Journal of Civil Engineering Research 2016, 6(3): 47-54
DOI: 10.5923/j.jce.20160603.01

Design of a Compost Waste Heat to Energy Solar Chimney Power Plant

Kevin R. Anderson[1,*], Yasser Salem[2], Suzanne Shihadeh[1], Pedro Perez[1], Benjamin Kampen[1], Souha Jouhar[3], Saman Bahrani[3], Kainan Wang[3]

[1]Solar Thermal Alternative Renewable Energy Lab, Mechanical Engineering, California State Polytechnic University, Pomona, USA
[2]Civil Engineering, California State Polytechnic University, Pomona, USA
[3]Construction Engineering Technology, California State Polytechnic University, Pomona, USA

Abstract This paper presents the design of a Compost Waste Heat to Energy Recovery Hybrid Solar Chimney Power Plant (SCPP). The project illustrates the concept of using compost waste heat to power generators housed in the SCPP. The design of the Hybrid Compost Waste Heat to Energy Recovery Hybrid Solar Chimney Power Plant is based on a full-scale 24 acre facility which can accommodate a community waste disposal needs. This paper presents the design and fabrication of the SCPP, followed by a building construction estimate for the project, and concludes with an economic analysis of the SCPP, factoring in the renewable energy, composting, recycling (waste management) and infra-structure sustainability aspects of the project. The proposed 24 acre hybrid SCPP facility has the potential of generating 100 MW with 83 M$ in revenue annually. The engineering construction cost estimate for fabrication of the SCPP is found to be 156 M$. The total cost per unit of energy produced for the SCPP is 0.62 US $ / kWh (0.56 € / kWh).

Keywords Compost Engineering, Renewable Energy, Cost Estimate, Construction Engineering, Waste Management

1. Introduction

Previous investigations in the literature have dealt with using solar chimneys as alternative energy resources. The concept of the solar chimney as a means to generate electricity is a feasible means of renewable energy technology. A comprehensive overview of solar chimney power technology is given in [1]. A prototype of a Solar Chimney Power Plant (SCPP) was constructed and operated in Spain between 1981 and 1990 as outlined in [2-6]. The study of [7] presents a solar thermal power plant utilizing a combination of a solar air collector and a central updraft tube to generate a solar induced convective flow which drives turbines to generate electricity. In the work of [8] the first pilot demonstration of a solar updraft tower power plant in Jordan is presented. The study of [9] evaluates the performance of a large-scale solar chimney power plant in South Africa. Results of [9] indicate 24 hour plant power operation, while illustrating considerable daily and seasonal power output variations. It is shown that plant power production is a function of the collector roof shape and inlet height. In the work of [10] a SCPP is proposed to be built as the first national SCPP in central regions of Iran. Studies show that Iran can be a part of the Mediterranean solar power generation chain in 2050 to provide electrical power demand of Europe. In order to evaluate SCPP performance, and power generation throughout Iran several different areas across the country were considered. The obtained results clear that solar chimney power plants can produce up to 28 MWh/month of electrical power. This power production is sufficient for the needs of the isolated areas and can be used to feed the grid. In the work of [11] the performance of SCPPs in parts of Iran are studied theoretically to estimate the quantity of the produced electric energy. The solar chimney power plant with a 350 m chimney height and 1000 m collector diameter is capable of producing monthly average up to 2 MW of electric power over a year. In the study of [12] a solar collector, chimney and turbine are modeled and iteration techniques are performed to solve the resulting mathematical model. In addition, the study proposes that the most suitable plant, affordable by local government standards to respond to the electricity demand of a typical village in Thailand, is the one with a collector radius and chimney height of 200 m and 400 m, respectively. In the work of [13] dimensionless variables are proposed to guide the experimental study of flow in a small-scale solar chimney. The recent work of [14] provides a comprehensive analytic study regarding the thermal modeling and design of SCPPs. In the work of [15] a sloped SCPP to provide electric power for remote villages in Northwest China is designed. The plant with chimney height of 252 m and chimney radius

* Corresponding author:
kranderson1@cpp.edu (Kevin R. Anderson)
Published online at http://journal.sapub.org/jce

of 14 m has a solar collector having a radius of 607.2 m inclined at an angle of 31° produces 5 MW electric power on a monthly annual average. In the work of [16] four designs of 100 MW SCPPs with different combinations of collector and chimney radii are proposed and the most cost effective one is chosen from among the four SCPPs. In the study of [17] a SCPP used to provide electric power for remote villages in northwestern China is analyzed. Three counties in the Ning Xia Hui Autonomous region where solar radiation is better than other regions of China were selected as pilot locations to construct a SCPP. The SCPP, in which the height and diameter of the chimney are 200 m and 10 m, respectively, and the diameter of the solar collector cover is 500 m, is capable of producing up to190 kW of electric power on a monthly annual average. In the research of [18] a SCPP is proposed to be built in the Qinghai-Tibet Plateau where there is abundant solar radiation, large diurnal temperature range, and salt lakes which can work as a heat storage system to improve the power output of the SCPP. The yearly power potential for the SCPP in Qinghai-Tibet Plateau is estimated to be 86.8 million TJ. When approximately 15% of the plateau land is used for the SCPP, the yearly power output may reach up to 17.4 million TJ which accounts for approximately 20% of China's energy consumption in 2008. The study of [19] considers the practice of sorting at the source and the use of combustible Municipal Solid Waste (MSW) components as fuel to generate heat for a hybrid solar, flue gas, chimney power plant in Malaysia. Energy recovery from MSW incineration using a hybrid solar, flue gas, chimney power plant (HSFGCPP) is proposed. The introduction of the HSFGCPP has the objective of solving the problem of the night operation mode of the SCPP by utilizing the exhaust/waste heat in the flue gas from different sources, and also by enhancing the power generation both during the day and at night. The Malaysian HSFGCPP system utilizes flue gas waste heat to supplement the solar energy input during daytime operation, and also utilizes waste heat at night. The hybrid solar, flue gas, chimney power plant of [19] is designed to include a flue gas channel where incineration waste heat or waste heat from other industrial purposes can be recovered as useful energy. The hybrid system is made with a transparent cover, which allows solar radiation into the collector, and a flue gas channel where the hot flue gas flows and transfers/loses its heat to the collector (which acts as a heat exchanger).

The current research extends the concept of a SCPP by proposing a hybrid use of compost waste heat recovery to augment the convection in the solar chimney without the use of incineration as outlined in the works of [20-24]. The Solar Chimney Power Plant (SCPP) operational principle is shown in Fig. 1.

The concept of Fig. 1 of using piles of waste which liberate heat in unison with a solar chimney originates from the US Patent 7956487 and Canadian Patent 2720544 held by Compo Energy, Inc. [25]. The compost heat release enhances the solar updraft which moves through fan turbines placed at the base of the solar chimney. Figure 1 illustrates the synergies between renewable energy, composting, waste management and sustainable agriculture. The SCPP of Fig. 1 operates as follows: air is heated by solar radiation under a plastic roof open at the base. The roof and the natural ground below it form a solar air collector. In the middle of the roof there is a vertical tower with large air inlets at its base. The connections between the roof and the tower's base are airtight. Since hot air is lighter than cold air it rises up the tower due to natural convection. Suction from the tower then draws in more hot air from the solar air collector, and cold air comes in from the outer perimeter. Solar radiation causes a constant updraft in the tower. The energy contained in the updraft is converted into mechanical and ultimately electrical energy by shrouded pressure-staged wind turbo generators at the base of the tower. The compost piles located on the floor of the greenhouse give off heat, which helps to promote the natural convection through the solar chimney. This occurs since the pre-existing natural convection velocity due to the temperature difference between the hot and cold air in the solar collector is enhanced due to the heat released from the compost pile. To this end, the proposed SCPP of this paper can be viewed as a hybrid device, in that use of compost waste heat to energy in unison with the traditional SCPP concept is solving a multifaceted problem, i.e. renewable energy and waste management technologies act in synergy. Previous economic analyses of the SCPP concept indicate that that large scale solar towers on the order of 100 MW and more are capable of generating electricity at costs comparable to those of conventional power plants [6]. Thus the development of this form alternative energy is valid. The added benefit of the current hybrid SCPP concept is that it also addresses waste management and landfill issues which currently exist in our society. One clear advantage and major difference of the current project is that no incinerators are used in the current project. Other advantages of the present concept of hybrid SCPP with respect to previous studies involving traditional non-composting SCPP's include the following: i) the current project uses more than just one renewable energy technology (solar updraft driven turbo generators, heat exchanger based compost waste-heat to energy extraction, PV panels on the roof of the solar air collector) thus, there is a variety of technologies being used, rather than just one key technology. From an economic standpoint, the current project has an advantage over other previous SCPP based projects in the sense that the current project not only allows for revenue generation from the electricity generated from the natural convection (enhanced by the compost waste heat release) via the solar updraft, but also the project yields economic revenue from the landfill waste management aspects of the hybrid SCPP including, compost fertilizer production, recycling, and tipping (municipal waste dumping) fees. To the authors' knowledge, to date no other SCPP project has merged the renewable energy aspects with the waste management aspects such as the current research proposes. Regarding the durability of the proposed design with respect to other previous SCPP based investigations, the current project is being designed to be robust, utilizing a metal building with transparent roofing as the main structure where the solar air collector is formed, a solar chimney, pressure staged turbo generators, and compost embedded heat exchanger based waste-heat to energy conversion devices. The compost engineering challenges such as aeration and moisture control will be integrated into the building engineering construction. To this end, novel concepts dealing with control system integration to maintain the compost at healthy levels will need to be addressed as the project comes to fruition. The focus of the present paper is on the Civil Engineering Construction Engineering Technology and Municipal Solid Waste Management aspects of the project. To this end, the current paper provides details of the construction engineering, cost estimating and an economic revenue forecast for return on investment for a SCPP for use in municipal waste recycling, and compost waste heat to energy recovery.

The outline of the present paper begins with an overview of the variety of renewable energy technologies available with the proposed hybrid power plant. A brief review of compost engineering is included in order to tie in composting aspects which need to be considered when designing the hybrid SCPP. Following are the construction details and a bill of materials and engineering costs for the proposed SCPP. The paper concludes with an economic analysis and review of benefits and return on investment of the SCPP.

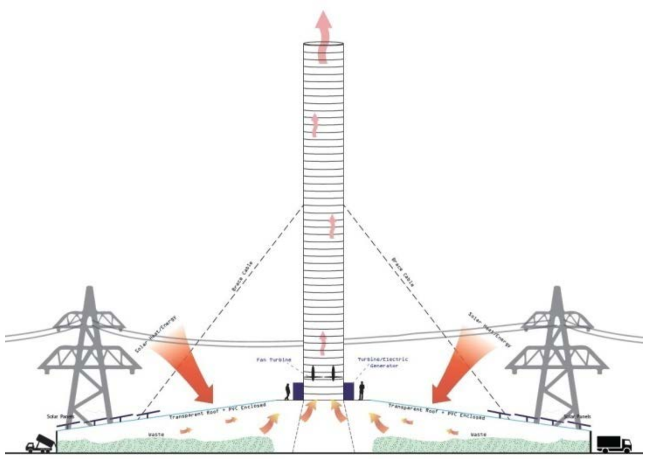

Figure 1. Hybrid Compost Waste Heat SCPP Tower

2. Design of Compost Waste Heat to Energy Recovery Hybrid Solar Chimney Power Plant (SCPP)

Figure 2 and Fig. 3 show renderings of the SCPP using 12 chambers covering 24 acres. Figure 2 illustrates an isometric view of the facility, while Fig. 3 shows a plan view of the facility. For the proposed facility shown in Fig. 2 and Fig. 3 the following parameters are assumed (for a typical baseline design); chimney height, h = 200 m, chimney diameter, d = 20 m, building square plan side length, L = 300 m, total square footage of building A = 97125 m^2 = 24 acres. As seen in Fig. 2 and Fig. 3, the power plant is comprised of a large metal building having 12 chambers covered with transparent roofing material, a large solar chimney supported by guidewires, and surrounding supporting infrastructure including the pressure-staged wind turbo generators.

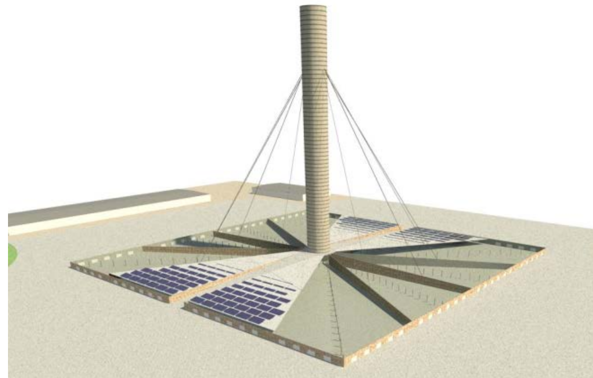

Figure 2. Hybrid Compost Waste Heat SCPP (Isometric View)

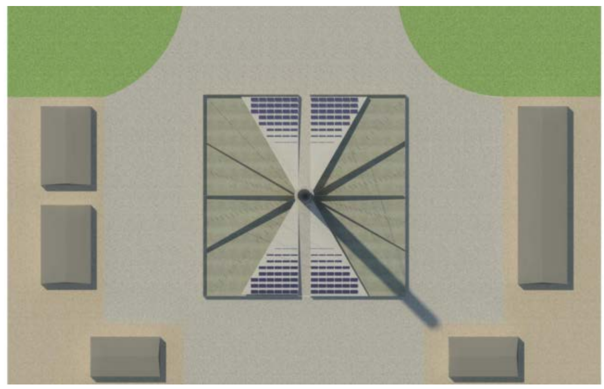

Figure 3. Hybrid Compost Waste Heat SCPP (Top View)

The purpose of having 12 chambers is to allow service of the SCPP by many municipal waste trucks and to allow maintenance of the plant as required. The present baseline for fabrication of this facility is in Apple Valley, Southern California, on Bureau of Land Management (BLM) property located in San Bernardino County, CA, U.S.A. The power plant will accept 2000 tons of waste per day. Trash trucks hauling approximately 18 tons each are the baseline operation scenario. Compost waste-to-energy recovery is used in unison with the solar energy taken from the sun in order to escalate the temperature of the air in the chimney such as to promote natural convection velocities in the duct/turbine system. The following key renewable energy and waste management technologies are used in the SCPP of Fig. 1 are summarized below: The following key renewable energy and waste management technologies are used in the power-plant of Figure 1 are summarized below:

1. Natural convection (enhanced from the elevated temperature of the waste pile) from chimney is used to generate electricity via turbines.

2. Waste-heat extraction via heat exchanger devices [26, 27] can be inserted into the piles of waste shown in Fig. 1.
3. Food waste heat to energy recovery via Hydrothermal Carbonization (HTC) [28] can be used in the pile of waste in unison with the waste heat extraction of item 2.
4. Photovoltaic (PV) arrays populating a portion of the available real estate on the roof of the building of the composting facility illustrated in Fig. 2 and Fig. 3.
5. Turbine / wind energy renewable energy technology research and development.
6. Recycling, composting and waste management technologies

2.1. Review of Compost Engineering

In this section a brief review of compost engineering is given in order to place required compost control parameters into the context of the design of the hybrid SCPP being proposed. The compost engineering handbook by Haug (1993) [29] as well as the comprehensive treatise by Epstein (2011) [30] are essential references for the compost engineering design. Compost is organic matter which has been decomposed and recycled as fertilizer. Compost is a key ingredient to organic farming. Composting is the biological decomposition of organic matter under aerobic conditions, in to fermentation which is anaerobic decomposition which occurs under anaerobic conditions. Composting is currently being carried out for feedstocks, sewage sludge, biosolids, septage, manure, animal carcasses, food waste, yard waste, industrial waste, and military wastes. Composting is an excellent way to disinfect wastes as it destroys bacteria, viruses and parasite. Composting can play a role in disinfecting human and animal wastes in developing countries. When a good composting process is reached and thermophilic temperatures for several days, the compost can be used for crop production including vegetables. As outlined in [30] the design of composting facilities must take into account, siting, planning, economic/cost analysis, and compost management issues such as odors and pathogens.

The process of compost must by controlled and managed. Composting involves making a heap of wetted organic material (green waste) and waiting for the materials to break down into humus after a period of months. Organic ingredients intended for composting can alternatively be used to generate biogas through anaerobic digestion. Composting is a multi-step, closely monitored process with measured inputs of water, air, and carbon- and nitrogen-rich materials. The decomposition process is aided by shredding the plant matter, adding water and ensuring proper aeration by regularly turning the mixture. Worms and fungi further break up the material. Bacteria requiring oxygen to function (aerobic bacteria) and fungi manage the chemical process by converting the inputs into heat, carbon dioxide and ammonium. The ammonium (NH4) is the form of nitrogen used by plants. When available ammonium is not used by plants it is further converted by bacteria into nitrates (NO3) through the process of nitrification. Monitoring the parameters of moisture, pH, odor and temperature helps aids the waste management engineering team in determining the status of the compost and gives a comparison of the progress of system with different initial conditions or ingredients. Moisture needs to be monitored, since composting proceeds best at a moisture content of 40% to 60% by weight. At higher moisture levels, the process is anaerobic and foul-smelling and at lower moisture levels, microbial activity is limited. Aeration needs to be controlled since if too much air is blown through the compost system, the compost can potentially dry it out. If the temperature drops sooner than expected and the compost looks dry, moisture may have become the limiting factor. In this case water is added the temperature should rise again. Odor is a concern when dealing with compost facilities, since the compost starts to smell bad if it is too wet. Excess water fills the pore spaces, impeding diffusion of oxygen through the compost materials and leading to anaerobic conditions. Mixing in additional bulking agent such as dry wood chips, cardboard pieces, or newspaper strips is likely to alleviate the problems affiliated with odor.

The Cornell University [31] compost worksheet is useful to the waste management / compost engineering team as a design tool to aid in the selection of the right type of components in the compost pile. The Cornell composting spreadsheet is a tool which allows the compost engineering team to select the correct proportions of ingredients such as leaves, garbage, food wastes, water, etc. in order to meet a C/N goal. The optimum C/N ratio can then be used as a metric to gage the health and progress of the compost pile.

Temperature is a measure of the amount of heat being generated as a byproduct of microbial breakdown of organic material. The overall temperature of the compost is an indication of how far along the system has progressed in the decomposition process. If the compost heats up to 40 or 50°C the ingredients contain adequate nitrogen and moisture for rapid microbial growth. A typical composting system will heat up to 40 or 50°C within 2 to 3 days.

As readily decomposable organic matter becomes depleted, the temperature begins to drop and the process slows considerably. Estimates provide heat flux emanating from a compost pile as 6548 W/m^2 [32] and on a volumetric (tonnage) basis 0.516 kW/t [33]. Monitoring the pH is important since, during the initial stages of decomposition, organic acids are formed. The acidic conditions are favorable for growth of fungi and breakdown of cellulose. As composting proceeds, the organic acids become neutralized, and mature compost generally has a pH between $6 < pH < 8$. If anaerobic conditions develop during composting, organic acids may accumulate rather than break down. Aerating or mixing the system helps to reduce the acidity. The above compost engineering parameters must be considered when designing the hybrid compost waste heat to energy / SCPP system discussed herein.

3. Economic Analysis of Compost SCPP

In this section of the paper, we present an economic analysis of the proposed hybrid compost waste heat to energy SCPP project. The various renewable energy technologies which generate revenue are address individually in the following sections. The analysis below has been made by referring to the USA standard costs.

1. Waste Heat to Energy Conversion Economics

An accurately constructed compost system will heat up to 40 to 50 °C within 2 to 3 days [31]. As readily decomposable organic matter becomes depleted, the temperature begins drop and the process slows considerably. For the waste heat to energy extraction technology, the heat generation on a tonnage basis is estimated to be on the order of Q = 0.516 kW/ton [33]. On a tonnage basis, the SCPP will process 17,000 t/chamber, for 24 chambers this gives 204,000 t. Thus, Q = 0.516 kW/t*204,000 t = 105 MW is the estimated potential for compost waste heat to energy conversion. Taking the duty to be 365 days and 8 hours per day gives 105 MW*365*8 hr = 307,371 MWh. For conservatism we assume an energy conversion efficiency of 80%, to obtain 245,897 MWh for the waste to heat energy conversion process. Taking the rate of electricity in San Bernardino, California, USA to be 0.1598 $/kWh, affords $39.3 M due to waste heat to energy conversion.

2. Tipping Fee Revenue Economics

Considering 4055 m^2 per acre, for 2 acres/chamber and a 3.048 m pile of waste yields 24,720 m^3. Assuming 1.5292 m^3/t affords 16,165 t/chamber. An assumed tipping fee of 52 $ per ton [24], gives $840,572 per chamber. Assuming the chambers will operate 4 per cycle gives 3.36 M$ per chamber. For 12 chambers, this gives 40.3 M$ annually for tipping revenue.

3. Recycling Revenue Generation

Assuming 8% of the waste can be recycled gives 16,320 t of waste which can be sold for recycling. At a rate of $40/t [25], this gives 0.65 M$ of revenue generated by selling the recycled waste.

4. Compost Fertilizer Generation

For composting, assuming 2/3rd of the waste can be used for composting gives at an assumed rate of $10 per ton of composting [25], 1.36 M$ of revenue generation from composting.

5. Solar PV Electricity Generation

The SCPP shown in Fig. 1 accommodates multiple renewable energy technologies to be realized in synergy. Using the available transparent roof real estate, one can populate that area with solar photovoltaic (PV) panels. Assuming a PV solar array area density of 27 W/m^2. For the 24 acre structure, assume that 80% of the roof is populated with PV panels. Then for a duty of 12 hours of sunlight per day, for 183 days of sunshine (since other days it will be raining and cloudy) gives 4232 MWh, at a rate of 0.16 $/kWh gives 0.68 M$ for PV solar.

6. Hydrothermal Carbonization (HTC)

The Hydrothermal Carbonization (HTC) Food Waste to Energy technology of (Pham et al. 2014) is assumed to comprise an additional 5% of the overall waste heat to energy conversion economics lending an additional anticipated $2 M annually.

7. Economics Analysis Summary

The above values which tally $83M annually are summarized in Figure 4. From Fig. 4, the majority of revenue 48% ($40.3 M) is due to tipping (waste management) handling fees, followed by 46% ($39.3 M) due compost waste heat to energy conversion, 2% ($1.4 M) for compost fertilizer sales, 2% ($2 M) for food waste to heat energy conversion, 1% ($0.7M) for recycling, and 1% ($0.68 M) for solar photovoltaic energy conversion. The above economic analysis is only a representative example. Actual values will change according to the size of the solar tower, PV array real estate population, feed-rate of waste to the power plant, etc. This analysis can be used as a roadmap to implement the proposed hybrid technologies offered by the hybrid compost waste heat to energy SCPP proposed herein.

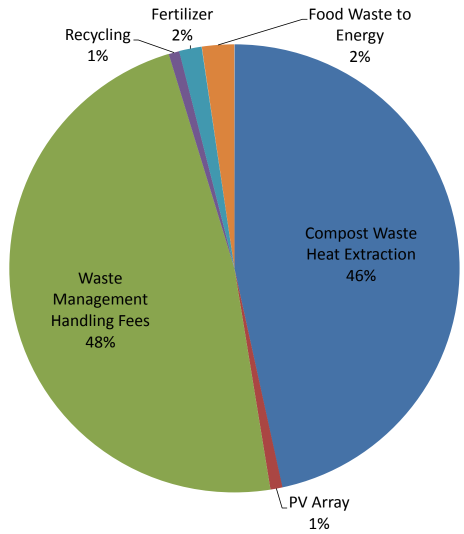

Figure 4. Economic Potentials for Hybrid Compost SCPP (values based on $83M annually)

4. Construction Engineering Cost Estimation of SCPP

The cost estimate was prepared using fundamentals of building construction estimating taking into consideration quantity surveying, employment rates, specifications, code compliance, materials and equipment costs. Typical industry standard values based on experience and judgement were assumed when preparing the cost estimate summary of Table 1. The total cost estimate of 156.4 M$ of Table 1 is found to be in agreement with prior estimates obtained by COMPO Energy, Inc. from general contractors.

Table 1. Cost estimating summary for the SCPP

Component	Cost (M$)
I. Solar Chimney	58.71
II. Foundation/Structural Support	12.47
III. Site Preparation	42.00
IV. General Conditions	42.25
Overall Construction Cost	156.4

The major assumptions for determining the building cost estimate of Table 1 include the following:

I. Solar updraft tower

- Chimney: reinforced concrete
- Chamber wall: 0.6096 m thick concrete walls
- Chamber walls reinforcing: 191.52 Pa lumped sum $4000/t
- Chamber roof: 0.0508 m thick tall supported in structural steel frames which span the chamber walls

II. Foundation and structural support

- Concrete slab under chamber base: 0.1524 m thick concrete slab under the footprint of the chamber
- Footing to support the chimney: 7 m dia. by 30m deep (approx. 1/3 of chimney height) caisson to support seismic and wind loads
- Footing reinforcing: lumped sum of $4.4/kg
- Structural support for the roof: 50 lb per m^2 of covered surface at $3000/t

III. Site preparation

- Precast concrete walls: $0.696 /$m^2$
- Waterproofing: $0.232/$m^2$
- Brace frames: $5500/frame
- W21X44 steel columns: $4000/t
- PVC roof: $2.32/$m^2$
- Site paving: $3.25/$m^2$
- Land use (purchase or long term lease): 20% extra space needed beyond footprint of the SCPP for maintenance access, etc.
- Maintenance building roof (including water proofing/sheeting/joist beams): $1.85/$m^2$
- Fencing: 1.524 m tall chain link fence around perimeter of the facility per OSHA
- Gates: double gates $3000 each
- Access roads: 3.048 m wide

IV. General conditions

- Permit fees: 2% of the construction cost
- Bond and insurance: 5% of the construction cost
- Contingency: 20% of the construction cost
- Contractor profit and overhead: 10% of the construction cost

The total cost/unit of energy produced can be generalized to any country, in order to give the main economic order of affordability of the proposed plant as follows. Considering the above analysis we obtain total cost / unit of energy 1.46 US $ / W or 0.62 US $ / kWh. Table 2 summarizes the total cost/unit of energy in a variety of national currencies where the proposed SCPP technology is expected to be implemented.

Table 2. Total cost / unit of energy in various currencies

Currency	Currency/W	Currency/kWh
Chinese Yuan	9.56	4.06
Colombian Peso	4680.63	1987.66
Egyptian Pound	11.45	4.86
Euro	1.33	0.56
Indian Rupee	98.19	41.70
Indonesian Rubiah	19396.83	8237.01
Iranian Rial	44094.92	18725.24
Japanese Yen	165.70	70.36
Malaysian Ringgit	6.04	2.57
New Zealand Dollar	2.19	0.93
Saudi Riyal	5.48	2.33
Thai Baht	51.95	22.06

5. Prototype Facility

In order to validate the concept of using compost waste heat to augment the convection in a solar chimney, an experimental prototype was constructed at California State Polytechnic University at Pomona's Lyle Center for Regenerative Studies. The experimental prototype facility of the compost waste-to-heat / solar tower is shown in Fig. 6. The data acquisition set-up used in the prototype facility is shown in Fig. 7. The facility includes access doors, a solar chimney and an aeration system. The prototype holds 27.9 m^2 of compost 1.524 m, affording 42.47 m^3. The actual power plant is 24 acres, with 12 chambers, thus each chamber is 2 acres = 8094 m^2, and the compost pile is 3.048 m tall, affording 24,670 m^3 per chamber. Thus the test prototype facility is 1:290 scale based on square footage and 1:580 based on cubic volume of the actual SCPP shown in Fig. 1. Figure 8 shows temperature versus time for the chamber experimental data. Noticeable from Fig. 8 is the presence of a solar diurnal load (due to the solar loading on the roof), which heats and cools the compost pile over the 24 hour period from sunrise to sunset. Regardless of the solar diurnal fluctuation, the air entrapped between the top of the compost pile and the transparent roof remains at 49°C < T < 54.4°C. Results of the prototype for aerated average surface pile temperature are: 248°C, outdoor air: 194°C. These findings are in agreement with those of the experiments of [26]. This provides a ΔT to the chimney of 272 K on average. From Fig. 8 the decay rate of the compost pile is seen to be on the order of -15°C/day. Thus, Fig. 8 can be used to estimate the thermal time constant (growth rate) and monitor the health of the compost system.

Figure 6. Prototype facility overview

Figure 7. Prototype facility data acquisition

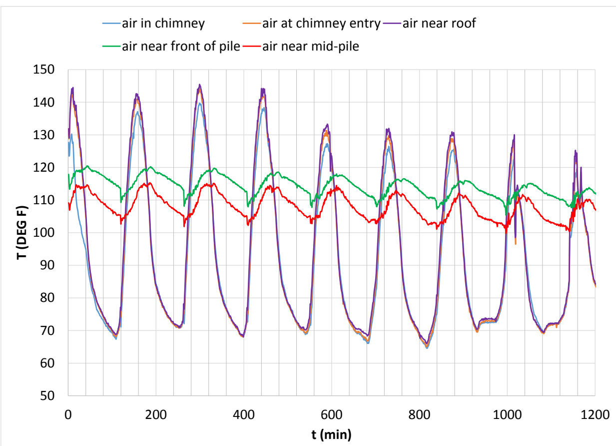

Figure 8. Temperature transient for prototype

6. Conclusions

This paper has presented the design of a hybrid compost waste heat to energy solar chimney power plant (SCPP) for addressing sustainable renewable energy needs. The paper has presented the concept of a hybrid power plant which uses a solar chimney, waste heat to energy conversion, and composting/recycling facility in unison. The baseline parameters for the SCPP, which include a chimney height of h = 200 m a chimney diameter of d = 20 m, and a collector footprint of 97,125 square meters. Results from experiments taken from a scale model prototype facility have been analyzed in order to predict the actual SCPP operation which shows that wind speeds on the order of 10 m/s (adequate to power commercial shrouded pressure-staged wind turbo generators) are witnessed. A detailed construction engineering cost estimate has been presented which bids the building cost to be 156 M$. The proposed 24 acre facility has the potential of generating on the order of 100 MW of compost waste-heat to energy extraction/conversion annually with a yield of 83 M$ in revenue. The total cost per unit of energy produced for the SCPP is 0.62 US $ / kWh (0.56 € / kWh).

ACKNOWLEDGEMENTS

The authors would like to thank COMPO Energy, Inc. for sponsoring the present research.

REFERENCES

[1] Zhou, X., Wang, F., and Ochieng, R.M. (2010) "A review of solar chimney power technology," *Renewable and Sustainable Energy Reviews*. 14(8), 2315-2338.

[2] Haaf, W., Friedrich, K., Mayr, G., Schlaich, J. (1983) "Solar chimneys part I: principle and construction of the pilot plant in Manzanares." *Int J Solar Energy*, 2,3–20.

[3] Schlaich, J., Mayr, G., Haaf, W. (1980) "Upwind power plants: the demonstration plant in Manzanares, Spain" *Proceedings of the National Conference on Power Transmission, Hamburg*, 97–112.

[4] Schlaich, J., Schiel, W., Friedrich, K. (2001) "Solar chimneys." *Encycl Phys Sci Tech*, 3, 1–10.

[5] Schlaich, J., Bergermann, R., Schiel, W., Weinrebe, G. (2004) "Sustainable electricity generation with solar updraft towers." *Struct Eng Int*, 14, 225–229.

[6] Schlaich, J., Bergermann, R., Schiel, W., Weinrebe, G. (2005) "Design of commercial solar updraft tower systems—utilization of solar induced convective flows for power generation." *J Solar Energy Eng Trans ASME*, 127, 117–124.

[7] Schlaich, J., Bergermann, R., Schiel, W. and Weinrebe, G. (2005). "Design of commercial solar updraft tower systems - utilization of solar induced convective flows for power Generation." *Journal of Solar Energy Engineering-Transactions of the ASME*. 127(1), 117-124.

[8] Al-Dabbas, M. (2012) "The first pilot demonstration: solar updraft tower power plant in Jordan." *International Journal of Sustainable Energy*. 31(6)399-312.

[9] Pretorius, J.P. and Kroger, D.G. (2006) "Solar chimney power plant performance." *Journal of Solar Energy Engineering-transactions of the ASME*, 128(3)302-311.

[10] Asnaghi, A, and S.M. Ladjevardi. (2012) "Solar Chimney Power Plant Performance in Iran." *Renewable and Sustainable Energy Reviews*. 16(5), 3383.

[11] Sangi, R. (2012) “Performance evaluation of solar chimney power plants in Iran.” *Renewable & Sustainable Energy Reviews*. 16(1), 704-710.

[12] Koonsrisuk, A., and Chitsomboon, T. (2013) “Mathematical modeling of solar chimney power plants.” *Energy*, 51, 314-322.

[13] Koonsrisuk, A., and Chitsomboon, T. (2007) “Dynamic similarity in solar chimney modeling.” *Solar Energy*, 81(12), 1439-1446.

[14] Fathi, N., Seyed Sobhan, A., and Vorobieff, P. (2016) “Numerical-analytical assessment on solar chimney power plant,” *Applied Thermal Engineering*, in press.

[15] Cao, F., Zhao, L. and Guo, L. (2011) “Simulation of a sloped solar chimney power plant in Lanzhou.” *Energy Conversion and Management*. 52(6), 2360-2366.

[16] Guo, P.H., Li, J.Y. and Wang, Y. (2014) “Annual performance analysis of the solar chimney power plant in Sinkiang, China.” *Energy Conversion and Management*, 87, 392-399.

[17] Dai, Y.J., Huang, H.B. and Wang, R.Z. (2003) “Case study of solar chimney power plants in Northwestern Regions of China.” *Renewable Energy*. 28(8), 1295-1304.

[18] Zhou, X., Wang, F., Fan, J., and Ochieng, R.M. (2010) “Performance of solar chimney power plant in Qinghai-Tibet Plateau.” *Renewable and Sustainable Energy Reviews*. 14(8), 2249-2255.

[19] Aja, O. and Al-Kayiem, H. (2014) “Review of municipal solid waste management options in Malaysia, with an emphasis on sustainable waste-to-energy options.” *Journal of Material Cycles and Waste Management*, 16(4), 693-710.

[20] Anderson, K.R., Shafahi, M., and McNamara, C. (2016) “Thermal-fluids analysis of a hybrid solar/compost waste heat updraft tower.” *Journal of Clean Energy Technologies*, 4, 3, 213-220.

[21] Anderson, K.R., McNamara, C. Shafahi, M., and Lakeh, R.B. (2016) “Experimental and numerical investigation of natural convection in a compost waste-to-energy solar tower.” *Proceedings of the First Pacific Rim Thermal Engineering Conference*, Hawaii, USA.

[22] Anderson, K.R., Shafahi, M., Perez, P., Kampen, B., McNamara, C., Shihadeh, S., Sharbat, A., Palomo, M., Baghaei Lakeh, R., Salem, Y., Jouhar, S., Bahrani, S., Wang, K., Juarez, J. (2016) “Case study of a solar tower/ compost waste-to-energy test apparatus.” *Proceedings of the 31st International Conference on Solid Waste Technology and Management*, Philadelphia, USA.

[23] Anderson, K.R., Shafahi, M., Lakeh, R. B., Monmeni, S. and McNamara, C. (2015) “CFD analysis of hybrid solar tower using compost waste heat and photovoltaics." IEEE SUSTECH 2015, *Proceedings from the Conference on Technologies and Sustainability*.

[24] Anderson, K.R., Shafahi, M., McNamara, C., Schroeder, W., Owen, D. and Castillo, I. (2015) “Analysis of a solar updraft tower utilizing compost waste heat.” *Proceedings from the ASME 2015 Power Conference*, San Diego, CA.

[25] Compoenergyinc.com, [Online]. Available: http://www.compoenergyinc.com/

[26] Agrilab Technologies, LLC. 2013. Heat capture and aerobic composting: Renewable thermal energy technology. [Online]. Available: www.agrilabtech.com

[27] Smith, M. and Aber, J. 2014. Heat Recovery from Compost: A Step-by-Step Guide on Building an Aerated Static Pile Heat Recovery Compost Facility. Manuscript in preparation for publication.

[28] Pham T.T., Kaushik, R., Parshetti, K.G., Mahmood, R. and Balasubramanian R. (2014) “Food waste-to-energy conversion technologies: current trends and future directions.” *Waste Management*, 39, 399-408.

[29] Haug, Roger Tim. 1993. *The Practical Handbook of Compost Engineering*. Boca Raton.

[30] Epstein, Eliot, 2011. *Industrial Composting: Environmental Engineering and Facilities Management*. Boca Raton, FL: CRC Press.

[31] Cornell Composting [Online]. Available: http://compost.css.cornell.edu/

[32] E. Sayed, G. Khater, and S. Ali. “Mathematical model of compost pile temperature prediction,” *Environmental and Analytical Toxicology*, vol. 4, no. 6, pp.1-7, 2014

[33] Green Mountain Technologies (2016) [Online]. Available: http://compostingtechnology.com/