$

where q_L heat loss per foot in W/ft, k is the thermal conductivity in BTU·in/hr·ft²·°F, T_G is the geothermal well temperature in °F, T_g is the ground temperature (assumed to be equal to the air temperature) in °F, d_O and d_i the diameters of the outside and inside of the pipe, respectively, and a unit conversion factor of 40.1 (inches to feet, BTU to W·hr) (Smith, 2018). Assuming the ground temperature to be just below freezing, and the outer and inner diameter of the pipe at 1.1 inch and 1 inch, respectively, we can calculate the heat loss per foot for both PEX and CPVC at geothermal well temperatures of 80°C (176°F), 90°C (194°F), 100°C (212°F), and 110°C (230°F), shown in Table 2. For the higher geothermal temperatures, approximately 1 kW/ft is lost through the ground circuit with PEX pipe, and roughly a third of that value with CPVC pipe.

Portland cement concrete (PCC) is the standard pavement material of the region and has a slightly higher conductivity than both types of pipes (0.53 W/m·K), thus not inhibiting heat energy transfer to the surface (Nevada DOT, 2014). The temperature gradient of PCC ranges from approximately 6 to 27°C/ft depending on factors such as PCC variety (the specific heat of PCC ranges from 840 to 1050 J/kg·°C; factors differentiating type include constituent grain size, porosity, etc.) (Liqun Hu, 2017). Thus, at geothermal well temperatures approaching 100°C with a moderate flow rate to retain proper circulation in the ground circuit, the heat distribution along the surface is a matter of designing the ground circuit geometry. It is estimated that for every 1-ft length of pipe, ~10 ft^2 of road is heated sufficiently. The amount of time it takes to heat the surface area depends on factors such as PCC type, well temperature, and flow rates, and ground circuit geometry design. Thus, heat distribution models need to be calculated to determine the time it takes for the surface area to exert the heat required to melt ice and snow with respect to the atmospheric conditions.

Pipe Type	Pipe Conductivity	Geothermal Well Temperature (°F)	Geothermal Well Temperature (°F)	Heat Loss kW/ft	Heat Loss kW/mile
PEX	2.84	230	110	1.009	5328.9
CPVC	0.943	230	110	0.335	1769.4
PEX	2.84	212	100	0.918	4849.3
CPVC	0.943	212	100	0.305	1610.2
PEX	2.84	194	90	0.828	4369.7
CPVC	0.943	194	90	0.275	1450.9
PEX	2.84	176	80	0.737	3890.1
CPVC	0.943	176	80	0.245	1291.7

Table 2. Sample calculations of q_L heat loss per foot per hour for both PEX and CPVC pipe using equations modified from Smith, 2018. Geothermal well temperatures are based on estimated temperatures of the geothermal reservoir at the base of the Carson range in the Reno-Tahoe region (NBMG, 2021). Approximately 0.3-1 kW/ft is lost with this temperature range through the pipe surface area for a 1-inch inner-diameter pipe.

Combining equations 2, 3, and 4 gives

$$q_G - q_L - q_0 > 0 \qquad (5)$$

where q_G is the heat output at the source per foot (W-hr/ft), q_L is the heat loss per foot (W-hr/ft), and q_0 is the heat output required for melting ice and snow per square foot (W-hr/ft,^{2} conversion to road distance depending on road, e.g. 126720 ft^2 per mile on a 2- lane highway, with each lane 12 ft wide). If the resulting heat value is greater than zero at the distance, then the ice and snow on the road will be melted.

Using equation (5), a few heat distribution models perhaps of most interest to this report can be calculated:

A. A geothermal heat pipe running from Gardnerville, CA up along Kingsbury Grade generally straight to the Stateline area for purposes of melting ice and snow on roads in the local South Lake Tahoe vicinity or, in addition to the aforementioned model, include melting ice and snow along Kingsbury Grade (NV Hwy 207).
B. A geothermal heat pipe running from Carson City, NV, melting ice and snow along Hwy 50, potentially crossing over Spooner Summit.
C. A geothermal heat pipe from Mogul/Verdi, NV running up along Hwy 80 towards Donner Pass.
D. A geothermal heat pipe running from Reno, NV, melting ice and snow along Mt. Rose Hwy, potentially crossing over Mt. Rose Summit.

It is important to reiterate that the lateral heat output along the road surface from the pipes of the road depends on the geometry of the pipe layout design. Since the goal is to sufficiently cover the entire surface area of the road, heat distribution modeling is required. The heat distribution models, which include flow rates in the calculations, require program algorithms for each of these possible scenarios and will require additional studies if plans to move forward are implemented. The appendix at the bottom list general estimated expenses for each component.

3.1 Primary Examples of Direct-use Geothermal Energy on Roads to Improve Winter Conditions

Geothermal energy can be supplied to the system by one of four methods: (1) through the use of heat pipes, (2) directly from a well to the circulating pipes, (3) through a heat exchanger at the well head, or (4) by allowing the water to flow directly over the pavement; all of these systems have been utilized to one degree or another throughout the world (Lund, 2005). There are apparently hundreds of undocumented cases of direct-use geothermal energy for roads around the world, and so it is impossible to create a comprehensive list of all of them. We can however benefit from studying the known documented reports of examples, as follows:

3.1.1 Japan

Several areas in Japan utilize geothermal energy for melting ice and snow, the prime example being at Sapporo in Japan, where water from the Jozankei Spa has been used for snow melting on roads since 1966 (Sato, 1979). The system covers 10,405.1 m^2 (112,000 ft^2), which for a standard American single-lane road (12 ft. or 4 m) this would run the length of 2.83 km (1.77 miles). 1 inch (2.54 cm) diameter polybutene pipes circulate geothermal water by three pumps at 40 to 50 GPM with inlet temperatures between 76.1 and 82.8°C (169°F and 181°F) through three separate loops of pipe embedded three to five inches deep at one-foot spacings. The water is then discharged to the Toyohira River at 25°C (77°F) (Lund, 2005). The heat output of this example meets the requirements for a continuous snowfall of 0.4 inches/hr (1 cm/hr) according to ASHRAE, 1995 (Lund, 2005).

3.1.2 Argentina

In the Copahue-Caviahue Thermal Area of west-central Argentina on the slopes of the Andes, 30 tons per hour of geothermal steam from a deep well is transported through an 8,500-foot (2.6 km) long pipeline is used for heating streets and the access road to a ski resort (Lund, 2005). Winter temperatures in the area are as low as -12.2°C (10°F); winds can reach 100 mph (161 km/hr) and snow depths average 13 feet (4 m). Using the geothermal heat, the pavement temperature can kept between 12.2 and 16.1°C (54 and 61°F) by radiant panels underneath the road surface consisting of serpentine hot water distribution pipes covering almost 24,000 ft^2 (2230 m^2) of road surface. The waste water is then discharged at the surface through a collector pipeline (Lund, 2005).

3.1.3 Poland

Although there are no reports available for geothermal road ice and snow melting systems in place in Poland, there are a few reports describing propositions that should be taken into consideration when designing a system. Zwarycz (2002) proposes a design for a snow melting and heating system for the airport at Goleniow, Poland, using 40 - 90°C (104 – 194°F) geothermal water in the Szczecin region (Zwarycz, 2002). Heliasz (2001) makes several suggestions how to use geothermal energy to melt ice and snow, such as using excess waste heat from local coal mines (Heliasz, 2001).

3.1.4 Switzerland

Although there are no direct-use geothermal energy systems for roads in Switzerland, there are a few interesting near-surface ambient temperature systems to regulate winter conditions. Eugster (2007) describes the use of a well-known and well documented geothermal installation: the SERSO pilot plant in central Switzerland, which went into operation in 1994 and is now still running. Essentially the system stores heat from the summer and circulates it during the winter (see Figure 3) (Eugster, 2007). This type of system could possibly be used for areas known for ice build-up causing dangerous conditions, such as Cave Rock Tunnel on the east shore of Lake Tahoe on Highway 50.

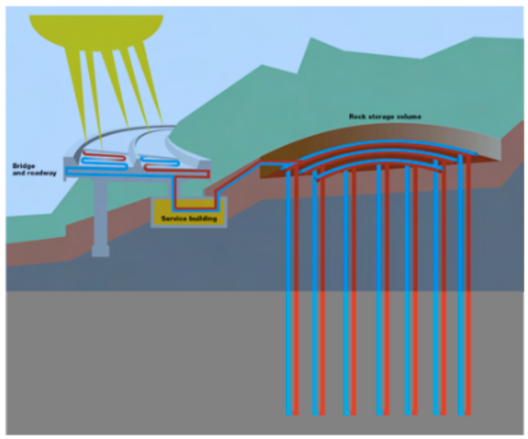

Figure 3. Schematic of SERSO geothermal pipe system using energy from the summer stored in the ground and constantly circulated in winter, preventing ice buildup on bridges in Central Switzerland. (Eugster, 2007)

3.1.5 New Jersey, USA and Wyoming, USA

Trenton, New Jersey was the location of a geothermal heat pipe system developed in 1969, which lead to construction of a design for two places in Wyoming (Nydahl et al., 1984). Figure 4 shows the design used, which utilized surficial geothermal energy (ground temperature 12.2°C (54°F)). Even though this ammonia-based system had several problems including turning some rocks to liquid, it helped form the basis for a standard heat pipe system design in Japan and Colorado a short time later (Lund, 2005).

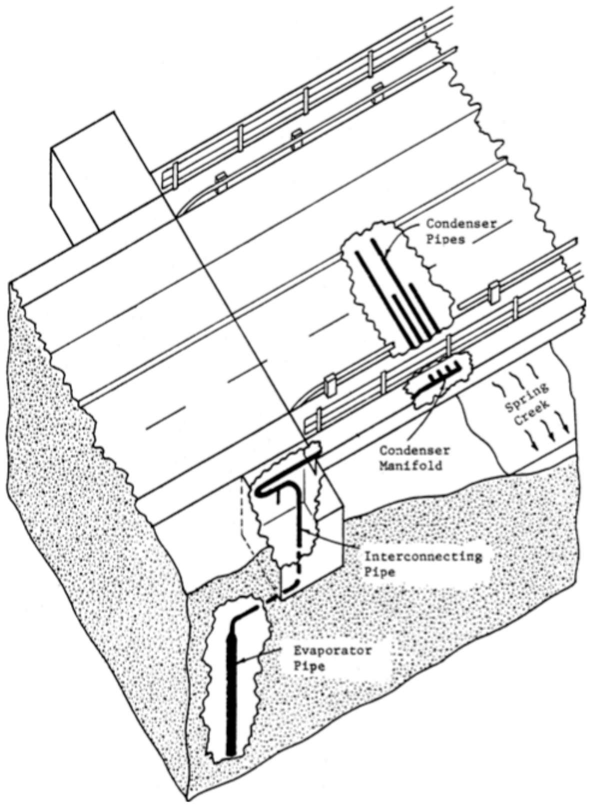

Figure 4. Schematic of Sybille and Spring Creek, Wyoming, USA geothermal heat pipe system from Nydahl, et al., 1984 [(23)]. The upper section of pipes that run perpendicular across the road would be one to implement into this project's design, and the lower section would perhaps be replaced with a pipe that runs along the highway or road straight from the geothermal well.

3.1.6 Colorado, USA

Swanson (1980) and Donnelly (1981) report on the feasibility of utilizing geothermal energy to melt ice and snow on the roads in the Glenwood Canyon area of Colorado about 160 miles west of Denver, CO. The Glenwood Springs, a well-known resort today, has well temperatures that ranged between 23.89 and 29.44°C (75 and 85 °F) at the time of the report all of the heat pipe modules reduced the time that their respective surfaces were snow covered by at least 96% using 25°C (77°F) water at 35 GPM (Glenwood, 2015; Donnelly, 1981; Swanson, 1980).

This system apparently uses an exchange of heat between water and ammonia in both liquid and vapor form; it is uncertain whether or not this system still exists in the present day, but it is known that direct-use geothermal energy is used in the area for a variety of purposes (Lund, 2005). Donnelly (1981) emphasizes the importance of use of geothermal energy in tunnel entrances, steep grades, curves, and locations that are especially prone to icing; these are some of the critical locations where this type of heating system may prove to be cost-effective (Donnelly, 1981).

3.1.7 Oregon, USA

The oldest geothermal pavement snow melting system was installed in Klamath Falls, Oregon in 1948 by the Oregon Highway Department. The grid consisted of 3/4-inch diameter iron pipes placed three inches below the surface of the concrete pavement connected to a geothermal well varying from 37.8 to 54.4°C (100 to 130°F). The heat transferred through a downhole heat exchanger to a 50-50 ethylene glycol-water solution that circulated at 50 GPM, producing 9.0 x 10^5 Btu/hr (30.77 W) providing a relative snow free pavement at an outside temperature of -23.3°C (-10°F) and a snowfall up to three inches per hour, not only for the roads but for the Oregon Institute of Technology (OIT) located there (Lund, 2005; Lund, et al. 2009).

4. Environmental and Budget Impact

Before this project begins, a mandatory full assessment of environmental impact will be conducted. An environmental and social impact statement (ESIS) is a standalone document and is almost always a prerequisite to embarking on a survey or exploration program (in this case after locating potential land and prior to conducting MT surveys, etc.). Any such ESIS should be presented in full to a potential financier (Hervey et al., 2014). The use of geothermal energy generally does not have a negative impact on the environment with respect to deep internal structure and tectonic processes, surficial land use, and in the case of a binary closed-loop heat pipe system as suggested, little to no impact on water budget (Hervey et al., 2014; Ormat, 2018).

In addition to revenue saved from the reduced dependence on snow removal equipment, revenue to local economies will be gained from increased tourist activity unaffected by winter conditions on the roads which utilize geothermal energy.

Overall costs are estimated in the Appendix below. It is estimated that installing the ground circuit will be the largest cost at about $1 million per mile (Caltrans, 2021), with the actual pipe material being the cheapest component, currently at $0.50 - $2.00 per foot. With the $1-2 million cost for installing a geothermal well, and including all other components, the project is estimated to be $30-50 million, depending on location. It has been suggested that if the project were initiated when the road needed resurfacing, a budget compromise may be possible.

Due to the direct-use of renewable geothermal energy, naturally this project will have a net positive environmental impact due to the reduced requirement for fossil fuel use by winter maintenance (e.g. snow plows, salt distribution, etc.), road safety (e.g. chain control checkpoints, tow trucks, emergency vehicles, etc.), and road repair work necessary due to degradation from chained vehicles (Athmann, 2008; Chebotet al., 2015; Corsi, 2006). A primary example of the environmental effects as well as accompanying budgets of the use of snow removal equipment and road salts are from Chebot et al. (2015), a technical report based on a 3-yr study written for Caltrans comparing new salting equipment to one they are seeking to replace. Much of the technical data they include is taken directly from Caltrans technical reports, which must be requested directly from Caltrans via email. Most of the material in the following sections describing examples from District 3 of the Lake Tahoe region are taken directly from Chebot et al. (2015).

4.1 Snow removal equipment fuel usage and cost

To use a local example to get an estimate of fuel and salt usage and resulting costs, let us reference Caltrans District 3, where snowfighting crews are responsible for nearly 3,200 lane-kilometers (2,000 lane-miles) of highways and secondary routes, located within the I-80 and Highway 50 corridors from the foothills of the Sierra Nevada Mountains in the West to the Nevada border in the East and encompasses the Lake Tahoe basin. Typically, each section of road must be serviced every two hours during a storm at the absolute minimum. Over the course of a 24-hour storm, Caltrans vehicles maintain the equivalent of 38,400 ln-km (24,000 ln-mi) of road. Assuming a very conservative fuel usage of 50 l/100km (4.7 mi/gal), the diesel for a single-day storm within District 3 can cost nearly $20,000. In reality, this figure is likely much higher due to idling trucks and very large pieces of equipment such as rotary plows and front-end loaders that consume considerably more fuel than spreader trucks (Chebot et al., 2015).

4.2 Road salt and abrasives usage and cost

Road salt, typically sodium chloride (NaCl), can cost between $55 and $165 per metric ton depending on quality and seasonal demand (Chebot, 2015 at al.; Shi, 2018). Nearly 730 metric tons of salt will be used if two deicing passes are made on every route in District 3 following the conclusion of the storm. The total rises to over 2720 metric tons when anti-icing and the 70:30 abrasive to salt mixture employed during plowing are taken into account. This salt comes at a cost of approximately $150,000 to $450,000 for just a single 24-hour storm. The 4080 metric tons of abrasive used adds to these costs (Chebot et al., 2015; Shi, 2018). Additionally, during winter snow removal operations in District 3, many equipment operators receive substantial amounts of overtime pay (Chebot et al., 2015).

4.3 Environmental impact of snow equipment removal fuel usage and road salt usage

Any anti-icing chemical, deicing chemical, or abrasive dispersed on a roadway will eventually be removed from the pavement and begin to incorporate itself into the environment, possibly with detrimental effects (Chebot et al., 2015; Shi, 2018). Several studies have shown road salt to negatively affect soil/vegetation and aquatic life (Athmann, 2008; Chebot et al., 2015; Corsi, 2006). This is especially true for both road salts and fuel for the immediate surrounding areas adjacent to the roads, but perhaps more importantly having adverse effects on drainage areas into local rivers and of course Lake Tahoe. In the case of the fuel usage, there is little impact on air pollution (Chebot et al., 2015).

4.4 Environmental impact of antifreeze solution in the heat pipe system

Ideally, to reduce environmental impact, as little as possible antifreeze solution should be incorporated into the fluids that flow in the ground circuit just in case there is possible leakage. Lund (2005) states antifreeze solutions are necessary, as most systems will not be operated continuously in cold weather, and thus the system must be protected from freeze damage. A mixture of 50/50 water and ethylene glycol is commonly used in geothermal heat pipe systems. This mixture is used to more efficiently reduce heat loss since glycol has a higher heat capacity (2.77 kJ/kg°C, Engineering Toolbox, 2003) than the more toxic ammonia (Lund, 2005). If leaked, the runoff will likely find its way into the local watershed and have adverse effects on the environment (Athmann, 2008; Chebot et al., 2015; Corsi, 2006). Fortunately this scenario is unlikely with both geothermal and ground circuits being closed-looped (Dandelion, 2020).

5. Conclusions

Geothermal reservoirs at the eastern base of the Sierra Nevada mountains can be used to improve winter conditions on roads, both along highways as well as in the city of South Lake Tahoe. Comparing both the design and economic sections of this report with the appendix below shows that since each winter storm can cost hundreds of thousands of dollars in road maintenance and loss in tourist revenue for a single area, this project is potentially economically feasible. At least a 3-4 year period for investment return is estimated. In order to determine a more precise economic feasibility, geophysical surveys and heat distribution calculations are imperative. The general order of operations for this project are:

1. Calculating/modeling heat loss along a ground circuit design based on estimated temperature ranges of local geothermal reservoirs using a modified version of equation (5).

2. Conducting geophysical surveys in target well areas (considering real estate and permitting, etc.); creating 3-D models of the geothermal substructure.

3. Designing the geothermal closed-loop and ground circuit pipe system.

4. Constructing and maintaining the system.

Acknowledgement

I would like to thank Cody Bass of the City Council of South Lake Tahoe, California, USA for asking me about this topic, which prompted me to write this report. I would also like to thank Dr. Mark Coolbaugh and Dr. John Louie for their insight, J.T. Ingraffia and Michelle Wilcox for helping me to edit this report at the beginning phases, Dr. Artur Jackson for assistance with calculations, and to the Geothermal Rising Conference (GRC) as well as my friends in the city of Reno, NV, USA for supporting this endeavor.

APPENDIX

Service	Time	Cost
Consulting, Geophysical Surveying, 3-D Modeling	3-4 Weeks	$100000 - 200000
ESIS Environmental Report Company	1-2 Weeks	$5,000
Real Estate	6-8 Weeks	Lease or Buy, Market Price
Leasing water permits	1-2 Weeks	$100000 - 200000
Drilling permits	1-2 Weeks	$100000 - 200000
System Design Engineers	3-4 Weeks	$100000 - 200000
Geothermal Well Drill	3-4 Weeks	$1-2 Million
General Contractor/Cost Estimator/Technical Report	Project Duration	$100000 - 200000
Ground Circuit Pipes Install w/Pumps	1-2 Years	$1 Million / Mile
Plate Heat Exchanger	1-2 Weeks	$100,000
Overhead	Project Duration	$5 million
Estimated Total	Project Duration	$25-30 million

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