Low-Temperature Soil Heating Using Renewable Energy

Anthony J. Rossman[1]; Nancy J. Hayden[2]; and Donna M. Rizzo[3]

Abstract: Data from a pilot study, in which renewable energy was used for low-temperature subsurface heating in a northern climate, suggests that such an approach may be useful for remediating low permeable soils. Low-temperature soil heating is expected to enhance remediation effectiveness by increasing contaminant volatility, diffusion, desorption, and microbiological activity. Direct and indirect solar energy was harvested with a hybrid photovoltaic/wind electric system. The electrical energy generated by the hybrid renewable energy system was distributed to the subsurface using a control system and wire, then converted to heat energy using a resistive element emplaced in an unsaturated silty layer 2.3 m below grade. Renewable energy system performance, soil temperature, and environmental data were collected. Ambient soil temperatures fluctuated seasonally within the silt layer from 4 to 15°C. The small renewable energy system performed as predicted and injected 441 kWh of energy into the soil over the eight-month study. This energy input translated to increased soil temperatures ranging from 7.7 to 19.4°C and from 3.3 to 4.3°C above ambient at distances 0.3 and 0.9 m from the heating well, respectively. The system supplied sufficient heat to maintain soil temperatures above ambient even in winter in Vermont, where low direct solar energy was available and sustained low ambient temperatures prevail.

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Introduction

Nonaqueous phase liquids (NAPLs) and matrix-diffused contaminants in the vadose zone can act as long-term sources for groundwater contamination. Nonaqueous phase liquids can become entrapped in low-permeable zones and slowly diffuse over time into these matrices, dramatically reducing the effectiveness of vadose zone remediation strategies, requiring a mobile fluid phase such as soil vapor extraction (SVE) (Pankow and Cherry 1996). Low-temperature soil heating has the potential to enhance the remediation rates of contaminants in troublesome low-permeable soils by increasing contaminant vapor pressure, rates of contaminant diffusion, and desorption (Rossabi 1999). In addition, soil heating may enhance natural attenuation rates and bioremediation strategies, especially in cold regions where biodegradation in the subsurface can be slowed dramatically during the cold winter months (Gibb et al. 2001).

Low-temperature soil heating using renewable energy sources is a remediation strategy with a lower potential environmental impact than traditional strategies and can be cost effective at sites with no existing electrical infrastructure. Electrical energy generated by a photovoltaic (PV) array and/or wind turbine is converted to thermal energy using resistive-element heating elements installed in the subsurface. These heating elements can be driven into contaminated low-permeable zones using a direct push well installation technique. Today's photovoltaic modules are warranted for 20–25 years. They are relatively portable and can be moved from site to site to lower long-term costs.

The overall goal of this research was to investigate the feasibility of renewable energy powered low-temperature soil heating using resistive elements for a low permeable silt layer. The specific objectives were: (1) to design and implement a pilot-scale field test using this new soil heating technology; (2) to determine natural fluctuations in the ambient soil temperatures; (3) to verify solar power predictions using common sizing techniques and published insolation data; and (4) to quantify the soil temperature response to the variable power input of a renewable energy (RE) system in low-permeable soil.

Background

Soil heating for contaminant remediation can be achieved through a variety of methods, including electrical resistance, hot fluid injection, and radio frequency techniques. Smith and Hinchee (1992) present a good review of these technologies and numerous case study summaries. Electrical resistive methods heat the subsurface using either resistive elements or electrodes. In the case of electrodes, the soil itself becomes the resistive element. Resistive heating can be especially useful in low-permeable zones, which are less accessible to fluid injection methods.

Most electrical resistive heating applications to date have heated the subsurface to high temperatures approaching or exceeding the boiling point of water. High-temperature soil heating has been shown to dramatically increase remediation rates in

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laboratory and field studies (She and Sleep 1999; Heron et al. 1998; Davis 1997; Smith and Hinchee 1992). The soil is heated to drive the contaminant into the vapor phase for subsequent removal using an exhaust collection or SVE system. While this can be effective in the short run, this aggressive strategy has high costs associated with the large energy consumption. High temperature heating can also affect the porous media in ways that are not thoroughly understood, including sterilization of a potentially beneficial microbial community.

Low-temperature soil heating for remediation has been gaining attention, especially in northern latitudes (Kosegi et al. 2000; Rossabi 1999; Filler and Carlson 2000). Chemical properties and mass transport processes are related to temperature, some more strongly than others. For low-temperature heating in the unsaturated zone, vapor pressure and rates of biological activity are of particular concern. Contaminant vapor pressure, for example, increases with increasing temperature, but this varies for different chemicals. For many chemicals of interest [e.g., trichloroethylene (TCE), tetrachloroethylene (PCE), toluene, and benzene], a doubling of vapor pressure can be expected at temperature increases from 15 to 30°C (Schwarzenbach et al. 2003). Rossabi (1999) estimated that the removal rate of PCE in a passive soil venting application would nearly double due to increased vapor pressures if enhanced by low-temperature thermal heating from 19 to 29°C. This is encouraging.

Biological processes are also temperature dependent. Many microorganisms that utilize contaminants are most effective at temperatures ranging from 15 to 40°C (Daniel et al. 2000). In cold regions, soil treatment and remediation efforts are often hampered by cold temperatures for at least half of the year. Recent studies, however, have shown that bioremediation can continue during cold periods. Gibb et al. (2001) found that initial biodegradation rates for crude oil varied from 64 mg hydrocarbon/kg dry soil/day at 5°C to 100 mg hydrocarbon/kg dry soil/day at 21°C during the bacterial growth phase. During the stationary phase, the degradation rates were the same, 11 mg hydrocarbon/kg dry soil/day, at both temperatures. These results suggest that even modest heating can have an effect on bioremediation efforts. Filler and Carlson (2000) found that electrical heat tape in insulated biopiles enhanced bioremediation at a reasonable cost. Increasing temperatures can also increase desorption and diffusion rates, which may enhance the bioremediation process. Kosegi et al. (2000) incorporated kinetic expressions for dissolution, biodegradation, and diffusion-limited desorption in a mathematical model to investigate the application of thermal enhanced in-situ bioremediation. Their simulations showed that increasing temperatures from 15 to 40°C could potentially reduce effluent concentrations by 94% and significantly reduce the time needed to meet target water quality goals. Diffusion and desorption rates will tend to increase with increasing temperature, although the magnitude varies for different chemicals and soil matrix properties. Other contaminant properties are less affected at these low temperature changes. Solubility, for example, remains relatively unchanged from 15 to 30°C for PCE and benzene (Imhoff et al. 1997; Schwarzenbach et al. 2003). Although solubility issues will play a larger role during remediation of NAPL in the saturated zone, solubility could be important in some cases even in the unsaturated zone.

Renewable energy technologies have only recently been considered for soil heating in contaminant remediation endeavors (Rossabi 1999; Nakamura et al. 2000). Rossabi (1999) investigated heat transfer in porous media using super-heated water created using solar energy in a trailer-scale collector. Nakamura et al. (2000) collected solar energy using modular concentrators and transmitted the energy using optical waveguides to the subsurface for thermally enhanced SVE. We are not aware of the application of renewable energy to resistive element heating for low-permeable soil heating; however, renewable energy systems offer many advantages in appropriate soil remediation applications, such as low operating and maintenance costs, cost-effectiveness in remote locations, portability, and the intrinsic appeal of mitigating environmental degradation without generating new environmental problems.

Table 1. Site Variables Used to Estimate Necessary Heat Requirements

Parameter	Value	Units
Porosity	0.43	—
Soil grain density	2,720	kg/m^3
Soil grain heat capacity	1,004	J/kg °C
Aqueous saturation	0.2	—
Water density	998	kg/m^3
Water heat capacity	4,200	J/kg °C

One criticism of renewable energy in typical residential applications is the intermittency of the source and the need for storage if utility interconnection is not available. Intermittency may prove to be desirable for soil heating applications because of the reversal of soil drying, however. When the element cools, it is speculated that water will be drawn into the pore space due to capillarity. It is well known that thermal conductivity increases with soil water content in dry soils (De Vries and Afgan 1975). In bioremediation and natural attenuation, if the soil becomes too dry, the microbial community will be compromised.

One drawback using renewable energy for soil heating is the difficulty associated with sizing the PV array and wind turbine to heat a given volume of soil to a specified target temperature. Most sites have a unique mixture of solar and wind potential, especially at northern latitudes. Site-specific resource information must be used to determine the proper scale of the system. Sizing objectives include determining how many PV modules are needed and the wind turbine swept area for a particular heating load to raise the temperature of a finite volume of soil. One of our objectives in this study was to verify solar power predictions using common system sizing techniques relying on published insolation data for use in future modeling and system sizing efforts.

A first estimate of the viability of soil heating using renewable energy was calculated using the common expression for heat capacity [Eq. (1)] and published values of the average solar resource:

$$c = \frac{dQ_{\text{heat}}}{mdT} \tag{1}$$

where c=specific heat of a material; dQ_{heat}=quantity of heat; m=mass of the material; and dT=change in temperature. Table 1 shows the values used to calculate the heat needed to raise the temperature of 1 m^3 of soil 10°C. This calculation shows that it takes 19.2 MJ, or 5.3 kWh, to heat 1 m^3 of silty soil 10°C.

The solar resource in northern latitudes is dynamic and varies by latitude and season. It is also dependant on microclimates. The solar resource available for a one-axis tracker oriented due south in Burlington, Vt., was used to calculate the average daily heat energy that could be delivered to the soil per rated kilowatt of PV array, as shown in Eq. (2). The indirect solar resource that could be harvested by a wind turbine was not included in this analysis

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Table 2. Values Used for Estimating Electrical Energy Delivered to Soil per Rated Kilowatt of PV Array

Parameter	Value	Units
$E_{\text{conversion}}$	0.12	—
A_{PVarray}	8.4	m^2
H_{January} Burlington, Vt.	3.3	$kWh/m^2/day$
H_{July} Burlington, Vt.	7.7	$kWh/m^2/day$
H_{December} Burlington, Vt.	2.4	$kWh/m^2/day$
$H_{\text{YearlyAve}}$ Burlington, Vt.	5.4	$kWh/m^2/day$
$H_{\text{YearlyAve}}$ Daggett, Calif.	9.1	$kWh/m^2/day$

Table 3. Average Daily Heat Energy That Could Be Delivered to Soil per Rated Kilowatt of PV Array

Location and date	Average daily energy supplied to subsurface (kWh)
Burlington, Vt., in January	3.34
Burlington, Vt., in July (maximum)	7.79
Burlington, Vt., in December (minimum)	2.43
Burlington, Vt., yearly average	5.46
Daggett, Calif., yearly average	9.21

because of the large variability in wind resources. The energy available in the wind can be substantial in areas with a large wind resource.

$$dQ_{\text{heat}} = HE_{\text{conversion}}A_{\text{PVarray}} \tag{2}$$

where dQ_{heat}=heat applied to the soil; H=average daily insolation; $E_{\text{conversion}}$=conversion efficiency from solar radiation to electrical energy to subsurface heat energy; and A_{PVarray}=area of a 1 kW PV array.

The conversion efficiency of monosilicon PV modules is typically 11–13% and the conversion efficiency of a resistive element is 100%. The control system and wiring was assumed to be 92% efficient. Table 2 shows the values used in this calculation and Table 3 shows the amount of energy that could be supplied to the subsurface on an average day throughout the year in Burlington, Vt, and a comparison of the yearly average of Burlington to sunny Daggett, Calif.

The combination of Eqs. (1) and (2) suggests that a PV array rated at 1 kW could deliver enough energy to heat 1 m^3 of silty soil in less than 2 days on an average day in January in Burlington, Vt. This is assuming, however, that the boundaries of the soil are insulated. A site located in Daggett, Calif., would supply almost double the energy to the subsurface, based on the yearly Burlington insolation average.

Methods

Site and Pilot System Description

The pilot system was installed in November in northern Vermont. A single resistive heating element was set 2.3 m below ground surface (bgs) of an uncontaminated grassy knoll of relatively homogeneous, unsaturated silt. A small hybrid renewable energy system was connected to the resistive element through an electrical enclosure that housed the control and electrical monitoring equipment. The hybrid energy system was a 600 W_{rated} PV array (eight 75 W_{rated} Siemens SP75 modules) mounted on a Zomeworks passive tracker and small 1.2 m rotor diameter wind turbine (Southwest Windpower Air403) 5 m above the ground surface. The ground surface was not covered or insulated, providing a worst-case scenario. One year of soil temperature background data were collected and heating began in January 2002 and concluded in October 2002. A schematic and photograph of the pilot study are shown in Fig. 1.

An electric system was chosen to move the solar energy to the subsurface instead of a thermal system that relies on moving fluids. While solar thermal systems are more efficient in converting solar energy directly to heat energy (60–80% as compared to 11–13%), an electric system with resistive elements affords a higher power dissipation density necessary for point source heating. An electric system also allows for the harvesting of wind

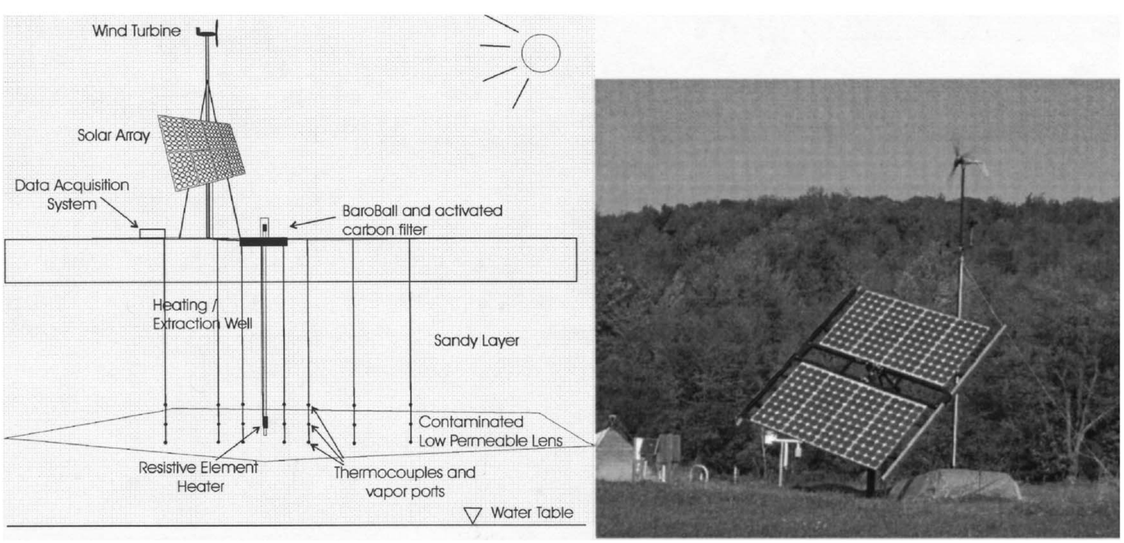

Fig. 1. Schematic and photograph of soil heating pilot site

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power—a substantial resource at many remote sites. In addition, electrical conductors are much easier to install in the field than pipes, and control systems for this technology are easier to implement in electric systems.

Resistive element point sources for heating were chosen instead of the electrodes used in volumetric heating because point sources allow greater flexibility in a potential remediation system design as well as greater compatibility with renewable energy systems. Point source heating wells incorporating resistive elements can integrate other technologies such as barometric pumping wells (passive soil vapor extraction) that could be useful in a dense matrix of heating wells. Electronics to match the impedance of the heating elements to the PV array which is necessary for maximum PV output, are available for lower voltage systems (<100 Vdc) that can be used in a resistive element topology. This is not the case yet for the higher voltages needed for volumetric heating configurations.

The heating well for the pilot study was constructed using 1 in. PVC electrical conduit and a heating element coupled to the base of the conduit. Wires connecting the heating element to the renewable energy control panel were run through the center of the conduit and the remaining conduit annular space was filled with a closed-cell polyurethane expanding foam.

A 2 in. split spoon sampler was used to collect soil and set the heating well. The soil was sampled to a depth of 2.28 m bgs, just above the final placement of the heating element. The 16.5 cm heating element was pushed into the sediment below the last split-spoon sample to ensure a good connection between the heating element and the subsurface formation. The heating well was set in place by hand with a 4 ft level to ensure that the well was perfectly perpendicular to the surface. The hole was backfilled with a bentonite slurry.

Soil samples were characterized as relatively homogeneous unsaturated silt. Soil samples greater than 1 m bgs were determined to be greater than 90% silt content by weight using the standard ASTM hydrometer method for grain size analysis (ASTM D-422). The continuation of the silt below the heating element was confirmed by multiple borings outside the perimeter of the temperature monitoring wells. The water content in three samples taken at 0.4 and 0.6 m bgs were all measured at 19%. In-situ soil permeability was not measured. The water table was estimated to be greater than 10 m bgs based on the difference in elevation of the site and the water surface elevations of a nearby stream and drainage ditch at the site boundaries.

Monitoring Methods

Environmental conditions and the subsurface temperature response were continuously logged during the pilot study using Campbell Scientific, Inc., dataloggers and a multiplexer. The power from the PV array, power from the wind turbine, and power to the heating element were measured separately to assess system efficiency and to confirm data integrity. Direct current (DC) power was measured by logging both the voltage and current, and multiplying the two together. The environmental conditions measured included the ambient air temperature, solar irradiance, wind speed and direction, precipitation, and barometric pressure. The electrical performance and environmental conditions were sampled every 5 s, and 10 min averages were stored and later retrieved.

A dense sampling matrix was used to record the three-dimensional soil temperature response as shown by the schematic in Fig. 2. Temperature monitoring wells were set at distances of 0.3, 0.6, and 0.9 m from the heating well in three vertical planes. An additional temperature monitoring well was set outside the heating area (10 m from the heating well) as the control. Each monitoring well had three discrete sampling locations; thermistors were set at 1.98, 2.28, and 2.58 m bgs. In plan view, the angle between monitoring wells was 120°. Thus, there were 10 sampling locations in the same horizontal plane 0.3 m below the heating element, 10 locations in the same plane just above the heating element, and 10 locations in a plane 0.3 m above the heating element. All thermistors were sampled hourly. The hourly samples were averaged every 12 hours and the averages were stored in final memory until retrieved using a laptop computer in the field monthly.

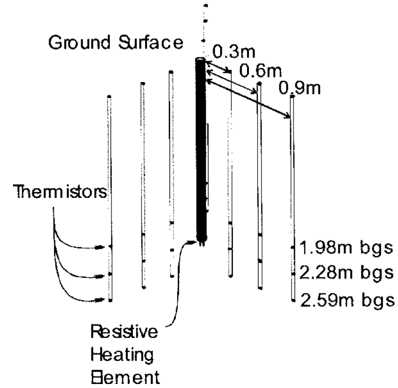

Fig. 2. Oblique side view of soil temperature monitoring network

The temperature monitoring wells were constructed using a 1/2 in. PVC pipe to provide a "backbone" to support the thermistors. Thermistors sealed in a 0.6-cm-diameter cylindrical stainless steel probe assembly 5 cm long were attached to the outside of the PVC pipe by wrapping electrical tape tightly 10–20 times around both the thermistor and pipe. Three thermistors were attached at 0.3 m intervals starting at the base of each monitoring well. A small hole was drilled next to the thermistor leads and data acquisition wire was run from each lead to the well top for a field connection. The remaining annular space of the conduit was filled with polyurethane expanding foam to prevent heat transfer between vertical sampling locations.

To install the monitoring wells, comprising three thermistors each, a 5/8 in. rod was driven hydraulically to a depth of 1.98 m bgs using a solid rod and a direct push rig, with special attention paid to the rods being set perpendicular to the ground surface with a 4 ft level. The rods were removed and the prefabricated temperature monitoring wells comprising the three thermistors were quickly slid into the holes before the formation collapsed. Thermistors always faced toward the heating well. Resistance was observed while pushing the wells and no natural collapse was observed. This indicated there should be a good connection between the thermistors attached to the outside of the PVC backbone and the formation.

The soil temperature response was calculated by subtracting the ambient soil temperature measured at the control well from the temperature measured at each sampling location at the same depth. This correction was done to negate the seasonal fluctuation in soil temperatures, which exceeded 10°C at 1.98 m bgs.

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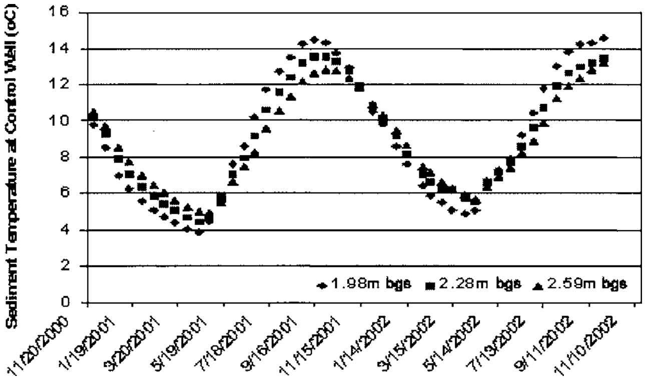

Fig. 3. Ambient soil temperature data collected prior to soil heating

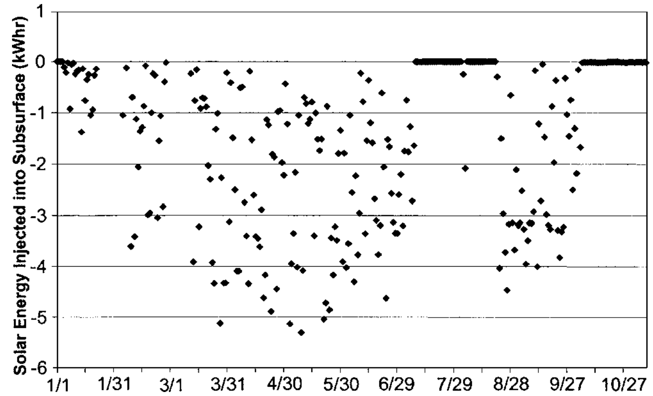

Fig. 5. Daily solar energy injected into soil

Results and Discussion

Ambient Soil Temperatures

Ambient soil temperature data were collected for 1 year prior to the start of soil heating to verify monitoring system performance and track seasonal soil temperature variation at the site. The results are shown in Fig. 3. Each trace represents the average soil temperature measured at the control well at discrete sampling depths (1.98, 2.28, and 2.56 m bgs). The soil temperature measured closest to the surface (1.98 m bgs) showed the greatest seasonal change in temperature, from around 4°C in March to just under 15°C in September. The deepest sampling locations (2.56 m bgs) had the least change, from 5°C to 13°C. Soil closest to the surface will be the most influenced by both direct solar gain and cold ambient air temperatures. These results indicate that there was good contact between the temperature monitoring wells and the soil formation, as evidenced by no vertical thermal short circuiting. This confirmed our original assumption that good thermal contact could be achieved between the monitoring wells and formation using a modified direct push technique.

Fig. 4 shows typical soil temperature data measured at the 30 monitoring locations for a single week in September, before the start of active soil heating. The temperature measurements at the control monitoring well match the measurements taken by the nine other sampling locations at the same depth in the study area. The temperature differences between sensors located at the same depth but different distances from the heating well were less than the average temperature difference between depths, again indicating good sensor placement and solid contact with the formation. The temperature differences within each group of sensors at the same depth represent slight sensor variability and the natural spatial variability in soil temperature at each depth.

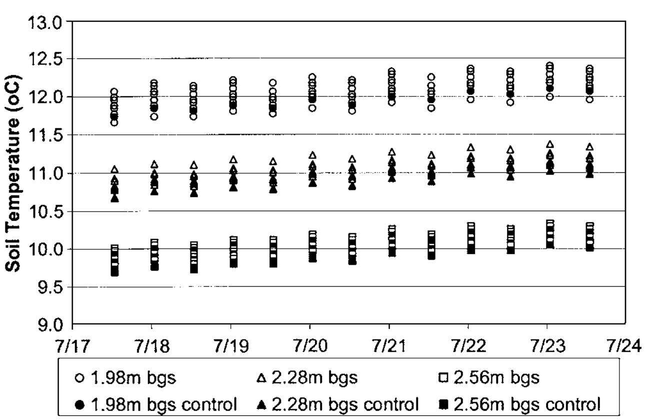

Fig. 4. Soil temperature data prior to heating at all locations within study area

Renewable Energy System Performance

The small hybrid renewable energy system generated 491.9 kWh of electrical energy and injected 436.3 kWh into the soil over the course of the 8 month pilot study. The photovoltaic array dominated the electrical generation at the site, with 486.7 kWh. The daily energy injected into the subsurface by the hybrid PV and wind system is shown in Fig. 5.

Site constraints dictated a low turbine placement of 5 m, which resulted in low wind speeds and turbulent air flow at the turbine. A more typical installation height for a small wind turbine is 25–30 m in laminar air flow. The low turbine height resulted in very low energy production, even though the site was considered moderately windy prior to monitoring. The wind turbine contributed only 5.2 kWh to the total RE energy production after negating energy losses to the turbine during extended periods of low wind speeds. In windy sites (average wind speeds greater than 4.5–5.0 m/s), a wind turbine is still recommended, given that it is properly sized and sited. A wind turbine can be more cost-effective than a PV array under the proper conditions.

A control system was needed to maximize the renewable energy generation and direct the energy input to the soil. If connected directly to a resistive heating element, a PV module will yield only around one-sixth of its generation potential due to the nonlinear current-voltage (IV) characteristic of PV modules. The overall efficiency of the control system for the pilot study was measured at 68%. This number represents the lowest estimate, because the 5 s sampling interval of the datalogger may not have been sufficient to catch energy pulses sent to the subsurface that lasted anywhere from a couple hundred milliseconds to several seconds.

The PV performance was investigated by comparing the measured generation to two predictive models. The first prediction was made by simply multiplying the daily insolation values for one-axis flat-plate collectors at each month by the rated power of the array and was determined to be 777 kWh, 58% higher than the measured value. This is only a crude approximation, because the insolation values were taken from the last 30 years from Burlington, Vt., nearly 40 miles away from the site. Burlington is also in the Lake Champlain basin, while the field site is located

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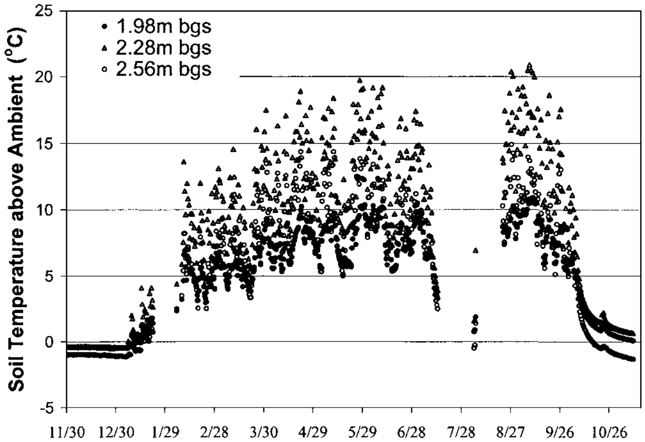

Fig. 6. Soil temperature response 0.3 m from heating well along the NE axis

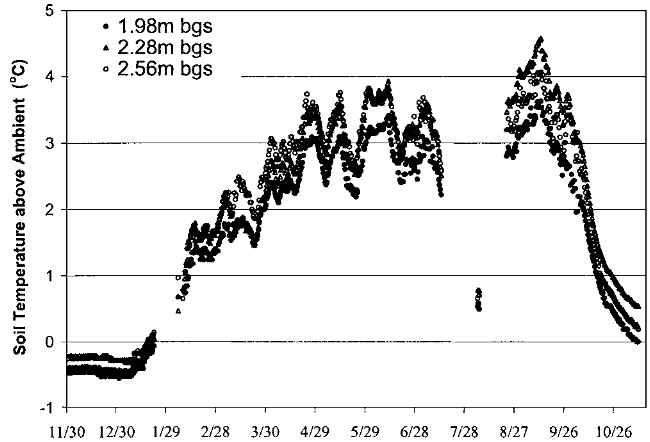

Fig. 7. Soil temperature response 0.9 m from heating well along the NE axis

farther northeast at the base of the Green Mountains, where weather patterns vary greatly from Burlington. A second prediction was done using field irradiance measurements and analytical procedures published by Sandia National Laboratories for characterizing the electrical performance of a PV array (King 1997). The Sandia model predicted the PV array would generate 532 kWh during the pilot study, using the assumption that the PV cell temperature is a conservative 20°C warmer than ambient conditions. This provided a good estimate and was only a 9.3% difference from the measured energy production of the array. Measuring the back of module temperature of the array would lead to a more accurate PV prediction.

Soil Heating

Soil heating began on January 5 and ended nine months later on October 5. Figs. 6 and 7 show the temperature increases at lateral distances of 0.3 and 0.9 m from the heating well along one of the three monitoring axes. The temperature varies more dramatically at the closer radial distance to the well, while there is a dampening effect at farther distances.

Soil temperatures increased 18, 10, and nearly 5°C at lateral distances of 0.3, 0.6, and 0.9 m from the heating well, respectively, when compared to the ambient soil temperature measured at the control well. The sampling locations at 2.28 m bgs exhibited the greatest temperature increase relative to ambient soil temperature, whereas sampling locations at 1.98 m bgs showed the lowest relative increase in temperature. This was expected, because sampling locations at 2.28 m bgs had the shortest physical distance to the heating element and sampling locations at 1.98 m bgs had the greatest distance from the resistive heating element.

A torrential rain event resulted in loss of power from the renewable energy system and a shutdown of the DAQ system. Corroded battery cables used in the control system caused the renewable energy power sources to disconnect from the heating element load from July 14 to August 5. The small battery bank was used in the control system to force the PV array to its maximum power point. The data acquisition system shut down during the rain event because of battery trouble as well. The datalogger's battery box was flooded due to the rainstorm, resulting in a completely submerged battery for all but two days from July 14 to August 5.

This inadvertent shutdown did provide insight to the soil's temperature response that normally would not have been seen. Soil temperature data were collected on two days, August 3 and 4. The soil temperature dropped to near ambient levels everywhere in the monitoring network during this soil "shutdown" period and is shown in Figs. 6 and 7. Power was restored and the temperatures increased from ambient to the preshutdown level within three weeks of power being reapplied to the soil. The data show that the soil temperature reached a quasi-steady state with the pulsed energy input from the PV array and varied proportionately with energy input into the sediment.

A comparison of the temperature response of sampling locations at the same depth and radial distance from the heating well gives an indication of the homogeneity of the soil in terms of thermal conductivity and heat capacity. Fig. 8 shows the increase in soil temperature from ambient at the three sampling locations 0.6 m from the heating well at a depth of 2.28 m bgs. Sampling locations at the same distance from the heating element in two of the three monitoring axes showed nearly identical temperature increases, while the corresponding sampling locations in the southern axis showed temperature increases of nearly 4°C more than the other two. This observation was not consistent for all sampling locations at the same depth and distance from the heat-

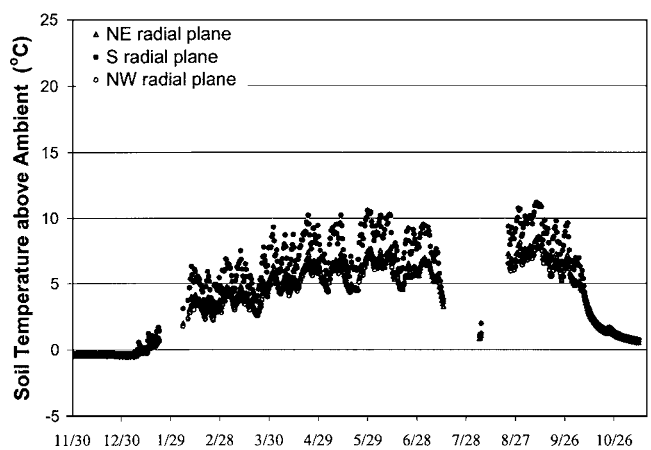

Fig. 8. Soil temperature response 0.6 m from heating well along the NE, S, and NW monitoring axes

Table 4. Assumptions Made for Cost Analysis

Assumption	Value
Lens area	1,011.7 m^2
Lens thickness	1 m
Heating well spacing	4 m
Total number of heating wells	64
Capital cost per heating well	$200.00
Capital cost for installing each heating well	$106.67
Array size per heating well	800 W
Total size of PV array	51.2 kW_{rated}
Total capital cost per watt of installed PV array	$7.50
Annual O&M cost as percent of PV array cost	0.5%
Project lifetime	30 years
Fixed interest rate	5%

ing well, and may have been caused by slightly different thermal conductivity in the soils in one of the vertical sampling planes or geometry effects of the heating element.

The first estimates of soil heating by Eqs. (1) and (2) were not close to the observed soil thermal response to heating. This was expected, because the assumption of a perfectly insulated boundary for the cubic meter of silty soil is a vast oversimplification, and heat losses due to rain events because the site was covered were unaccounted for. Numerical simulations using a subsurface heat transfer model for porous media and hourly insolation values are expected to give better predictions.

Cost Information

The widespread use of a new technology depends on a variety of factors, one of which is cost-effectiveness. The pilot study described in this paper was installed for just under U.S. $8,000, neglecting the data acquisition system and labor. Including labor and data acquisition costs, the pilot study cost approximately U.S. $15,000. This pilot study demonstrated that a 600 W PV array mounted on a single axis tracker in northern Vermont was able to heat outwards of 1 m to an average temperature increase of 10°C without insulating the site surface or side boundaries.

To fully implement this remediation strategy at a contaminated site requires a matrix of many heat injection wells, each similar to the one demonstrated in the pilot study, placed directly into a low-permeable area of high contamination. These heating wells would need to be powered by an appropriately-sized renewable energy system to attain a specific heating goal. Because every site has a different volume of soil to heat and a different mix of solar and wind resources available at the surface, the renewable energy system size will vary from site to site. Detailed numerical modeling of both the soil heating and renewable energy systems will be crucial for determining the least-cost system configuration.

A cost analysis for a hypothetical remediation site was performed based on the experimental results obtained from the pilot study. A 1-m-thick low-permeable lens covering a 0.1 ha (1/4 ac) area was used for the cost analysis. Using a heating well separation distance of 4 m, there would be 64 heating wells installed powered by a 51.2 kW_{rated} PV array. An 800 W_{rated} fixed array is assumed for each well instead of the tracking 600 W_{rated} one used in the pilot study, because fixed arrays are used in larger PV installations and are more cost-effective on larger scales. Cost analysis assumptions are shown in Table 4.

The annual cost over 30 years for this hypothetical 0.1 ha site in Vermont would be $29,171 with a present cost of $448,426 using a 5% fixed effective interest rate. It should be noted that no insulation was used in this pilot study, so seasonal temperature variations in the subsurface could be monitored. Insulation definitely should be used in a full-scale implementation of low-temperature soil heating technology. If insulation was used, the distance between the heating wells could be increased dramatically and these costs would come down considerably. A site with a better solar resource would also bring the costs down.

Conclusions

Data were collected in the low-temperature soil heating pilot study. The results show that low-temperature heating using resistive elements powered by a renewable energy system can be done. Ambient soil temperature data were collected for a year prior to heating, and the measurements were sensitive enough to record soil temperature inversions at distances as small as 0.3 m apart. Electrical performance of the PV array was predicted well by the Sandia National Laboratory Model. Comparisons of soil temperatures were made for both the vertical and horizontal monitoring planes. Measured soil temperatures increased approximately 20°C above ambient at locations 0.3 m from the heating well, 10.0°C at 0.6 m from the heating well, and nearly 5°C at 0.9 m from the heating well. These results were extrapolated to a 0.1 ha site for an annual cost of just under $30,000, assuming a 30 year period and a fixed effective rate of 5%. The cost-effectiveness of this remediation strategy as compared to other strategies will depend on electric rates and availability of the electric grid on site. Insulation of site boundaries and the surface will bring this cost down as well.

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Notation

The following symbols are used in this paper:

$A_{PVarray}$ = area of 1 kW PV array;
c = specific heat of material;
dQ_{heat} = heat applied to soil;
dT = change in temperature;
$E_{conversion}$ = conversion efficiency from solar radiation to subsurface heat energy;
H = average daily insolation; and
m = mass of material.

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