GSJ: Volume 8, Issue 12, December 2020, Online: ISSN 2320-9186
www.globalscientificjournal.com

THERMODYNAMIC ANALYSIS OF SOLAR UPDRAFT TOWER POWER PLANT: A CASE STUDY OF JAMSHORO, SINDH

Hamza Khan[a], Dr. Khanji Harijan[b], Ans Ahmed Memon[b]

[a] *Department of Post Graduate Studies, Mehran University of Engineering and Technology, Jamshoro, Pakistan,*
Phone: +92-311-0139681, E-mail: hamza.khan1995@yahoo.com
[b] *Department of Mechanical Engineering, Faculty of Engineering, Mehran University of Engineering and Technology, Jamshoro, Pakistan.*

KeyWords
Renewable Energy, Solar Updraft Tower Power Plants, Solar Chimneys, Solar Power Production, Jamshoro Sindh.

ABSTRACT

We are living in era of energy crisis. In this hour of need the renewable energy is the best choice among all. The Solar Updraft Tower Power Plant is an adaptation of the use of sustainable energy resources, a distinct and innovative synthesis of three exiting ideas: greenhouse effect, chimney effect and wind effect. The present research primarily on the thermodynamic analysis of “Solar Updraft Tower Power Plant”: A case study in Jamshoro Sindh, presenting the estimation of power potential from this technology in Jamshoro by focusing the transfer of heat from the sun to the collector, up to the production of electrical power by the wind turbine, considering the air as an ideal gas. The governing equations used in the simulation consist of the Continuity equation, Navier-Stokes equation, Energy equation, and Radiation transfer equation. The mathematical equations were modeled in a simplified form by considering normal thermodynamic actions of the air to determine the performance of prototype plant in terms of electrical power production. The equations were modeled and simulated on the software Engineering Equation Solver. It can be concluded that the SUTPPs are very appropriate for remote areas where there is plenty of solar energy capacity; such as Tharparker, Jamshoro and some areas of Balochistan. These types of technologies should go on the road to commercialization with the diminishing supplies of fossil fuels and the exacerbation of air emissions and greenhouse effect.

INTRODUCTION

Pakistan is facing a serious power challenge since 2007 due to the massive gap in production and consumption which has escalated to many hours of load shedding throughout the region. The country's installed generation capacity is approximately 24,565 MW and the power shortfall is approximately 3000 MW to 6000 MW across peak times. [1][2]. The key explanation for the energy crisis in Pakistan is that the energy system is primarily dependent on thermal resources, including coal, oil and natural gas, which are both costly and under tremendous scarcity pressure.[3]

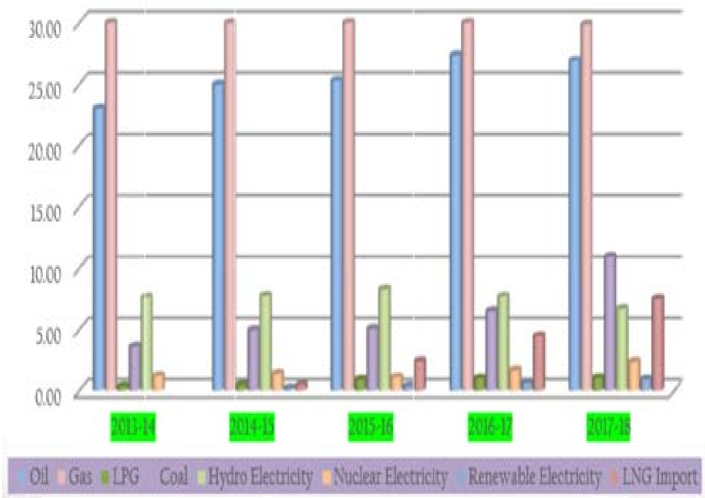


Figure 1"Primary Energy Supplies by Source (MTOE)"[4]

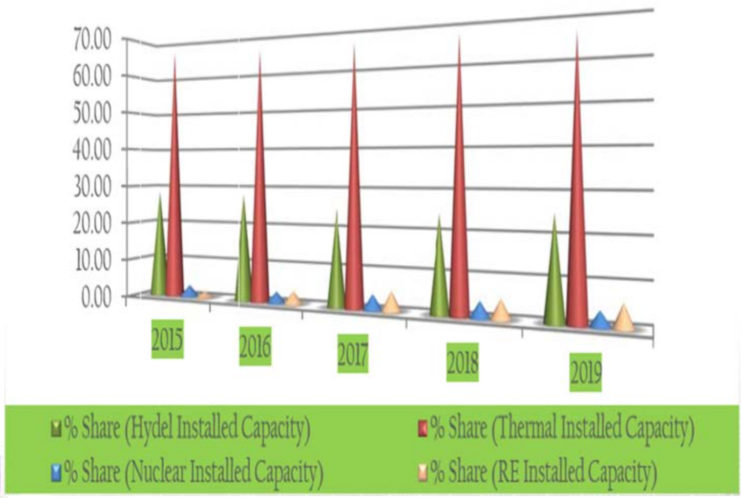


Figure 2 "Share of Installed Generation Capacity by Type (%)" [5]

The contribution of renewable energy resources (solar, wind and bagasse) towards the electricity production of Pakistan is only 5% [5] while the production from thermal, hydroelectric and nuclear are 66%, 25% and 4% respectively [4].

Solar energy is a potentially viable choice for cleaner energy production [6]. "Solar Updraft Tower Power Plant" is amongst the newest atmosphere friendly approaches of power producing plant. It is also called as solar chimney power plant. It comprises of three important components, the solar air collector region, the tower and the wind turbine. This approach is still under research due to some of its drawbacks related to its efficiency and reliability, since it is a new and immature approach right now. But probably in near future this plant would be used as one of the leading large scaled power generating units. It has been commercialized in many countries of the world like Spain, China, Australia, Germany and Canada. [7]

The present research primarily on the thermodynamic analyses of "Solar Updraft Tower Power Plant": A case study in Jamshoro Sindh, focusing the estimation of power potential from this technology in Jamshoro by focusing the transfer of heat from the sun to the collector, up to the production of electrical power by the wind turbine, by considering the air as the ideal gas. The mathematical equations were modeled in a simplified form by considering normal thermodynamic actions of the air to determine the performance of prototype plant in terms of electrical power production. The equations were modeled and simulated on the software Engineering Equation Solver.

LITERATURE REVIEW

To date, several researchers around the world have initiated numerous solar tower projects. Leonardo Da Vinci drew a drawing of a solar tower named as smoke jackas [8]. Later in 1903, Isodoro Cabanyes, a Spanish engineer, became the first to suggest the concept of using a solar chimney to generate electricity [9].

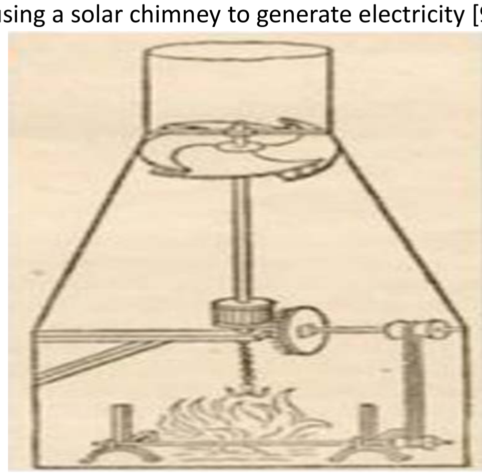


Figure 3 "The spit of Leonardo da Vinci (1452-1519)"

Figure 4 "Solar engine project by Isodoro Cabanyes"

During the 1931, a German Science Writer Han Gunther had initiated a model of "La Energia Eléctrica", titled as “Projecto de motor solar”. In the fireplace like structure hot air manages to rotate pentagonal fan. “Prof Engineer Bernard Dubos”, in 1926 presented to the French Academy of Sciences, the development of a “Solar Aero-Electric Power Plant” in North Africa by means of solar based fireplace proceedings the slant of the high stature mountain in the wake of watching a few sand spins in the southern Sahara. The solar powered pinnacle "Nazare" got a French patent for his development in 1964. In 1975 the “American Robert Lucier” documented a patent solicitation dependent on a progressively complete plan. This patent was conceded in 1981 [10].

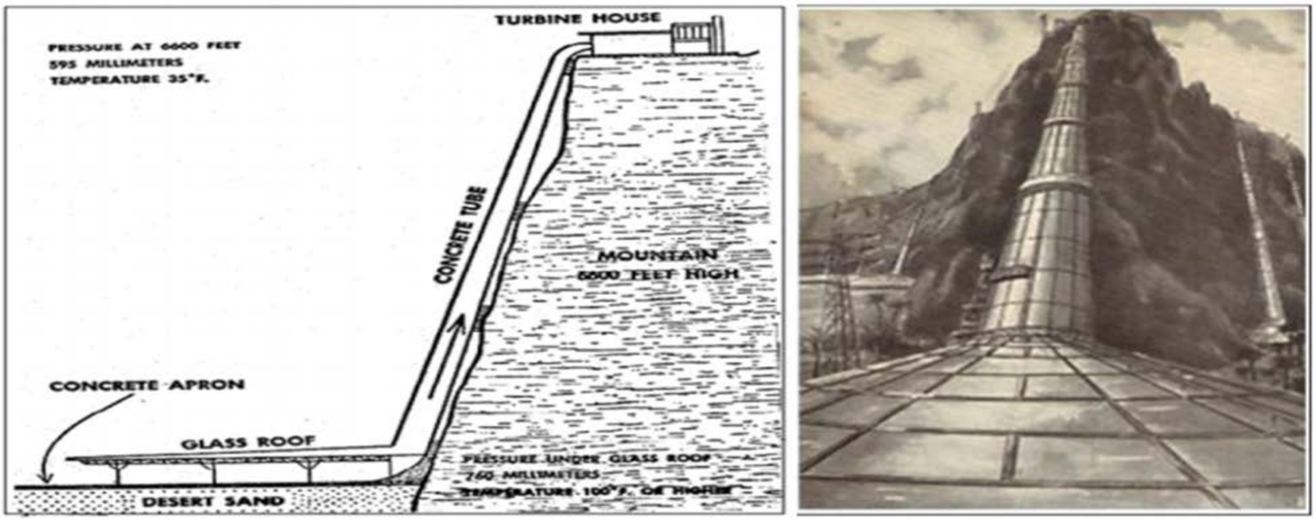


Figure 5 "Principle of Professor Dubos ‘s power

In 1982, Jörg Schlaich, a German structural engineer and his crew, took the initiative of building the first Spanish model prototype in Manzanares, Spain, with a chimney height of 200 m and a maximum power output of 50 kW. The results of the Spanish prototype were successfully put in operation confirmed the practicability and reliability of the solar updraft tower power generation application. [11]

Figure 6 "Manzanares solar chimney power plant"

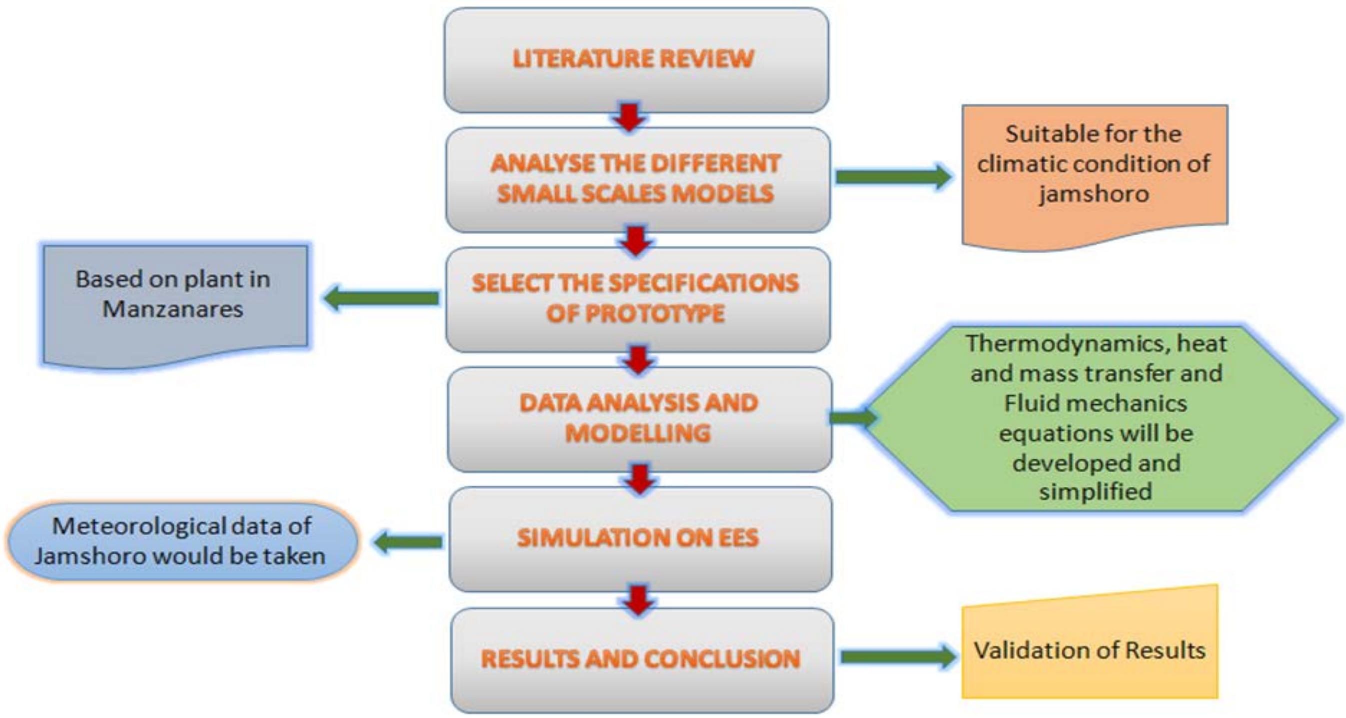
Another paper presented an investigation study of the solar chimney power plant in the Arabian Gulf region, where this was observed that a 500 m high chimney power plant and a 1000 m diameter collector roof would generate at least 8MW of electricity. [12]

Another paper presented an analysis research on solar chimney power plant in Iraq (Baghdad City) where this was observed that a 300m high chimney power plant and a 244m diameter collector roof would produce at least 42.5KW of power. And 300 high chimney power plant and 300m diameter collector roof would produce at least 60KW besides other factors kept constant. [13]

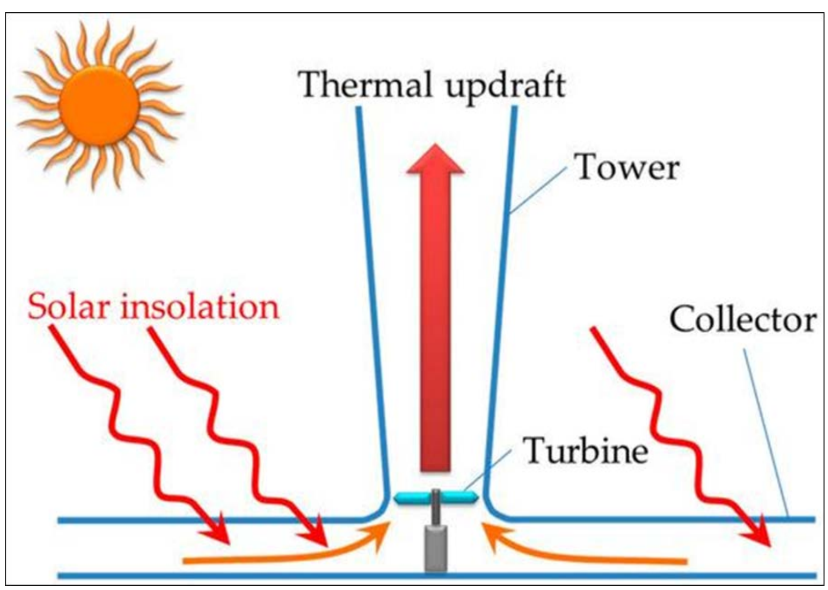
OBJECTIVE:

To carry out thermodynamic analysis of SUTPP with the help of Engineering Equation Solver (EES) to estimate the overall power production of the plant in Jamshoro, Sindh.

ADOPTED METHODOLOGY:



WORKING PRINCIPLE:



The “Solar Updraft Tower Power Plant” transforms radiation from the sun into electrical power by incorporating three well-known fundamentals principles: greenhouse effect, chimney effect and wind turbines in a creative way. Direct and diffuse solar radiation reaches the glass roof, at which different energy fractions are reflected, consumed and transferred. There is a vertical tower in the center of the collector area. Warm air is created by the solar radiation under a wide canopy of glass, then by means of a process of natural convection the hot thermal gradient of ground heats up the adjacent air, allowing air to ascend towards to the tower base due to pressure difference created between the hot air and surrounding air. The buoyant air inside the ground drags towards the base of the tower hence, bringing more air towards the collector region and thus causing a forced convection and hot air circulation in the collector. During this air circulation, the temperature increases while the air velocity remains relatively consistent due to the rising collector height. As the hot air is less dense than the cold, it rises to the chimney and allowing the blades of turbine to rotate in its periphery. Solar radiation induces a persistent updraft in the region. The energy stored in the updraft is converted by the turbines at the base of the tower into mechanical energy and by traditional generators into electrical energy. [14]

STRUCTURAL PARAMETERS OF THE PROTOTYPE:

In our experiment, structural parameters were taken as same as that of the prototype plant in Manzanares in order to estimate the potential of this technology for Jamhoro city. Main structural parameters and technical data of prototype are given as:

Description	Value
SUT height	194.6 m
SUT radius	5.08 m
Collector inlet height	1.2 m
Collector outlet height	2.5 m
Collector shape	Circular
Collector radius	122 m
Collector area	46,678m^2
Turbine configurations	Vertical axis single rotor type
Number of turbine blades	4
Operation mode	Stand-alone

INLET CONDITIONS OF SUTPP:

Description	Value	Unit
Temperature	298	Kelvin [K]
Density	1.076	Kilogram per cubic meter [Kg/m^3]
Pressure	90000	Pascal [Pa]
Velocity	1.5	Meter per Second [m/s]
Solar Radiation	1017	Watt per square meter [W/m^2]

Table 1 "SUTPP Inlet Conditions at Jamshoro [15] [16] [17]"

MATHEMATICAL MODELING:

Our prime objective was to calculate the Electric Power production from the wind turbine that how much the power could be generated through the "Solar Updraft Tower Power Plant" under normal climatic conditions of Jamshoro, Sindh. That was possible after thermodynamic analysis of the plant and by considering thermodynamic losses associated with them. That brought us to the sub-calculations of temperature change of air after passing through the Collector, Pressure drop through the wind turbine and variation in pressure and velocity of air in Chimney. Once these parameters were calculated the Electric power was found accordingly. Calculations are taken at the peak time of solar radiations that is at 12.00 PM, UTC +05:00, Jamshoro, Sindh. For conventional solar collector the temperature-entropy diagram with heat storage system as natural ground is described in fig.7

The power extracted from the turbine can be evaluated from the Energy equation and Gibbs relation from classical thermo-dynamics. So, for the simplicity, in this calculation the efficiency was taken the same. The power output was calculated as,

$$P = \int v\, dp \approx \dot{m}\, \frac{P_{turb}}{\delta P_{turb}} \quad \text{.........} \ (1)$$

After simplification:

$$P = \eta_{tg}\, \delta P_{turb}\, V_{avg} \quad \text{.......} \ (2)$$

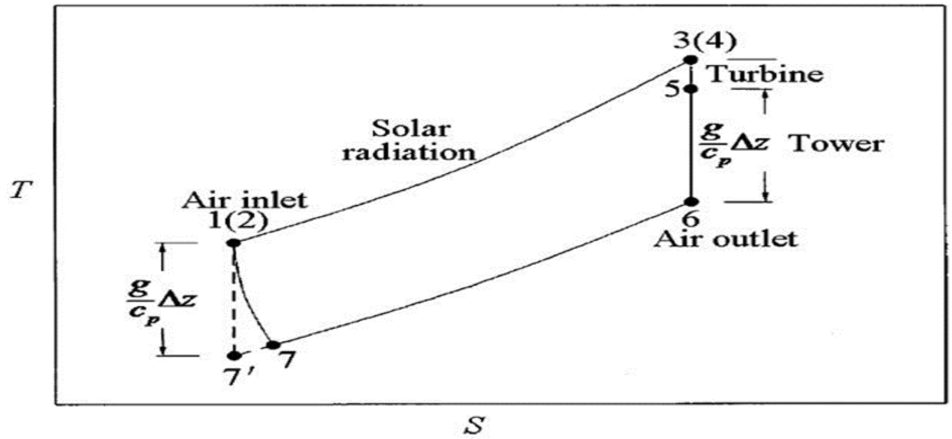


Figure 7 "Temperature-Entropy chart of Air in SUTPP"

Here η_{tg} is efficiency of the turbine = 80% [18], δP_{turb} is the total change in pressure from inlet of the collector to the outlet of the chimney and V_{avg} is the average velocity of the air throughout δP_{turb} was found from the equation,

$$x = \frac{\delta P_{turb}}{\delta P} \quad \text{.......} \ (3)$$

Here x is pressure drop factor = 2/3 which is taken from [19] as optimal pressure loss. (For constant air temperature increase) and δP was found from,

$$\delta P = P_1 \left(1 - \left(\frac{1 - y\left(\frac{H_{ch}}{T_1}\right)}{1 - y\left(\frac{H_{ch}}{T_5}\right)} \right)^{3.5} \right) \quad \text{........} \ (4)$$

Variable $y = \frac{g}{c_p}$, and

$$V_{avg} = \frac{\dot{m}}{\rho_{avg}} \quad \text{............} \ (5)$$

$$P_{avg} = \frac{P_4 + P_5}{R_g\, (T_4 + T_5)} \quad \text{............} \ (6)$$

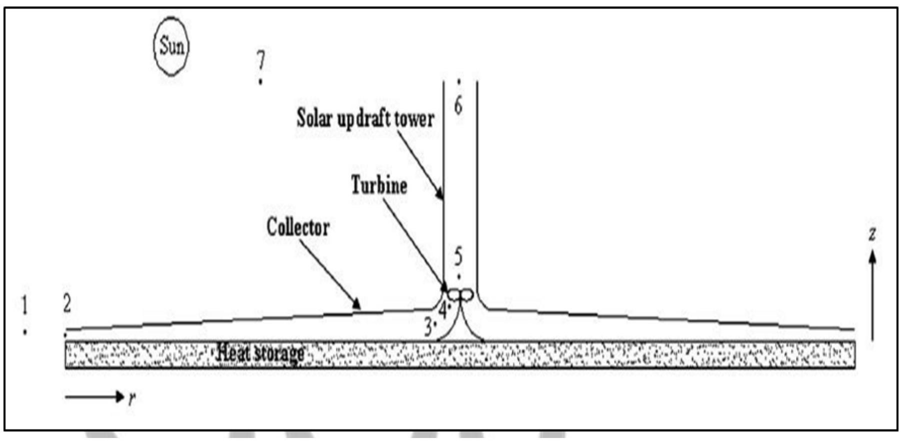
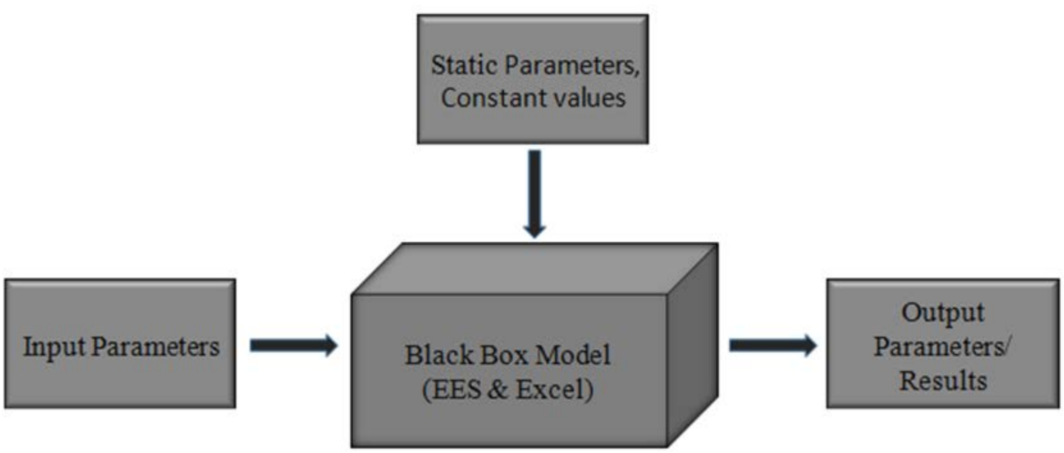


Figure 8 "Schematic diagram of a conventional solar updraft tower power plant"

The pressures P_4 and P_5 , and temperatures T_4 and T_5 was found by applying heat transfer equations in fig 7, and other constant values was obtained from EES built-in function.

Black Box Model:



Results and Discussions:

Generally, researchers in the field of SUTPP concluded that wind turbines have high efficiency of converting the kinetic energy of air from collector into mechanical energy to generate power. Although it is essential to understand that the appropriate requirements for achieving high output of SUTPP should be taken into consideration. Four appropriate circumstances, i.e. wide space area, better climate factors, locally produced construction materials, workmanship, and a vast desert area, should be met in order to generate optimum electricity from SUTPP [20]. Almost above all conditions are satisfied by the region of Jamshoro. Inlet conditions for the turbine was taken as same as that of outlet of the collector. EES results are tabulated as,

Properties after wind turbine calculation results:

Description	Symbol	Value	Unit
Pressure	P_5	88090	Pascal [Pa]
Electric power	P	52818	Watt [W]
Density	ρ_5	0.9852	Kilogram per cubic meter [Kg/m^3]
Temperature	T_5	311.5	Kelvin [K]
Velocity	V_5	9.29	Meter per Second [m/s]

Table 2 "Properties of air after wind turbine"

Climatic data of the whole day of Jamshoro i.e. on May 20, 2020 of Solar Radiation is extracted from [15] and the Average Maximum-Temperature from [16][17] and plotted graphs of different parameters against total time of the day and it was also observed how some factors affected the magnitude of electric power.

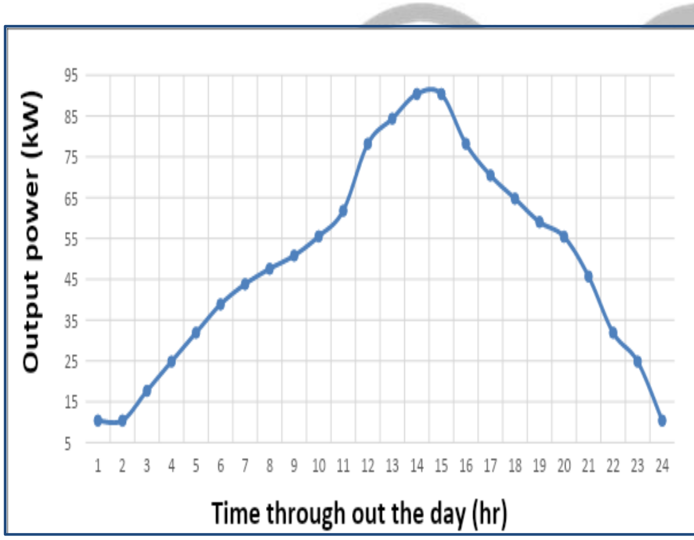


Figure 9 "Relationship between Electric power and Hours of the day"

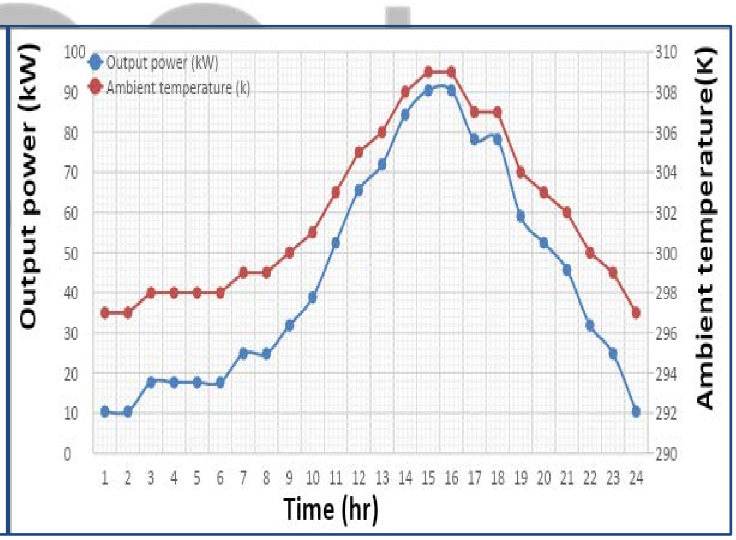


Figure 10 "Relationship between Electric power and Ambient Temperature"

The graph of fig. 9 shows the relationship between overall electrical power output and time of the whole day in hours. It is appeerent that at the peak hours of the day like 12, 13, 14 and 15 hours, the power is extremely at a high magnitude and in night hours the power is low but not zero which is due to the radiations emitted by ground surface.

The graph in fig. 10 shows relationship between of Electric power and ambient temperature for the whole day time. X-axis is the temperature axis showing temperature of the air at each hour of the day from start of the day up to the end.

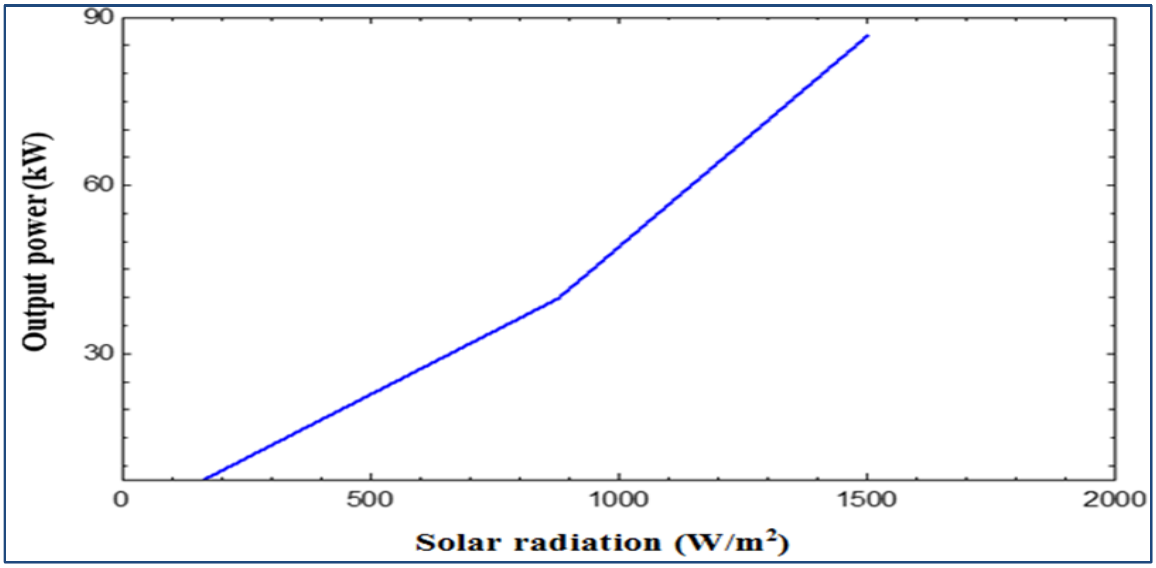


Figure 11 "Relationship between Solar radiation and output electric power"

The fig 11 shows the dependency of the output power on the solar radiations. It is showing that if the solar radiations increase the magnitude of electrical power will increase and vice versa.

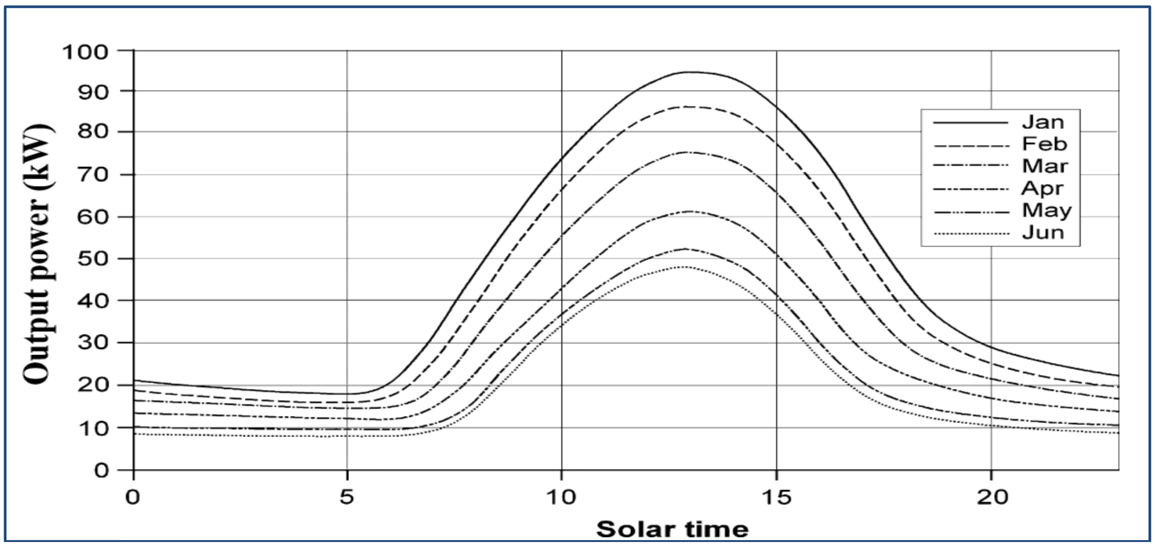


Figure 12 "Relationship between Output power and solar time of a day for 6 months"

This graph shows the peak time in which the temperature rises to maximum point and so that maximum power can be generated is around 10:00 A.M to 15:00 P.M. This graph helps in determining the feasibility of the plant.

CONCLUSION:

Thermodynamics analysis has performed by modeling and simulation of SUTPPs in order to assess the performance in the region of Jamshoro, Sindh. To estimate SUTPP's power production potential, mathematical models were developed. Then the outputs with experimental prototype results have been validated from Manzanares. The subsequent charts reveal Jamshoro's power production for one day and six months. Other graphs have also been drawn of electrical power relation with the different parameters of SUTPP itself. The solar irradiation has been observed as the most significant factor in deciding the power production of the plant. It has been concluded that by increasing the height of the chimney, the collector area and the collector transmission, the power output can be increased.

Solar chimneys are very appropriate for remote areas where there is plenty of solar energy capacity; such as Tharparker, Jamshoro and some areas of Balochistan. Solar updraft towers for power generation, the technological viability of which has already been shown. During operation, the technology is almost pollution-free and provides fuel free service. It can produce power day and night, and no fossil fuel or cooling water is needed. The key considerations for forecasting commercial success of SUTPP are in theoretical stages. For implementing it commercially, the environmental implications of SUTPP technology must have considered. These types of technologies should go on the road to commercialization with the diminishing supplies of fossil fuels and the exacerbation of air emissions and greenhouse effect.

Acknowledgment

We are grateful to Mehan University of Engineering and Technology Jamshoro for providing this platform, support and facilities to expedite our research effectively.

References

[1] Z.R. Tahir, Muhammad Asim (2017), "Surface measured solar radiation data and solar energy resource assessment of Pakistan: A review", Renewable and Sustainable Energy Reviews.
[2] IFC. (2016) A solar developer's guide to Pakistan. The international finance corporation. World Bank Group.
[3] Muhammad Irfan, Zhen-Yu Zhao, Munir Ahmad and Marie Claire Mukeshimana, (2019), "Solar Energy Development in Pakistan: Barriers and Policy Recommendations", Sustainability,11, 1206
[4] National Electric Power Regulatory Authority (NEPRA), Pakistan. State of Industry Report (2019), Available online at https://nepra.org.pk/publications/Annual%20Reports.php (accessed on 3-June-2020)
[5] Institutes of Energy Economics and Financial Economics (2018), "Pakistan's Power Future". Available Online at https://ieefa.org/wp-content/uploads/2018/11/Pakistans-Power-Future_December-2018.pdf (accessed on 3-June-2020)
[6] Pritam Das and V. P. Chandramohan (2018), "CFD analysis on flow and performance parameters estimation of solar updraft tower (SUT) plant varying its geometrical configurations", Energy Sources, Part A: Recovery, Utilization, And Environmental Effects.
[7] Ikhlef Khaoula, Larbi Salah (2018) "Technico-Economic aspect analysis in the design of solar chimney power plants". International Conference on Green Energy and Environmental Engineering, Proceedings of Engineering and Technology-PET, Vol 37 pp.30-33.
[8] R. Wengenmayr and T. Bührke (2011), "Renewable Energy", John Wiley & Sons.
[9] C. Ngo and J. Natowitz (2009), "Our Energy Future: Resources, Alternatives and the Environment. John Wiley & Sons", pp.184-186, 2009
[10] T. Hamilton (2011), "Mad Like Tesla: Underdog Inventors and Their Relentless Pursuit of Clean Energy", ECW Press, pp.93-103.
[11] Amel Dhahri, Ahmed Omri (2013), "A Review of solar Chimney Power Generation Technology" International Journal of Engineering and Advanced Technology (IJEAT) ISSN: 2249 – 8958, Volume-2 Issue-3, February 2013
[12] Hamdan MO (2010), "Analysis of a solar chimney power plant in the Arabian Gulf region", Renewable Energy, doi: 10.1016/j.renene.2010.05.002
[13] Mohammed H. Ali (2013), "Analysis Study of Solar Tower Power Plant & Its Configuration Effects on Its Performance in Iraq (Baghdad City)", Modern Applied Science; Vol. 7, No. 4; ISSN 1913-1844 E-ISSN 1913-1852 Published by Canadian Center of Science and Education
[14] Xinping Zhou, Yangyang Xu (2016), "Solar Updraft Tower Power Generation". Solar Energy 128, pg 95-125.
[15] https://power.larc.nasa.gov/data-access-viewer/
[16] https://www.climatestotravel.com/climate/pakistan
[17] https://www.accuweather.com/
[18] Atit Koonsrisuk, Tawit Chitsomboon (2013),"Mathematical modeling of solar chimney power plants", Energy 51 314-322.
[19] Hannes Von Allworden, Ingenuin Gasser, Muhammad Junaid Kamboh (2018), "Modeling, Simulation and optimization of general solar updraft towers". Applied Mathematical Modelling 64 265-284
[20] Xinping Zhou, Yangyang Xu (2016), "Solar Updraft Tower Power Generation". Solar Energy 128, pg 95-125.
[21] Schlaich, J., Bergermann, R., Schiel, W., Weinrebe, G., (2005), "Design of commercial solar updraft tower systems – utilization of solar induced convection flows for power generation", J. Solar Energy Eng. – Trans. ASME 127, 117-124