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Upgrading Low Exergy Geothermal Resources to Higher Exergy Resources Applying Hybrid Power Generation System

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ABSTRACT

In this research the solar chimney combined with wind power was investigated as a novel idea of hybrid power generation system. This system is designed for power generation with wind turbine, which has been placed in bottom of the chimney (tower). Wind blade circulates due to known phenomena of "hot air rises" because of temperature difference between lower and upper parts of the tower, which creates thermal updraft air. As long as thermal updraft is induced inside the tower by solar radiation, this system can produce electricity. This system requires wide area with acceptable solar radiation to maintain steady power production. Considering capital investment of proposed system, the efficiency is lower compare to that of other solar power generation methods. To overcome this disadvantage and to utilize low temperature geothermal resources, a new hybrid system was proposed that uses solar chimney idea, wind blade and geothermal heat source. Quantitative analysis of proposed system was performed to achieve basic ground for further developments. An experiment was designed and set up in small scale consists of tower and a pool containing hot water as a heat source. This paper describes outcomes of experiment and compares them to the results from quantitative analysis.

1. INTRODUCTION

There is absolute exergy loss in most of geothermal power plants from separated brine. Several attempts have been made to utilize reinjection water. One of the attempts is utilizing the exhaust heat from reinjection water for the heat source of the solar chimney. Increasing energy demand, declining energy resources, and the potential environmental impact of conventional energy resources development, underscore the need for a sustainable approach to the development and management of earth's energy resources (Rosen and Dincer, 2001). This increasing demand and higher cost for energy and declining fossil fuels in near future, makes research and development on renewable energies feasible. Utilization of renewable energy sources are limited by their availability and efficiency (Jalilinasrabady, 2019). Among them geothermal energy has been developed and its reliability has been proven, the main problem with geothermal electricity production is its locally dependence, meanwhile there are low and medium temperature fields that electricity production in those fields are not possible with current technologies, in such fields direct utilization of geothermal resources is possible if there is any demand from local people (Jalilinasrabady et al., 2016). In this regard, utilization of geothermal resources and better understanding of conversion systems is becoming increasingly more important (Jalilinasrabady and Itoi, 2013).

Geothermal heating has been used since Roman times for bathing, cooking and as a way of heating buildings and spas using sources of hot water and hot steam that exist near the earth's surface. Water from hot springs is now used worldwide in spas, for space heating, and for agricultural and industrial uses (Dickson and Fenelli, 2004).

Geothermal energy utilization is commonly divided into two categories, i.e., electric production and direct application. The utilization method depends on parameters such as local demand for heat or electricity, distance from potential market, resource temperature, and chemistry of the geothermal fluid. These parameters are important to the feasibility of exploitation. Utilization of geothermal fluid depends heavily on its thermodynamic characteristics and chemistry. These factors are determined by the geothermal system from which the fluid originates (Jalilinasrabady and Itoi, 2012).

Sustainable utilization of earth resources has been high demanded topic which is under improvement and development. Geothermal energy is one of the renewable resources that need further studies for its sustainable utilization. Cascade use of geothermal fluid is the ideal way of its optimum usage, but uncertainty is always accompanying these projects (Jalilinasrabady et al., 2012). Plant operations of geothermal fields depend on demand for heat or electricity in the region and reservoir ability to support these utilization units.

Wind is another renewable energy source, investment for wind farms has been increased in all over the world, but its efficiency and cost effectiveness needs improvement.

Solar Chimney, developed by J. Schlaich, absorbs thermal energy through transparent solar collector, induces thermal ascent flow within the chimney set in the center of the solar collector and generates electricity using wind turbine at the bottom of the chimney (Fujiwara et al., 1983). 100 kW prototype had been operated for 7 years from 1982 in Spain with success of generating 50 kW (Richards 1981, 1982, 1982).

A new wind turbine system that consists of a diffuser shroud with a broad-ring brim at the exit periphery and a wind turbine inside it has been developed by Oyha et al., 2006.

The shrouded wind turbine with a brimmed diffuser has demonstrated power augmentation by a factor of about 2-5 compared with a bare wind turbine, for a given turbine diameter and wind speed. This is because a low-pressure region, due to a strong vortex formation behind the broad brim, draws more mass flow to the wind turbine inside the diffuser shroud (Ohya and Karasudani, 2010).

Efficiency has been challenging for development of renewable energy sources; it is one of the key parameters which make them cost effective and economical. To increase their efficiency parallel to technical development in each of renewable energy sources, their combination has been considered.

In geothermal, there is enormous research on low temperature electricity production technology such as innovative ORC cycles, EGS and et cetera. This paper is to explain the possibility of creating hybrid system which will use the idea from solar chimney, heat from geothermal and power from wind. An experiment was designed and set up in small scale consists of tower and a pool containing hot water as a heat source. This paper describes outcomes of experiment and compares them to the results from quantitative analysis.

2. METHODOLOGY

In most of geothermal power plants there is considerable amount of exergy loss due to reinjection. Despite technical issues related to reservoir management, if this reinjection doesn't participate in sustainability of the reservoir, the injected waste fluid usually with temperature around 100°C can be considered as a total exergy loss (Jalilinasrabady and Itoi, 2012, Jalilinasrabady et al., 2010).

As it was mentioned before, one of the disadvantages of geothermal resources is that, they are locally dependent resources; high temperature zones are located in active volcanic areas. Meanwhile there are plenty of places on the planet with low temperature geothermal fields, places like Middle East, Africa that direct utilization of geothermal is usually limited to bathing purposes. There have been attempts and researches to develop methods for electricity production of low temperature resources. Most of them have been focused on ORC cycles (Jalilinasrabady et al., 2011). These small units usually are not very simple and may have maintenance and environmental issues in case of disaster especially in rural areas. If some new idea can help to produce electricity with these low temperature fields and as a bottoming unit with currently operating plants, it will be game changing for geothermal power production and will support its renewability and sustainability.

The idea of wind turbine is working and currently there are wind farms contributing to power production. Considering exergy loss from geothermal fields and technical progress of wind and solar chimney, it seems there is good potential of electricity production with hybrid system which is simple, local and renewable. Figure 1, illustrates the suggested hybrid system, hot geothermal water comes to pond, air is being heated above the pond and since hot air raises, inside chimney air velocity will rotate turbine blade to produce electricity. This system has 3 main parts including geothermal heat supply system, chimney and wind.

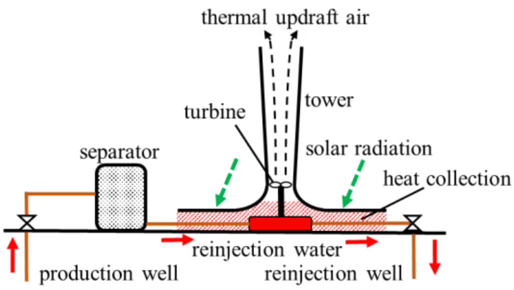


Figure 1: Hybrid geothermal wind system.

2.1 Geothermal heat supply system

Disposed water from separator or naturally discharged hot water from hot spring with temperature of 60-100°C will be brought to the pond. To calculate heat loss from the pond, heat loss calculation from swimming pool was used, since majority of the pond will be covered by chimney, calculated value of heat loss is predicted to be less. In this part of the paper heat transfer phenomena between pond and chimney and fluid dynamic is being neglected, but for further investigation, it needs to be clearly studied.

2.1.1 Heat loss from the pond

Heat loss from outdoor pools is mainly due to convection, evaporation, radiation, conduction and rain (Svavarsson, 1990). The main heat losses from the swimming pool occur by convection and evaporation. The obtained results from earlier research and analyses show that heat losses due to the other three factors (radiation, conduction, rain) can be estimated to be equal to 10% of total heat loss due to convection and evaporation (Jalilinasrabady, 2004). Heat loss due to conduction is small, because of good insulation in the pool building materials. Heat loss by means of rain and radiation is also not very big. In the following calculation, 10% of total heat loss by convection and evaporation will be assumed for these three mentioned factors.

Heat loss due to convection: Heat loss due to convection depends strongly on the air temperature around the pool and the wind speed. Equation 1 shows that heat loss through convection will increase with higher wind speed and lower outside temperature (Jalilinasrabady et al., 2013):

$$q_c = h_c(T_w - T_a) \tag{1}$$

where q_C is the amount of heat loss by convection (W/m^2), T_w is water temperature in the pool (°C), T_a is air temperature in the pool's surrounding (°C) and h_c is the convection heat transfer coefficient (W/m^2°C) which is very dependent on wind speed.

The relationship between heat transfer coefficient and wind speed is shown in equation 2 that is named Rimsha-Doncenko formula:

$$h_c = 4.19(k + 0.45v) \quad (2)$$

where v is wind speed at 2 meter height from the ground surface (m/s) and k is the empirical coefficient (W/m^2°C) as shown in equation 3.

$$k = 0.93 + 0.04(T_w - T_a) \quad (3)$$

Heat loss due to evaporation: Heat loss due to evaporation takes place when there is different partial pressure of water vapor at the pool's surface and in the air over the pool. This will cause evaporation of water at the pool surface, and this requires energy that is taken from the water. This kind of heat loss in the pool can be calculated with Equation 4 from Rimsha – Doncenko (Svavarsson, 1990):

$$q_E = 4.19(1.56k + 0.70v^2)(e_w - e_a) \quad (4)$$

where q_E is the amount of heat loss by evaporation (W/m^2), e_w is the partial pressure of steam at surface (mbar) and e_a is the partial pressure of steam in the air over pool (mbar).

Energy requirement for heating the pond

The total heat loss from the pond has been calculated and the same quantity of heat must be added to the water supplied to the pond. This can be done through a heat exchanger that transfers heat from geothermal water to fresh water that is used as pool water, or geothermal water can be directly fed into the pot:

$$q_T = q_i \quad (5)$$

where q_i is required quantity of heat for the pool (W/m^2). Equation 6 (wark, 1988) is used for calculation of the amount of geothermal water needed as a heat source and the temperature of pool's heated water by heat exchanger. Equation 6 is known as the energy balance equation in the steady-flow condition:

$$Q_i = mc_p(T_2 - T_1) \quad (6)$$

here m is the amount of water required for circulated in the system (kg/s), c_p is specific heat capacity of water (J/kg°C), T_1 is the temperature of inlet geothermal water (°C), T_2 is the temperature of outlet geothermal water (°C) and Q_i is the amount of required heat for the pool (W). The results are m = 6.42 kg/s and T_2 = 65°C. The pond diameter was assumed to be 20 m. Figure 2, shows the variation of geothermal fluid mass flow rate with temperature of pond's water leaving the pond. As it can be seen to maintain pond's temperature in higher temperature, higher amount of mass flow rate is needed.

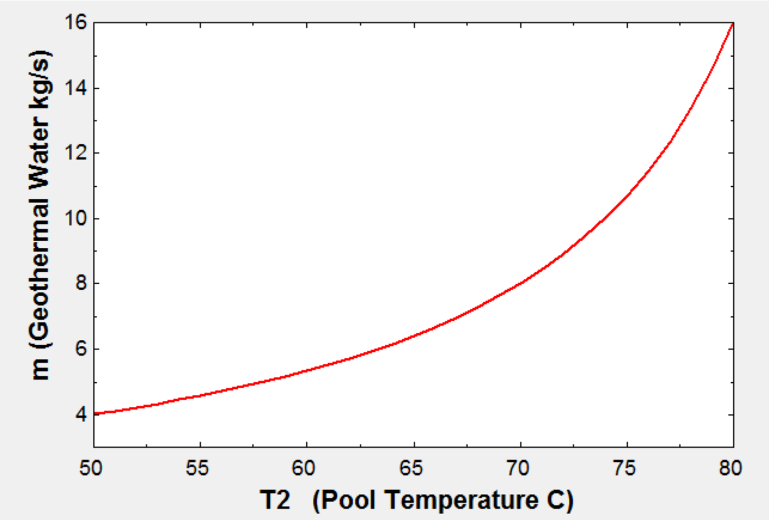


Figure 2: Temperature and mass flow rate variation of geothermal water leaving the pond.

Chimney

A solar chimney, or thermal chimney, is a form of passive ventilation that can be applied to a structure. It uses the principles of heat transfer and fluid mechanics to naturally ventilate a structure without the need of an outside source of electricity. A solar chimney takes advantage of the fact that as the temperature of air changes, the density of air changes as well. Another application of solar chimney has been applied for electricity production with three essential elements of glass roof collector, chimney and wind turbines. Air is heated by solar radiation under a low circular glass roof open at the periphery. In middle of the roof is a vertical chimney with large air inlets at its base. As hot air is lighter than cold air it rises up the chimney. Thus solar radiation causes a constant updraught in the chimney. The energy this contains is converted into mechanical energy by pressure-staged wind turbines at the base of the chimney and into electrical energy by conventional generation (Bergermann, 2002).

The idea of solar chimney is promising, but constructing tall towers demand high capital investment especially in developing countries. Visual environmental impact could be considered as another major disadvantage of this technology. But combining this idea with geothermal would solve these problems. Electricity produced by a solar chimney is in proportion to the intensity of global solar radiation, collector area and chimney height. By considering geothermal as a heat source, only chimney height will be the most influential parameter, this height will dictate air velocity inside chimney that will rotate wind turbine. Equation 7 was used to estimate wind speed inside chimney:

$$Q = CA\sqrt{2gh\frac{T_i - T_o}{T_i}} \tag{7}$$

Q Stack effect draft flow rate (m^3/s)

A Flow area (m^2)

C Discharge coefficient (0.65-0.70)

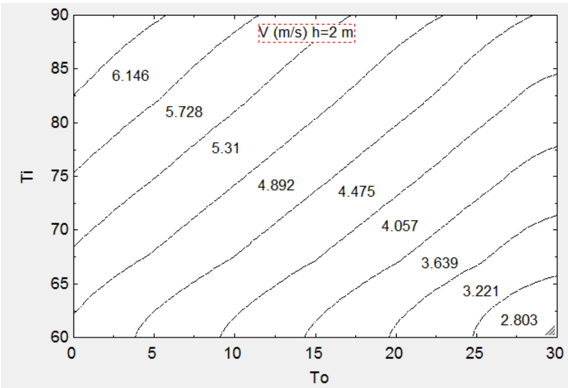
g Gravitational acceleration (9.81 m/s^2)

h Height (m)

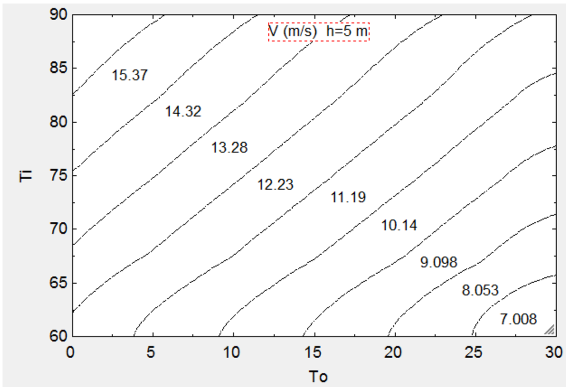
T_i Average inside temperature (K)

T_0 Outside air temperature (K)

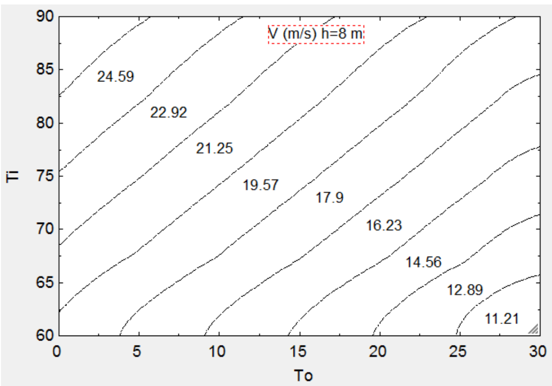
Figure 3 shows variation of velocity with chimney inlet and outlet temperature and its height of 2, 5, 8 and 10 m.



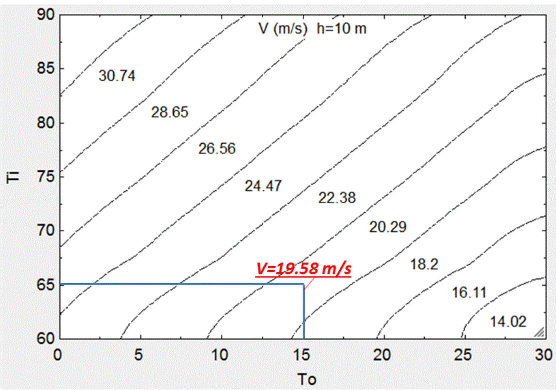
Velocity inside tower with 2 m height



Velocity inside tower with 5 m height



Velocity inside tower with 8 m height



Velocity inside tower with 10 m height

Figure 3: Velocity variation of with chimney inlet and outlet temperature and chimney height of 2, 5, 8 and 10 m.

At very low wind speeds, there is insufficient torque exerted by the wind on the turbine blades to make them rotate. However, as the speed increases, the wind turbine will begin to rotate and generate electrical power. The speed at which the turbine first starts to rotate and generate power is called the cut-in speed and is typically between 3 and 4 m/s. As the wind speed rises above the cut-in speed, the level of electrical output power rises rapidly. However, typically somewhere between 12 and 17 m/s, the power output reaches the limit that the electrical generator is capable of. This limit to the generator output is called the rated power output and the wind speed at which it is reached is called the rated output wind speed. At higher wind speeds, the design of the turbine is arranged to limit the power to this maximum level and there is no further rise in the output power. How this is done varies from design to design but typically with large turbines, it is done by adjusting the blade angles so as to keep the power at the constant level. As the speed increases above the rate output wind speed, the forces on the turbine structure continue to rise and, at some point, there is a risk of damage to the rotor. As a result, a braking system is employed to bring the rotor to a standstill. This is called the cut-out speed and is usually around 25 m/s (WINDPOWER PROGRAM, 2013). Considering these explanations for ambient temperature of 15℃ and maintaining pond temperature at 65℃ wind velocity can be estimated to be 19 m/s with chimney height of 10 m.

Wind turbine

The available power in a stream of wind of the same cross-sectional area as the wind turbine can be calculated from:

$$W = \frac{1}{8}\eta\rho\pi D^2 U^3 \tag{8}$$

W Power output (W)

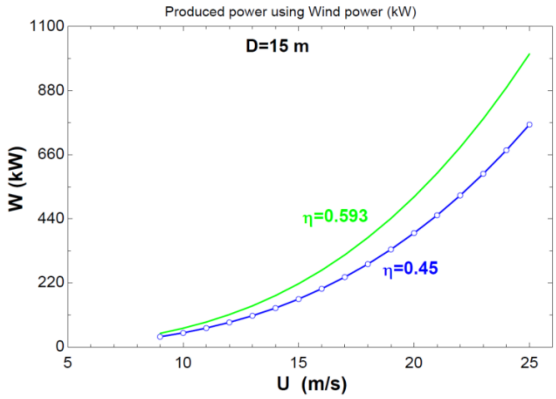
η Betz limit (59% and 0.45)

ρ Density (kg/m^3)

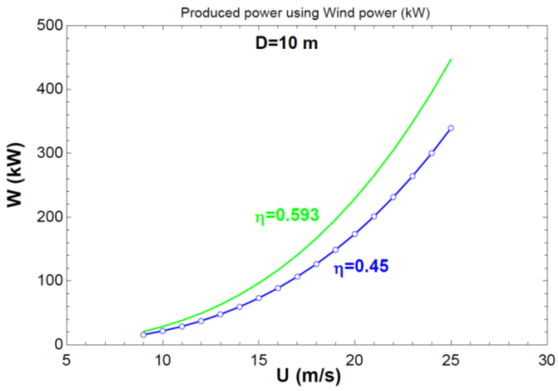
D Rotor diameter (m)

U Wind speed (m/s)

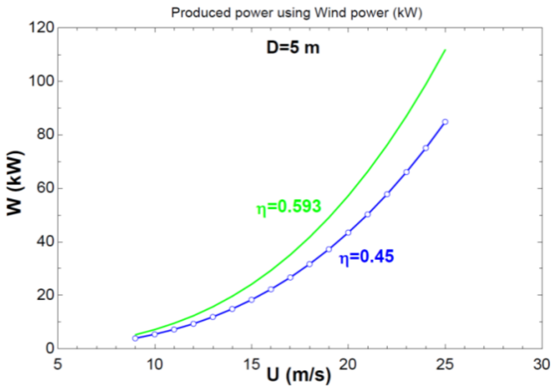
Figure 4 shows variation of produced power with wind speed inside chimney for tower diameters of 1, 5, 10 and 15 m assuming betz limit of 0.59 and 0.45.



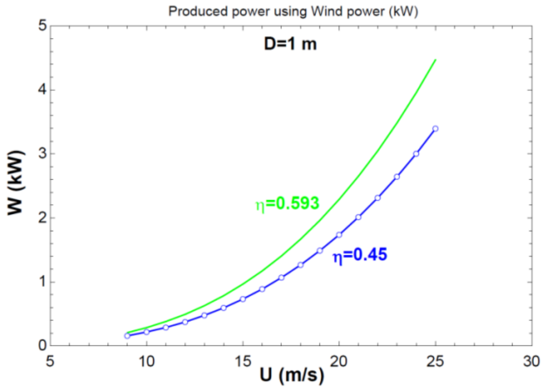
Tower diameter of 15 m



Tower diameter of 10 m



Tower diameter of 5 m



Tower diameter of 1 m

Figure 4: Produced power variation with wind speed inside chimney for tower diameters of 1, 5, 10 and 15 m assuming betz limit of 0.59 and 0.45.

2.1 Laboratory experiment

A laboratory experiment was performed in small scale to confirm the idea of thermal updraft. The tower of 2000 mm height with 320 mm in diameter was installed over the tank with 600 mm height and 700 mm width which is attached to a heater and thermometer. Three thermometers were located at 350 mm over the pool, in the pool and the same height of the tower respectively.

Experimental Procedure

The tank was filled with tap water. The tap water was heated up by prescribed temperature in the heater. The heated water was conveyed from the tank to the inside pool through the pipe. Flow rate was set at 8 l/min. The velocity in the tower and each temperature were measured after the temperature at the inside pool became stable.

Experimental conditions

Three types of experiments were carried out by changing experimental condition.

Case 1, the temperature of the water in the tank was set at 65°C and the experiment was carried out following experimental procedure. Then the apparatus was not attached the tower, the velocity was measured without tower.

Case 2, the temperature of the water in the tank was set at 75°C, the experiment was carried out and the velocity in the tower and three temperatures were measured for 3 consecutive hours.

Case 3, the temperature of the water in the tank was set from 60°C to 90°C and the experiment was carried out in winter (the ambient temperature is from 27°C to 30°C) and summer (the ambient temperature is from 27°C to 30°C).

Experimental results

Table 1 shows the average values for temperature inside the pool and average of the velocity in the tower, respectively.

Table 1. Average temperature and velocity measurement

Tower conditions	Average temperature inside the pool (°C)	Average velocity in the tower (m/s)
Without tower	60.5	0.446
With tower	58.9	1.03

Thermal updraft was generated in condition of using hot water as a heat source of solar chimney. Figure 5, shows two histograms of 2000 seconds in the data measured for 3 consecutive hours of temperature over the pool and velocity inside the tower.

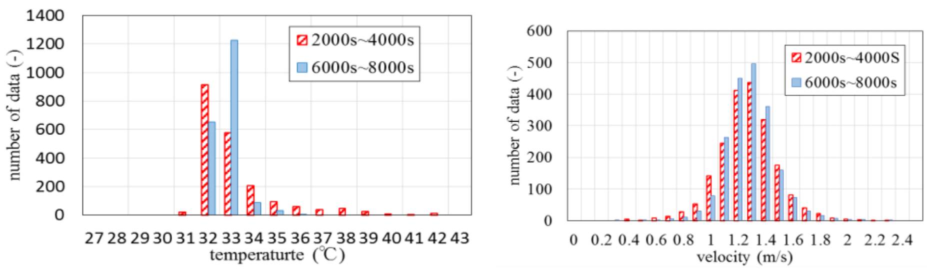


Figure 5: Histogram of measured data of temperature over the pool and velocity in the tower

Inside pool temperature was not stable, but the velocity was almost stable. Figure 6, shows average temperature inside the pool versus average of the velocity in the tower measured in winter and summer. Comparing the velocities measured in winter and summer implies that the difference between ambient temperature and heat source temperature increases with increasing of velocity in the tower.

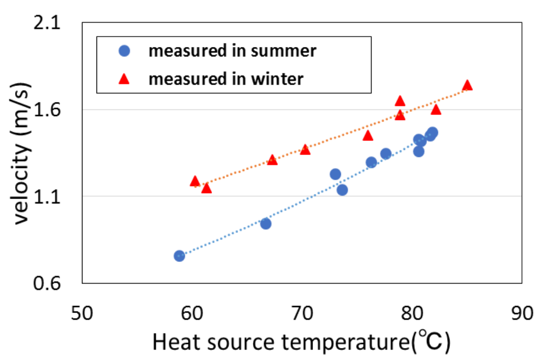


Figure 6: Temperature average versus velocity average

DISCUSSION

A novel approach for power production using hybrid system of geothermal, wind and solar has been proposed. The idea is at its early stage of development and needs further investigation such as numerical simulation, laboratory scale experiment and actual field test, their results can lead to comprehensive cost benefit analysis and site selection for potential fields worldwide. Its hybrid nature helps each of involved renewable energy sources to strength their weakness and cover each other. Places with geothermal potential of almost all classification could benefit from this system due to:

Development of solar chimney would not be necessary, compare to hybrid system they are expensive due to high capital investment for construction. They also face with serious visual environmental impact criticism. Applying this idea, can solve the problem of solar plant's low efficiency during night time and under soil piping system wouldn't be needed.

There will be continues stable wind speed to rotate the rotor. Exergy loss through geothermal brine will be minimized. Hot springs with low temperature classification could be considered for power production.

Each of these renewable energy sources are dependent on location, hybrid idea will widen their application. Places like Middle East, Africa that direct utilization of geothermal is usually limited to bathing purposes, can use this method to produce electricity.

Combined efficiencies and power output of hybrid system for different chimney diameters of 1, 5, 10 and 15 m with betz values of 0.45 and 0.59 are shown in Table 2. As it can be seen from Table 2, with 5 m increase in chimney diameter from 10 m to 15 m (rotor diameter), the efficiency of the hybrid system will be increased by 2.25 times. Even clear economic analysis is needed, but it seems convincing that constructing chimney with 5 m larger diameter doesn't seem challenging task considering its impact on the efficiency of the plant.

Table 2: Efficiencies and produced power of hybrid system for different chimney diameters of 1, 5, 10 and 15 m with betz values of 0.45 and 0.59.

No.	Diameter (m)	W (kW), Ƞ=0.45	W (kW), Ƞ=0.59
1	15	335.3	441.8
Plant efficiency		13.90%	18.31%
2	10	149	196.4
Plant efficiency		6.18%	8.14%
3	5	37.25	49.09
Plant efficiency		1.54%	2.04%
4	1	1.49	1.96
Plant efficiency		0.06%	0.08%

Similar to all new developments there are several questions to be answered about new hybrid system considering its environmental issues, their mitigation methods and operational concerns:

Environmental visual impact: Geothermal manifestations are usually located at natural parks and building 10-15 m towers will raise visual impact for the environment, but it seems necessary to mention that chimney will be as tall as vertical separators, so this impact can be justified in the fields that geothermal power plants are already installed and under operation. About other national parks the impact can be mitigated by building in slops, coloring, painting and etc. But its visual impact is less than wind farms and solar chimney and sometimes solar farms.

In operating power plants if there was reinjection difficulties, power companies may hesitate interrupting injection line to avoid any possible surprises.

In proposed hybrid system, the pond water temperature can go as low as 20°C higher than ambient temperature or less. In case of power plant, brine reinjection with low temperature can be additional challenge to overcome scaling problem. This issue will not be important in case of hot springs, since they are being naturally discharged to the environment.

Geothermal water in some cases is corrosive; this corrosion can affect turbine blades and may increase maintenance routines of the system. This issue can be managed for every individual project depending on their fluid chemistry. Close loop heat exchanging system can be alternative solution for this problem.

CONCLUSIONS

A simple, local and renewable novel design has been proposed for power production using the idea from solar chimney which combines three renewable resources of geothermal, wind and solar. Quantitative analysis has been carried out using basic equations.

Sample project was defined with ambient temperature of 15°C, circular pond with diameter of 20 m was assumed, according to heat loss calculation 6.4 kg/s of 90°C geothermal water is needed to maintain pond's temperature at 65°C. Chimney with 10 m height and 15 m diameter was assumed to be installed over the pond, with these specifications it was estimated that the velocity inside wind tower will reach to 19.5 m/s and that will produce 441 kW and 335 kW of electricity with betz limit of 0.59 and 0.45 respectively. Discharged water from the pond still has potential for direct use application.

Thermal updraft was generated in condition of using hot water as heat source. It was confirmed that with rising of the temperature inside the pool, the velocity of thermal updraft generated in the tower was increased.

Results are promising and it seems that suggested idea is competitive with other renewable energy sources, further studies are necessary to achieve more realistic results to start actual project.

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