Up-Draught Solar Chimney and Down-Draught Energy Tower – A Comparison

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Abstract

In the paper two power plant types that utilize a convective flow for electricity generation are discussed: The so-called 'Solar Chimney', and a down-draught power plant named 'Energy Tower'.

Both power plants utilize a convective flow caused by the density difference between the air column inside a large chimney - open at the bottom and the top - and the surrounding atmosphere:

- *Inside a Solar Chimney the air is less dense than the adjacent atmospheric air outside the chimney. This is accomplished by combining a large air collector with the central chimney. Hot air is produced by solar radiation and flows up the chimney, driving turbines installed at the chimney base.*
- *The air inside an Energy Tower is denser than the adjacent air outside the chimney due to water being sprayed into the chimney at the chimney top. The water evaporates, thus cooling the air inside the chimney below ambient temperature, which therefore flows down the chimney.*

The thermodynamic basics required to model both power plants are given. Similarities and differences are pointed out. Results obtained with the simple models are compared to each other, to the values found in literature, and – in the case of the Solar Chimney – to measured values of a Solar Chimney prototype. In the case of the Energy Tower a comparison to measured values was not possible, as no test results from a prototype have been published yet.

In general, there is good agreement between the values found using the simple models and the values from literature. In the case of the Energy Tower this is true with the restriction that agreement is only found as long as very optimistic meteorological conditions are taken as given. Otherwise the calculated electric output is significantly lower than the numbers claimed by the proponent.

It is found that under real world meteorological conditions the electric power that can be generated with an Energy Tower is in the range of one fifth up to a maximum of approximately one third of the electric power of a Solar Chimney of the same (chimney) dimensions. When comparing the two power plant types, it must be kept in mind that the Solar Chimney requires a large air collector surrounding the chimney, whereas the Energy Tower does not.

1. NOMENCLATURE

symbol	**physical property**	**dimension**
Greek Letters		
φ	relative humidity	-
α	heat transfer coefficient	W/m²K
β	thermal loss coefficient	W/K
$(\tau\alpha)$	transmittance – absorptance product	-
Latin Letters		
c	specific heat capacity	J/kg K
m	mass	kg
p	pressure	N/m² [=Pa]
G	Global solar radiation	W/m²
h	enthalpy (mass specific)	J/kg

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symbol	**physical property**	**dimension**
H	height	m
T	temperature	K
v	air transport velocity	m/s
x	water content (water load) of moist air	-
z	elevation	m
Indices		
a	(dry) Air	
amb	ambient	
l	liquid	
s	saturation	
w	water	
z	in z-direction	
Constants		
g	gravitational acceleration	9.81 m/s²
c_{pA}	heat capacity of air	1 004 J/KgK
c_W	heat capacity of water	4 180 J/kgK
r_0	evaporation enthalpy of water	2 250 000 J/kgK
ρ_W	density of liquid water	1000 kg/m³
R_A	specific gas constant for air	287.1 J/kgK
Abbreviations		
DALR	Dry Adiabatic Lapse Rate	1 K/100 m
O&M	Operation and Maintenance	
PV	Photovoltaic	

2. INTRODUCTION

During the last three decades, mainly two proposals to harness the energy of convective flows for electricity generation were discussed: The so-called Solar Chimney proposed by Schlaich (1995), and a down-draught power plant - patented by Carlson (1975) and named 'Energy Tower' by its main proponent Zaslavsky (1999).

In the paper both power plant types are introduced, simple models for calculation of the flow and the useable energy to be extracted are given, and results of simulations are presented. Additionally, based on basic thermodynamic calculations, sensitivity to external meteorological factors is investigated.

Finally a comparison is made that aims at showing the characteristics of both technologies, in order to give a sound base for decision makers.

First we perform a technical comparison to assess which technology seems preferable at which site, i.e. under which meteorological conditions. The technical comparison also includes an evaluation of the components required by both plant types, and the ones that are only required by one or the other.

Based on the component list of the technical evaluation, a comparative cost assessment is performed. To keep the comparison generally applicable, not absolute sums are given, but comparative values.

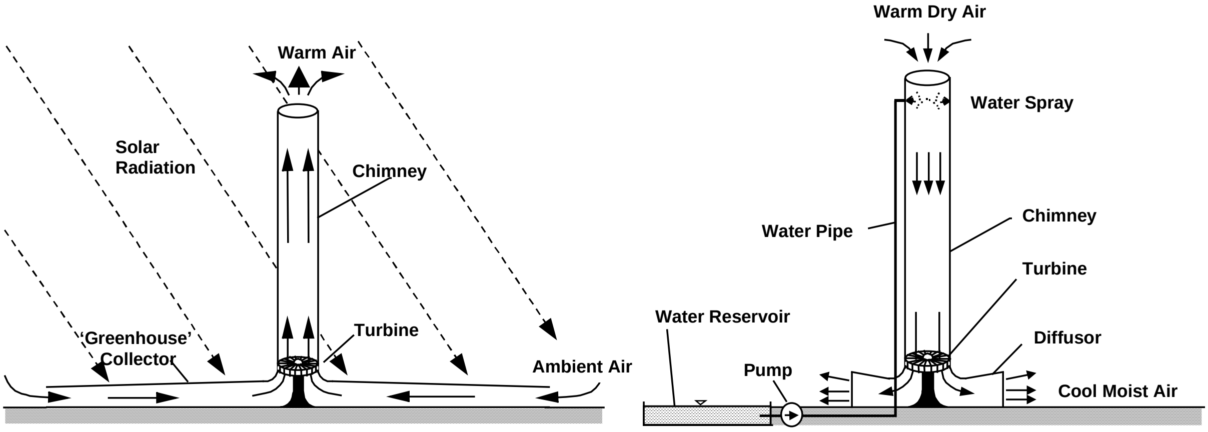
Eventually a brief assessment regarding ecological features is presented in the form of a table, without a final valuation of the various characteristics.

The aim of the assessments is not to tell which plant type is better, but to give enough background and to list comprehensible facts, so that the reader himself can judge - with regard to his particular site and requirements - which option seems more promising for his specific conditions.

3. BASICS

3.1. Functional Principle

Both power plant types have in common that they utilize the density difference between the air column inside a large chimney - open at the bottom and the top - and the surrounding atmosphere (Figure 1). This density difference causes a pressure difference $\Delta p_{chimney}$ that is used to drive a turbine installed inside the chimney. To this end a fraction Δp_{dyn} of the pressure difference is used to accelerate the air, the rest is used to drive a pressure staged turbine ($\Delta p_{turbine}$) and to compensate friction losses ($\Delta p_{friction}$). But there is also a significant difference:



Solar Chimney Energy Tower

Figure 1: Schematics of Solar Chimney and Energy Tower

– Inside a **Solar Chimney** the air is less dense than the adjacent atmospheric air outside the chimney. This is accomplished by combining a large collector greenhouse with a central chimney: Hot air is produced by direct and diffuse solar radiation under a large glass roof (i.e. an air collector). The heated air flows to a chimney situated in the center of the collector and is there drawn upwards due to buoyancy forces. This updraft drives wind turbines installed at the base of the chimney (Schlaich, 1995). The ground under the collector greenhouse functions as a thermal storage. This effect can be increased, e.g. by covering the ground with black water-filled tubes. Thus it is possible to operate a Solar Chimney even at night at a reduced output, i.e. 24 h/day (Kreetz, 1997).

– The air inside an **Energy Tower** is denser than the adjacent air outside the chimney. This is accomplished by spraying water into the chimney at (or close to) the chimney top. The water evaporates, thus cooling the air inside the chimney below ambient temperature. As cool air is denser than the surrounding - relatively warm - atmospheric air, it flows down the chimney.

In both cases the flow causes more ambient air to be sucked into the solar collector entry (Solar Chimney) or the chimney top (Energy Tower) respectively, making the air flow (quasi-) stationary as long as ambient conditions allow, i.e. as long as enough energy is provided to the process in the form of hot air from the collector (Solar Chimney) or as long as water is pumped up the chimney and sprayed into the air flow and there is enough dry and warm ambient air available at the same time (Energy Tower).
To produce electricity, pressure staged turbines capable of working on a small pressure difference (order of magnitude 1000 Pa), but large volume flows, are required. In principle it is not important where the turbines are placed, as the chimney is air tight and the mass flow through it therefore remains constant over its height. Still, for obvious engineering and practical reasons, the turbines will be placed as close to the ground as possible.

3.2. Physics

The basic equations required for an assessment based on thermodynamic laws are given in the following.

Atmosphere. We start with a description of the outer atmosphere ('outer' in contrast to the situation inside the chimney), as the knowledge of its properties is required for the modeling of both plants. The layer of the troposphere considered is from ground to chimney height.

Evolution of atmospheric pressure with height. The well-known barometric elevation formula yields the atmospheric pressure p as a function of ambient pressure on ground level p_0 and elevation z (Liljequist, 1984):

$$p(z) = p_0 \, e^{-\frac{g}{R_A T} z} \tag{1}$$

Dry Adiabatic Lapse Rate. Combining (1) with the general equation for ideal gases, we obtain the corresponding temperature gradient

$$\frac{dT}{dz} = -\frac{g}{c_p} \tag{2}$$

Assuming c_p=1005 J/kgK and g=9.81 m/s² this yields dT/dz= - 0.98 K / 100m which is often rounded to -1 K/100m. This gradient is called 'Dry Adiabatic Lapse Rate (DALR)'. It means, that when a 'packet' of air is vertically moved in the atmosphere, and no condensation occurs (hence 'dry'), the temperature decreases by approx. 1 K with every 100 m the 'air packet' is lifted, or vice versa, i.e. the air temperature increases when the packet is moved downwards.

Evolution of humidity. In general, the evolution of temperature and humidity depends on the site and the current weather situation (Schneider-Karius, 1953; Hesse, 1961). For the sake of simplicity only two basic cases are considered in our calculations here:

1. Temperature distribution following a DALR and humidity increasing with height. To calculate the evolution of humidity with height, constant water content of air is assumed. This 'base case' can be found in reality when a good exchange of air masses inside the troposphere is given in the lower layer of the atmosphere due to turbulent air flow (cf. Schneider-Karius, 1953, pp. 15 ff.).
2. Temperature distribution following a DALR and humidity remaining constant with height (cf. Schneider-Karius, 1953, pp. 23 ff.).

Density of moist and over-saturated air. The density difference between the air column inside the chimney and the outer atmosphere is the prime mover of the process. The density of moist air with a water content $\varphi = p_w/p_s$ less or equal to unity (=saturation) can be calculated as follows (cf. Baehr, 1996, pp. 214 ff.):

$$\rho = \frac{p}{R_L \, T}\left[1 - 0.378 \, \varphi \, \frac{p_s}{p}\right] \tag{3}$$

For over-saturated air with a water content $x > x_s$ (where $x = m_w/m_a$) the density is

$$\rho = \frac{m}{v} = \frac{m_a \left(1 + x\right)}{\frac{m_{a,s}}{\rho_{a,s}} + \frac{m_{a,l}}{\rho_{w,l}}} = \frac{1 + x}{\frac{1 + x_s}{\rho_{a,s}} + \frac{x - x_s}{\rho_{a,l}}} \tag{4}$$

Solar Chimney. We will now do a basic evaluation of a Solar Chimney, namely of its components collector, chimney and turbine.

Collector. The air collector of the Solar Chimney converts solar radiant energy (both direct and diffuse solar radiation) to useful heat of the air flowing through that chimney. The efficiency η_{coll} of this conversion can be described using the two collector parameters $(\tau\alpha)$ and β, where $(\tau\alpha)$ denotes the transmittance-absorptance product and β is the collector's thermal loss coefficient. The parameters can be obtained from measurements (Fechner, 1999), e.g. the ones taken at the Manzanares prototype (Haaf, 1985), or from a detailed simulation of the collector.

$$\eta_{coll} = \left(\tau\alpha\right) - \frac{\beta \, \Delta T}{G} \tag{5}$$

Typical efficiencies range from 40 to 60 %. In our model collector exit temperature and the corresponding density is calculated using this collector efficiency. Required input values are collector inlet temperature (= ambient temperature), insolation, transmittance of collector glazing and collector (ground) absorptivity.

Chimney. Pressure difference Δ p of the chimney is calculated using equation (6), where $\Delta \; p_{chimney}$ is the total driving pressure potential available (Stephan, 1995).

$$\Delta p_{chimney} = g \int_{0}^{H} \left(\rho_{chimney} - \rho_{atmosphere} \right) dz \tag{6}$$

Turbine. The turbine extracts a fraction *xtm* of the total driving potential Δp, the rest is needed to accelerate the air flow and to make up for friction. We obtain

$$\Delta p_{chimney} = \Delta p_{turbine} + \Delta p_{friction} + \Delta p_{dyn} \tag{7}$$

Using the standard definition for dynamic pressure

$$\Delta p_{dyn} = \frac{1}{2} \rho \, v^2 \tag{8}$$

and introducing the overall friction coefficient ζ for the complete air flow from (collector) entry to (chimney) exit in order to define friction losses

$$\Delta p_{friction} = \zeta \frac{1}{2} \overline{\rho}_{chimney} v_{chimney}^2 \tag{9}$$

we obtain equation (10) to calculate air velocity inside the chimney:

$$v_{chimney} = \sqrt{2 \frac{\Delta p_{chimney}}{\overline{\rho}_{chimney}} \cdot \frac{(1 - xtm)}{(1 + \zeta)}} \tag{10}$$

According to equation (10), air velocity in the chimney increases with decreasing pressure extraction coefficient, and decreases with increasing friction coefficient. Mechanical power extracted at the turbine can be written as

$$P_{mech} = \Delta p_{turbine} \, \dot{V} = \Delta p_{turbine} \, A_{turbine} \, v_{turbine} \tag{11}$$

If the 'coupling' between chimney and collector is not considered, i.e. for $\Delta p_{chimney}$ = constant, we find that maximum power can be extracted when *xtm* equals *2/3*. This is analogous to the Maximum Power Point (MPP) found for PV-systems.
The 'coupling' between chimney and collector deserves a short explanation: Collector and also chimney efficiency are not constant for a given insolation. Air velocity in the chimney – and hence in the collector, as both are connected – directly influences temperature rise in the collector and friction in chimney and collector: With decreasing air velocity the temperature rise in the collector goes up and friction decreases. Higher air temperature also means higher chimney efficiency. On the other hand, thermal collector losses increase with rising collector temperature. Still, in Solar Chimney systems the optimum pressure extraction factor is larger than 2/3, when collector effects are considered.

Complete System. To simulate the complete system, a simple iteration is required to account for feedback between chimney and collector: Calculation starts e.g. with an estimate for collector temperature rise and the corresponding pressure potential. Based on this $\Delta p_{chimney}$, the resulting air velocity is calculated, which in turn leads to a new temperature rise in the collector. This is the starting value for the next iteration loop and so on, until the difference between two consecutive calculations is smaller than a set threshold.

Energy Tower. We will now give the basic equations required to do a brief analysis of Energy Tower performance. To keep it short, whenever possible reference is made to the corresponding section in our Solar Chimney discussion.

Spraying of water into a moist unsaturated air flow. In the proposed Energy Tower, the density difference required to start the convective flow inside the chimney is obtained by cooling the ambient air sucked in. The cooling in turn is due to the evaporation of water that is sprayed into the flow at (or close to) the chimney top. Therefore, the temperature drop obtained by this spraying and evaporation process (**Figure 2**) is calculated first. Without a significant loss of accuracy, the mixing process can be considered adiabatic, as heat transfer through the chimney walls is negligible compared to the other energy flows considered.

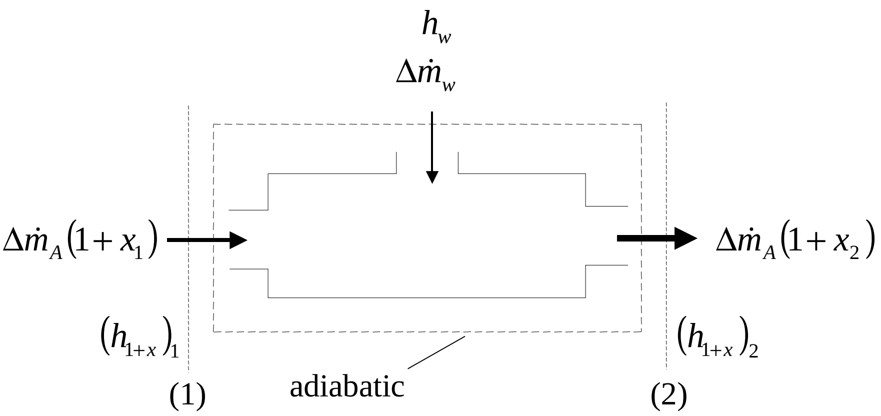


Figure 2: Adiabatic Mixing of liquid water and moist unsaturated air

We start with writing the mass balance (12) and the energy balance (13),

$$\dot{m}_A(1+x_1)+\Delta\dot{m}_W=\dot{m}_A(1+x_2) \tag{12}$$

$$\dot{m}_A(h_{1+x})_1+\Delta\dot{m}_W\,h_W=\dot{m}_A(h_{1+x})_2 \tag{13}$$

and then make use of the fact that the enthalpy of the mixture can be calculated as the sum of the enthalpies of the components (Baehr, 1996)

$$h_{1+x}=h_A+x\,h_W \tag{14}$$

The enthalpy of the air is calculated using equation (15), the enthalpy of the water can be calculated using equation (16) for the case when all water is gaseous, i.e. the moist air is unsaturated ($\varphi \le 1$), and using equation (17), when the saturated moist air contains liquid water (Baehr, 1996).

$$h_A=c_{pA}\,T \tag{15}$$

$$h_W=r_0+c_{pW}\,T \tag{16}$$

$$h_{1+x}=c_{pA}\,T+x_S(r_0+c_{pW}\,T)+(x-x_S)\,c_W T \tag{17}$$

From this equations the resulting temperature of the air-water flow can be calculated. Then the equations to calculate density given in the section 'atmosphere' are applied to calculate densities inside the chimney. For the calculations we assume the droplets to evaporate directly after being sprayed into the chimney. This also means that the temperature drop and the rise in density are considered immediate.

Chimney. To calculate the driving pressure potential and the resulting flow, the same procedure as described for the Solar Chimney can be used, with the difference that the sign (direction) of pressure potential and flow is opposite.

Turbine. Again the same calculation procedure as for the Solar Chimney can be applied. As there is no collector to be considered, the optimum pressure extraction factor $xtm = {}^2/_3$ is used. Actually, this is the right value to optimize gross turbine power. To obtain maximum net power, a slightly larger pressure extraction factor is required, as mass flow through the chimney – and therefore also required pumping power - decreases with increasing pressure extraction factor. Therefore for values of xtm being slightly larger than ${}^2/_3$, net power is higher than for $xtm={}^2/_3$ because of lower parasitics for pumping, even though gross turbine power is less. Still, for the sake of simplicity and ease of insight $xtm={}^2/_3=constant$ is assumed for this investigation.

Complete System. As it was the case with the Solar Chimney, we also have to iterate to solve the Energy Tower equation system. One possibility is to start with an educated guess for air velocity and the water mass flow to be sprayed into the chimney, calculate the resulting temperatures and densities in the chimney and evaluate the corresponding driving pressure potential. Now the air flow through the chimney and saturation level at the

chimney exit can be calculated, and the next iteration loop starts.
For the investigation presented here, the water spray mass flow was selected in such a way that the air flow reaches saturation at the chimney base level, i.e. liquid water is avoided in order to prevent the turbines from damage due to droplets. This also means that no fog will exit at the chimney outlet.
The theoretical option to remove excess water from the air flow before it reaches the turbines is not considered here, in order to keep the calculation simple, and also to avoid the pressure loss and technical effort associated with such a system.

3.3. Model Validation

To validate the models, results from literature (Schlaich, 1995); Zaslavsky, 1999; Hoffmann, 1991); Haaf, 1985) are compared to the values obtained using the simple models described above. A selection of this comparison is presented below.

Solar Chimney. For Solar Chimney model validation measured data from the Manzanares prototype plant for 1.9.1989 are used (Schiel, 2000). The chimney and meteo data utilized are given in **Table 1**.

Table 1. Main Solar Chimney and Meteo Data used for Model validation

Meteo data for 8.6. 1987, time 11:20 (10 minute average) Manzanares		
Global Solar Radiation^A	1 017	W/m²
ambient temperature (2m above ground level)^A	18.5	°C
ambient pressure^A	92930	Pa
polytropic exponent for outer atmosphere^B	1.4	-
Geometry		
Mean Collector Diameter^A	244	m
Chimney height^A	194.6	m
chimney diameter^A	10.16	m
Efficiency / Losses		
collector absorptance coefficient α^B	0.65	-
collector loss coefficient β ^{B}	15	W/m²K
turbine efficiency (design values)	0.85	-
generator and gearbox efficiency ^{B}	0.9	-
pressure extraction coefficient xtm ^{B}	0.75	-
pressure loss co-efficient (for complete plant) ^{B}	0.15	-

^{A} measured Data ^{B} derived data or assumption

Table 2. Comparison between measured data from Manzanares Solar Chimney prototype and simulation results

	Measured	Simulated	
Upwind velocity	8.1	8.0	m/s
total driving pressure potential chimney	n/a	130	Pa
temperature at collector exit	38	41	°C
Power	48.4	48.5	kW_{el}

There is good agreement between measurement and simulation concerning upwind velocity and collector exit temperature. The electric power calculated with the simple model is within less 0.25 % of the measured value (**Table 2**). With respected to the uncertainties concerning especially the real turbine (efficiency, pressure extraction coefficient) and ground properties (heat capacity etc.), this accuracy is more than satisfactory.

Energy Tower. For the Energy Tower no real-world data is available. Therefore the simple model is validated against the results published in Zaslavsky (1999). Using the dimensions and the water mass flow given there, and assuming an ambient temperature of 45°C and a relative humidity of 16 %, our model yields a net electricity output of 386 MW, which is within 0.5 % of the 388 MW given by Zaslavsky (1999).

Based on the results of the comparison presented above, both models are considered valid for the scope of the investigation of this paper.

3.4. Sensitivity Analysis

We will now investigate the influence of the respective main meteorological parameters on power production.

Solar Chimney. The main meteo parameters that influence Solar Chimney power production are solar radiation and, to a smaller extent, ambient temperature. There is also a small influence of ambient pressure: Power delivered increases with increasing atmospheric pressure. As this influence is very low (assuming an ambient pressure of 90 000 Pa instead of 101 300 Pa, electric output of our 100 MW reference plant decreases by approx. 2 %), it is not discussed in detail here.

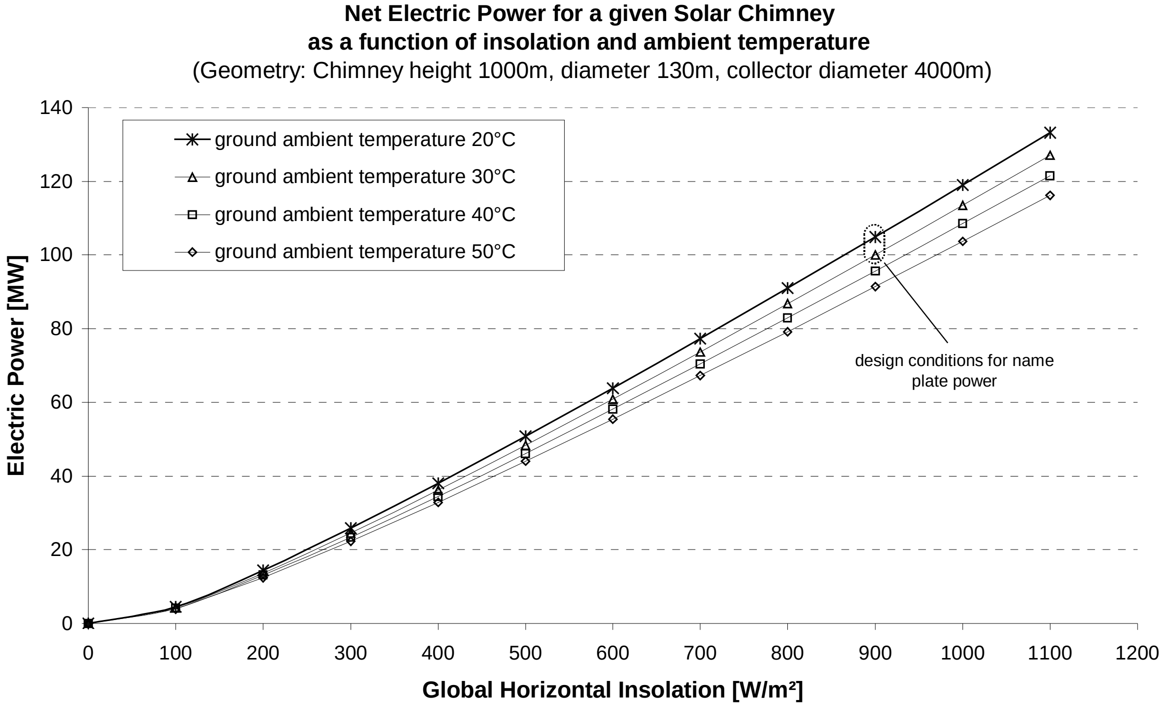


Figure 3. Net Electric Power for the reference Solar Chimney as a function of solar insolation and temperature at ground level

In **Figure 3** net electric power for the reference Solar Chimney is plotted as a function of solar insolation and temperature at ground level. Apparently, for insolation levels above approx. 300 W/m², there is a practically linear correlation between insolation and electric output. There is also a noticeable effect of ambient temperature on electric output. At constant insolation level, lower ambient temperatures facilitate higher electric output. At an insolation level of 1000 W/m² e.g., electric output is 119 MW at an ambient temperature of 20 °C at ground level, whereas at an ambient temperature of 50 °C output drops by 13 % to 104 MW.

In **Figure 3** the reference conditions for name-plate (instantaneous) power, i.e. 100 MW, are marked.

It should be mentioned here that in order to increase the Solar Chimney plant capacity factor, i.e. annual delivered energy, the collector size and its thermal capacity (thermal storage) can be increased. Doing so, detailed simulations show that power production is also much more uniform, i.e. 'flattened' (Kreetz, 1997). A detailed discussion of this special feature is beyond the scope of the present paper.

Energy Tower. The main meteo parameters that influence Energy Tower power production are air humidity and ambient temperature. In **Figure 4** net electric power for the reference Energy Tower is plotted versus relative humidity at ground level.

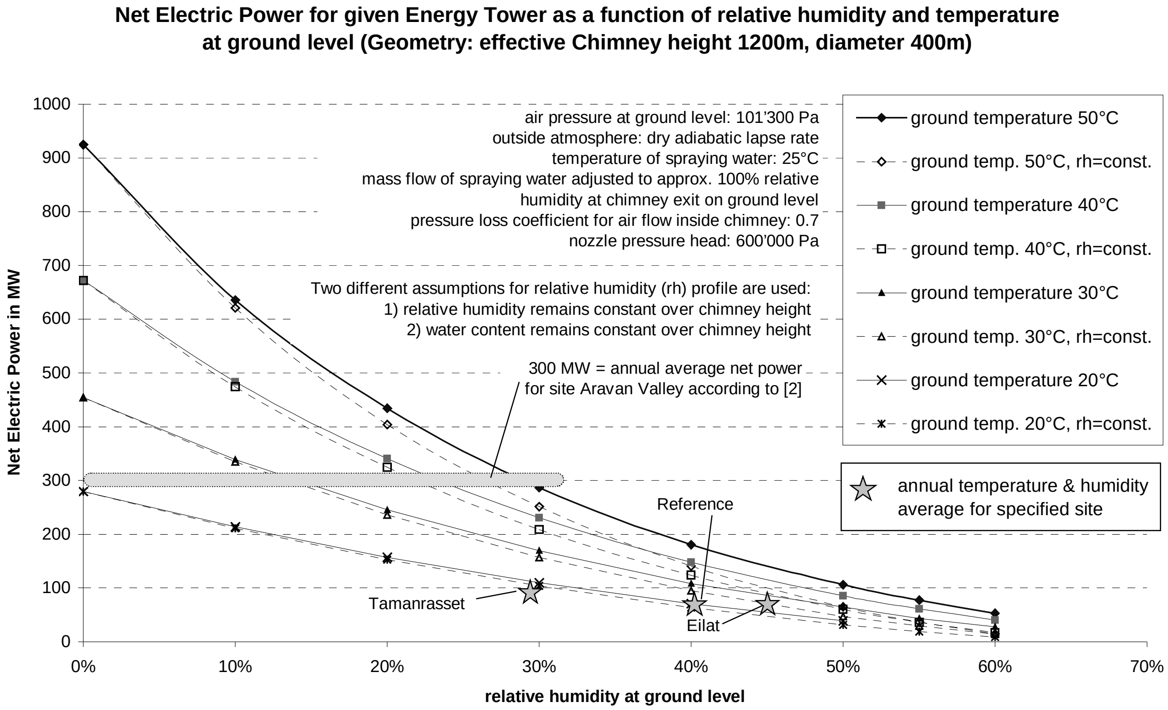


Figure 4. Net Electric Power for reference Energy Tower as a function of relative air humidity and temperature at ground level. The stars mark annual average values of relative air humidity and ambient temperature for the reference site and two other real-world sites (Eilat/Israel and Tamanrasset/Algeria).

From **Figure 4** it can be seen that the Energy Tower's net electric output decreases with decreasing ambient temperature, and it also decreases with increasing ambient atmosphere humidity. There is also a small influence of the evolution of ambient humidity with elevation: Electric power output is smaller, when relative humidity is constant over elevation in contrast to the case when the atmospheric water load is constant. The latter is the case when turbulent atmospheric conditions guarantee an even distribution of water. The described influence increases with rising humidity; obviously for a relative humidity of 0 % electric power output is identical for the cases of constant humidity and constant water load.

Annual average meteorological conditions for Eilat (Israel) and Tamanrasset in the Sahara desert (Algeria) are marked by stars in the diagram. The corresponding annual average power output for an Energy Tower is approximately 70 MW for the reference site or Eilat (where there is sufficient sea water), and 130 MW for Tamanrasset (where it will never be operated, as there is no water available) respectively, compared to 300 MW stated in Zaslavsky (1999) to be the Aravan valley annual average.

3.5. Modelled Electricity Output vs. Output Values from Literature

Solar Chimney. First we compare the net electric output at reference meteo conditions, calculated using the described models, to the numbers given in literature: At reference conditions (**Table 3**), 800 W/m² Global insolation on a horizontal surface, and an ambient pressure of 100 000 Pa our simple model yields an electric output of 103 MW, which is about 3 % more than name-plate power given by Schlaich (cf. Kreetz, 1997). Thus, there is good agreement.

Energy Tower. Under reference meteo conditions, the Energy Tower delivers 69 MW (relative humidity at exit 100 %, water spray mass flow 3950 kg/s). 69 MW is significantly less than the 388 MW given in Zaslavsky (1999).

Running the Energy Tower model with a prescribed ambient temperature of 45°C and a relative humidity of 16 % (assuming constant water load of the atmospheric air) yields a net electricity output of 386 MW, which is only 0.5 per cent less than the number given in Zaslavsky (1999). We therefore conclude that the difference results from the different ambient conditions, i.e. reference ambient temperature 22 °C and reference relative humidity 41 %, as the values published in Zaslavsky (1999) can be recalculated with our model if the above mentioned, very favourable ambient conditions are assumed.

Comparison. Both plant types show a strong influence of ambient conditions on power production: Whereas the Solar Chimney requires high insolation levels to achieve a high electric output, the Energy Tower requires warm and extremely dry air to perform as desired.
Wide areas with favourable conditions for the Solar Chimney, i.e. global horizontal insolation levels higher than e.g. 2000 W/m²a, exist at many places around the world (Meteotest, 1999), e.g. practically in all deserts.
Sites with favorable conditions for an Energy Tower, i.e. a with very low humidity of e.g. less than 25 %, are very scarce, if not to say non-existent, especially when taking into account the additional site requirements, namely that abundant water supply has to be close to the power plant site, and that the plant should not be located in a valley or surrounded by mountains, as it might otherwise suffocate itself.

4. COMPARISON

4.1. Power Plant Electricity Output

We will now present the results of power plant simulations that are based on the (partially refined) basics given before. To this end we start with the definition of reference meteo conditions and reference plants to be analyzed.

Reference Meteo Conditions. In **Table 3** the meteo conditions used for the calculations are listed. The same three sites that are shown in **Figure 4** are used for the comparison:

- A 'reference' site, which is not identical to the values given by Schlaich (1995) or Zaslavsky (1999) respectively, but typical for many dry sunny places on the globe. It was the intention to define realistic reference conditions in such a way that neither the Solar Chimney nor the Energy Tower are favored.
- In Zaslavsky (1999) the Arava valley north of Eilat in southern Israel is the proposed location. As no meteo data was available for this exact place, data for Eilat – south of the Arava valley - from Meteonorm 4.0 (Meteotest, 1999) are used here for comparison.
- The third site is Tamanrasset (Algeria) in the heart of the Sahara desert in North Africa, an extremely dry location. Hence, this site offers favorable climatic conditions for the operation of an Energy Tower, if we neglect the fact that there is no water available.

Table 3. **Reference Meteo Conditions and real world conditions (annual averages)**

	Reference^{A,B}	Eilat (Israel) ^{B}	Tamanrasset (Algeria)^{B}
ambient temperature @ ground level	20 °C	25 °C	22 °C
relative humidity @ ground level	41 %	45%	28%
temperature gradient in 'outer' atmosphere^{C}	0.01 Km^{-1} (DALR)	n/a	n/a
annual global radiation on horizontal surface	2 278 kWh/m²a	2 086 kWh/m²a	2 365 kWh/m²a

^{A} typical dry sunny site, e.g. Upington ZA
^{B} average values from Meteotest (1999)
^{C} assumption

Reference Plants: Definition and Power Output. Two sets of reference plants are defined in **Table 5**: The first set (Solar Chimney I and Energy Tower I) with the chimney geometry as proposed by Schlaich for a 100 MW Solar Chimney (chimney type I), and the second set with the chimney geometry as proposed by Zaslavsky for the Energy Tower (chimney type II)[1]. Meteo conditions are varied to investigate their influence on plant performance.

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[1] The latter is considered here for comparison. Its inclusion does not mean that we suggest to built such a chimney.

In Table 4 general parameters used for the simulation are listed.

Table 4. Reference Plants – General Parameters

Solar Chimney & Energy Tower		
turbine – generator – set efficiency	0.8	-
Solar Chimney		
turbine pressure extraction factor	0.9	-
pressure loss coefficient[A]	1.4	-
collector absorptance coefficient ($\tau\alpha$)[B]	0.8	-
collector heat loss coefficient [B]	10	W/m²K
Energy Tower		
pump efficiency (for Energy Tower)	0.85	
water spray nozzle pressure	600 000	Pa
pressure loss coefficient[A]	0.7	-

[A] defined as $\Delta p_{friction} / \Delta p_{dyn}$ [B] different values than for Manzanares prototype, as glass cover (not mostly plastic foil) is used

Table 5. Reference Plants – Geometry and Power Output. Geometry from Schlaich (1995) (updated) and Zaslavsky (1999)

	Chimney Height	Chimney Diameter	Water Mass Flow	Collector Diameter	Design Point (Net) Electric Power	plant load factor	annual net electricity output
Reference Site [A]							
	Plants with chimney as proposed for 100 MW Solar Chimney power plant (chimney type I)						
Solar Chimney I	1000 m	130 m	-	4000 m	100 MW	0.30	272 GWh/a
Energy Tower I	1000 m	130 m	399 kg/s	-	14.8 MW	1	55 GWh/a
	Plants with chimney as proposed for Energy Tower power plant (chimney type II)						
Solar Chimney II	1200 m	400 m	-	13 000 m	1150 MW	0.32	3451 GWh/a
Energy Tower II	1200 m	400 m	3950 kg/s	-	69 MW	1	604 GWh/a
Tamanrasset							
	Plants with chimney as proposed for 100 MW Solar Chimney power plant (chimney type I)						
Solar Chimney I	1000 m	130 m	-	4000 m	100	0.32	280 GWh/a
Energy Tower I	1000 m	130 m	627 kg/s	-	11.5 MW	1	101 GWh/a
	Plants with chimney as proposed for Energy Tower power plant (chimney type II)						
Solar Chimney II	1200 m	400 m	-	13 000 m	1150 MW	0.34	3471 GWh/a
Energy Tower II	1200 m	400 m	6265 kg/s	-	131 MW	1	1148 GWh/a
Eilat							
	Plants with chimney as proposed for 100 MW Solar Chimney power plant (chimney type I)						
Solar Chimney I	1000 m	130 m	-	4000 m	100 MW	0.28	247 GWh/a
Energy Tower II	1000 m	130 m	418 kg/s	-	6.4 MW	1	56 GWh/a
	Plants with chimney as proposed for Energy Tower power plant (chimney type II)						
Solar Chimney II	1200 m	400 m	-	13 000 m	1150 MW	0.30	3065 GWh/a
Energy Tower II	1200 m	400 m	4130 kg/s	-	69 MW	1	604 GWh/a

[A] Typical dry sunny site, e.g. Upington South Africa

Electricity output for plant with type I chimney (height 1000m / diameter 130m). We now have a look at the annual power production of the two power plants with a type I chimney. For this comparison, we investigate electricity production at three sites: Reference site, Tamanrasset and Eilat (**Table 5**).

For the Solar Chimney (assumed collector diameter 4000 m) a detailed simulation using hourly weather data for each site was used (Weinrebe, 2000), power production of the Energy Tower is estimated using the power production under annual average conditions and assuming a plant load factor (PLF) of 100%, i.e. 8760 operating hours per year. At the reference site we obtain a net electricity production of 272 GWh/a compared to 55 GWh/a for the Energy Tower. For the solar chimney this denotes a plant load factor of 30 %.

At Tamanrasset, the Solar Chimney produces 280 GWh/a (PLF 32 %), compared to 101 GWh/a for the Energy Tower. Finally, at Eilat we find 247 GWh/a for the Solar Chimney (PLF 28 %) and 56 GWh/a for the Energy Tower.

The ratio between the electric energy provided by the Solar Chimney and the electricity provided by the Energy

Tower ranges from 2.8 : 1 (Tamanrasset) to 4.9 (Reference Site), i.e., as a rule of thumb, a Solar Chimney power plant having a chimney of 1000 m height and 130 m diameter approximately yields three to five times the electricity of an Energy Tower having the same chimney dimensions under real world meteorological conditions.

Electric output for plant with type II chimney (height 1200m / diameter 400m). The collector diameter assumed for the Solar Chimney is 13 000 m. Again, we start with the reference site: There we obtain a net electricity production of 3451 GWh/a (PLF 32 %) for the solar chimney, and 604 GWh/a for the Energy Tower.
At Tamanrasset, we find 3471 GWh/a (PLF 34 %) for the Solar Chimney, compared to 1148 GWh/a for the Energy Tower. Finally, calculations for Eilat yield 3065 GWh/a for the Solar Chimney (PLF 30 %) and 604 GWh/a for the Energy Tower.
Calculated electricity production of the Energy tower is very similar at the reference site and at Eilat. Evidently, the favourable lower humidity at the reference site is offset by lower average ambient temperatures compared to Eilat. In contrast to that, electricity production of the Solar Chimney varies between the sites: It is lower at Eilat due to the comparatively lower annual insolation there.
Again, we eventually calculate the ratio between the electric energy provided by the Solar Chimney and the electricity provided by the Energy Tower. It ranges from 3 : 1 (Tamanrasset) to 5 : 1 (Eilat). Thus, the same rule of thumb as before applies for the power plants having a chimney with a height of 1200 m and a diameter of 400 m: A Solar Chimney yields three to five times the electricity of an Energy Tower having the same chimney dimensions.

4.2. General Technological Aspects

To get an additional insight into the technology in general, selected characteristics are listed in **Table 6**.

Table 6. Selected technological characteristics of Solar Chimney and Energy Tower

	Solar Chimney	Energy Tower
chimney	large chimney required	
height-to-diameter-ratio from a structural point of view	favourable	unfavourable
corrosion	no particular challenge	spraying of salt water makes corrosion major problem
	-	high performance water spray system
collector	large collector	-
operation	-	huge amount of water required (approx. 180 kg H_2O/kWh)
	-	channel or pipeline to sea
	-	high capacity water pumps
turbine	pressure staged high volume flow turbine(s)	
	-	demister (may be required [A])

[A] to prevent turbine(s) from damage due to condensed water

In both cases large chimneys are required, preferably larger than they have ever been built before. In the case of the Energy Tower there is the additional difficulty that the height-to-diameter-ratio of the chimney is very unfavourable regarding stability, as the large diameter, i.e. the small curvature, results in ovalling with unfavourable stress distribution and increases the problem of buckling. Also corrosion due to the spraying of large amounts of salt water as well as the water requirement itself seem critical for the Energy Tower. For the Solar Chimney, a very large cost-effective collector is a prerequisite.

4.3. Economy and Ecology

Economy. It should be kept in mind that the Energy Tower does not need a collector. Still, it delivers only one fifth to one third the annual power of a Solar Chimney having the same chimney dimensions.
Moreover, for the same net electric output an Energy Tower requires a significantly higher installed generator capacity, as required pumping power is of the same order of magnitude as net power. Typical values for pumping power range from 70 to over 80 % of net power, i.e. installed generator capacity has to be higher than net power

by this percentage. In addition high performance pumps are required, a spraying system has to be built, operated and maintained.

To keep our comparison simple, we neglect these facts for a moment and concentrate only on the differences in power output for given chimney dimensions. Then economy can be wrapped up with the following statement: As long as the cost for the Solar Chimney's collector does not exceed two to four times its chimney cost, resulting electricity costs for the Solar Chimney are less or equal compared to Energy Tower electricity cost.

Ecology. In **Table 7** selected catchwords regarding the ecology of the two plants are listed.

Table 7. **Selected catchwords concerning Solar Chimney and Energy Tower ecology**

	Solar Chimney	Energy Tower
land requirement	high	moderate
water requirement	onlyx for construction	very high
salt	-	very high
possible effect on micro climate	low[A]	high[B]

[A] heated air rises with and without Solar Chimney

[B] surroundings of Energy Tower are significantly cooled, moistened and salted

Whereas environmental impact of the Solar Chimney is high regarding land requirement, the Energy Tower requires a comparatively smaller area. Taking a look at the other topics, the picture changes: The Energy Tower needs about 180 kg of water per kWh of net electricity produced, whereas the Solar Chimney requires no water for operation.

Assuming a typical seawater salinity of 3 %, approx. 5.4 kg salt per $kWh_{el,net}$ or 3.3 Mio tonnes per year of salt are 'produced' from an Energy Tower at Eilat, assuming the proposed chimney with a height of 1200m and a diameter of 400m. If this salt is carried away by the air flow and distributed over the surroundings of the Energy Tower, the effect on the land will be dramatic. To extract the salt from the air flow before it leaves the Energy Tower will be a technological (pressure loss) and economic challenge. Even if the salt contained in the air flow leaving the Energy Tower is not considered, the effect of the cool and moist air flow on micro climate in an otherwise hot and dry area (a prerequisite for the Energy Tower site) will be significant.

In contrast to that, the effect of the warm air flow leaving the Solar Chimney top will be much less, as the chimney just 'concentrates' the ambient air heated by solar radiation that would rise anyway, with or without a collector and chimney.

5. SUMMARY AND CONCLUSIONS

Two power plant types that utilise natural convective flows - the Solar Chimney and the Energy Tower – were described and investigated. Basic thermodynamic models for the calculation of both plant's behaviour, mainly their electric output, were developed. Using elementary thermodynamic and meteorological equations, good agreement between calculated plant behaviour and the values given by their respective proponents was found.

In order to achieve a power production that principally seems sufficient for economic operation, both plant types require very specific site conditions. Especially weather conditions are critical. Sites with the meteorological parameters required by the Solar Chimney (mainly high global solar insolation) are abundant, whereas really suitable sites for the Energy Tower (hot and extremely dry ambient air) seem very scarce.

As a rule of thumb it is found that a Solar Chimney yields three to five times the electricity of an Energy Tower having the same chimney dimensions. Thus, as long as the cost for the Solar Chimney's collector does not exceed two to four times the chimney cost (which is by far not the case), the Solar Chimney is equally or more cost effective than an Energy Tower.

As both have the potential to deliver clean energy in the sense that they do not operate on fossil fuels and thus reduce the emission of greenhouse gases and other pollutants, Solar Chimney as well as Energy Power are options that deserve further investigation. Hence, provided suitable sites are available and remaining technological challenges (e.g. salt extraction in the case of the Energy Tower) are mastered, the construction and operation of a prototype (in the case of the Energy Tower) and first commercial plants (in the case of the Solar Chimney, as the principle has already been proven by the operation of a prototype in Spain over several years) are the logical next steps.

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