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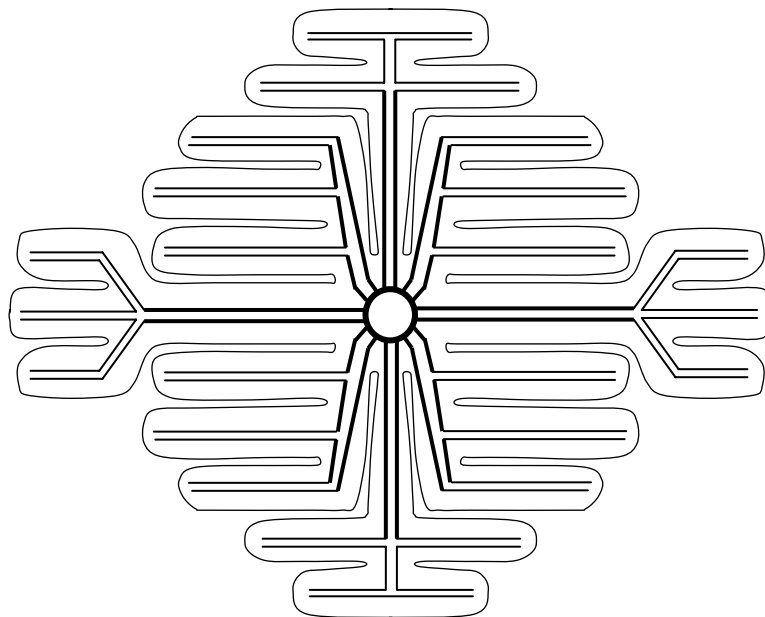
DOCTORATE THESIS

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by

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Solar Chimney, water spraying Energy Tower,
and linked renewable energy conversion devices :
presentation, criticism and proposals



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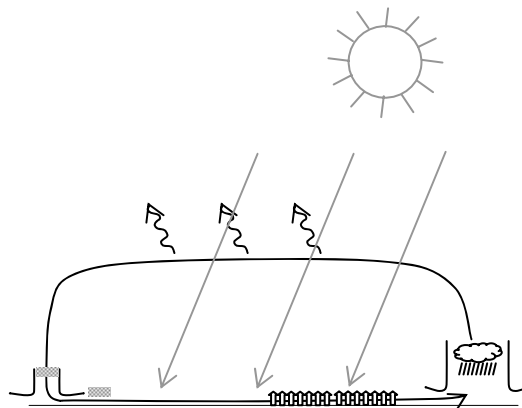
ABSTRACT

Mainly two projects are studied : a solar tower constituted from a wide circular glass collector and a 1 km high chimney, where hot air flows upwards and drives some turbines ; and a downwards tower where dry air is cooled down by the evaporation of sprayed water droplets ("energy tower"). Each of both projects is born by a competent team, but their credibility is undermined by competitors, whose publications include serious basic errors.

Some other renewable energy conversion devices, which haven't been more studied in France, have common features : research of "poor" processes (physical efficiency, materials, operating fluids), but a centralised production in order to get the benefit of scale economies.

In all cases, the economic optimisation doesn't let enough parameters vary together, and can't determine the optimal configuration. Some technical improvements are proposed for the solar tower, with the goal to be able to design a larger solar collector and a higher tower, and boost the global efficiency.

Possible effects on the global biosphere circulations are described, in order to find the most neutral or beneficent solution, e.g. a combination of energy towers and bigger towers having many common features with solar chimneys.



MATTERS

Physics (Energy conversion) and Economics

KEY-WORDS

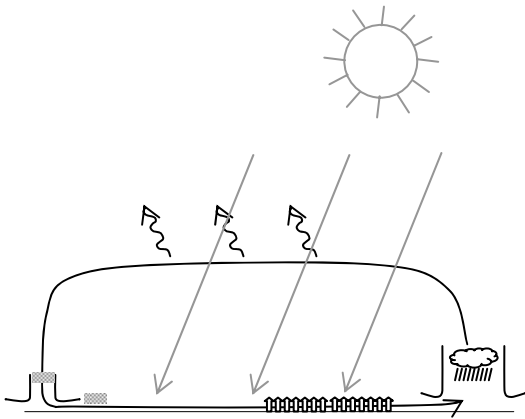
Renewable energy ; Electricity production ; Solar chimney (or tower) ; Energy tower ; Economical optimization ; Scale economies ; Atmospheric and thermohaline circulations ; Water desalination

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*Solar chimney, water spraying Energy tower, and linked renewable energy conversion devices :
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"When rain and sun
are quarrelling,
who says : "no, no, no" ?
It's the rainbow".

(From my son Damien, who was aged 4, at the time
I began to work about this subject, 5 years ago)

(His text in French :
Quand se disputent
La Pluie et le Soleil,
Qui leur dit : "Non, Non, Non" ?
C'est l'arc-en-ciel)

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Mainly two projects are studied : a solar tower constituted from a wide circular glass collector and a 1 km high chimney, where hot air flows upwards and drives some turbines ; and a downwards tower where dry air is cooled down by the evaporation of sprayed water droplets ("energy tower"). Each of both projects is born by a competent team, but their credibility is undermined by competitors, whose publications include serious basic errors.

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The technical devices it describes can't be patented, as they have been published :

- some of them through my book : "Vent artificiel, Tall is beautiful", Ed. du Cosmogone, Lyon, France, 2003,

- all of them through the French version of the present doctorate thesis, which has been officially registered, and thus copied and spread among the French university libraries,

- and of course through the present English version, which I sent to all the subject specialists I know.

SUBJECT BORDERS AND PRESENTATION

If one looks for other solar-derived energy conversion processes than the best known (photo-voltaic, wind turbines, hydroelectricity, and also concave mirrors light concentration systems), only "poorer" research areas remain.

One of them is the thermal energy of the seas (TES, conversion of the temperature difference between the ocean's bottom and surface, to generate electricity and in some cases fresh water). France is one of the leaders about it, so, as the field of this thesis is limited to what isn't much studied in France, TES isn't included in it. However, there are some similarities with the techniques which will be examined here :

- utilisation of a rather low temperature heat source (thus with a low physical efficiency),
- compensation of this drawback, through the valorisation of large quantities of free resources (ground area or thermodynamically energetic fluid volume),
- therefore centralised electricity production, including scale economies,
- interaction between the issues of electricity production and fresh water scarceness,
- the origin of the phenomenon lies in the external geophysics, considered as a thermal machine ultimately operating between a heat source (the sun) and a heat sink (the interstellar space), and also using intermediate heat sources (any material heated by the sun) and sinks (polar zones, the high atmosphere), and convection exchanges between these intermediate sources and sinks (the atmosphere's and oceans' movements).

In spite of these links with TES, the here examined technologies haven't, to my knowledge, been the subject of any recent academic publication by French-speaking authors.

And, like TES which manages to approach the economical break-even point from a heat source and a heat sink whose very low temperature difference seems to forbid any attempt in such a direction, the here studied techniques are based on seemingly unreasonable ideas :

- the most detailed one has two reasons to be described in such a way : it seems to operate without a heat sink, and a project of near half a billion euros is on its way with only one previously built prototype, which had a 17,000 times lower annual electricity production capacity.
- an other one operates by using only ambient air and water, which seems to identify it as a member of the sarcasm-drawing category of the "water engines". Because of this, I first thought that only scientists with a poor interest in the 2nd law of thermodynamics could have been bold enough to engage this research, to such an extent that we will see some problems with the 1st law ! But the idea remains a good one, and other studies about this subject are very serious.

- finally, a third technology is based on the idea of using water as a thermal insulator ! And, also here, this is not a physical nonsense, and therefore the low cost of such a material makes it potentially interesting.

These energy conversion projects will, first of all, be presented through a description of research publications ; second will come a more critical part, and, third, some proposals, improvement hints, and new researches that seem necessary. As a conclusion, some aspects of their technical and economical environment (access to the final consumers, etc.) will be discussed.

I PRESENTATION OF EXISTING PROJECTS AND RESEARCHES

I.A The Australian solar chimney project

I.A.1 General principles

The solar chimneys principle is simple : the sun heats the ground under a canopy ("collector") ; this heat is given to passing air, which expands ; going into a hollow tower, it obeys the buoyancy principle : "hot air rises", and by the way it can drive one or several turbines in order to produce electricity.

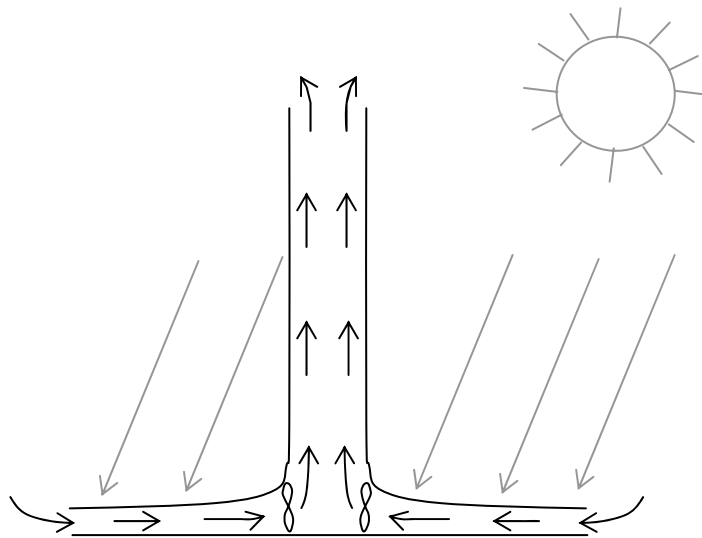


figure 1

From 1982 to 1989, a solar chimney prototype operated in Manzanares (Spain, 150 km south from Madrid), from the impulse of German scientists and funds. This prototype had a 200 m high tower and a 45,000 m² collector, and reached a 44 MWh/y production, with a 50 kW¹ peak power. The two-part "Solar Chimneys" article¹ gives a good idea of its promoters' reflection and expectations at its building time.

¹ i.e. the equivalent of 880 peak power hours per year, which is only 10 % of the total annual number of hours. We'll come back further to this ratio's strange low value.

Among these scientists, is an architect, Jörg Schlaich, who published, in German in 1994 and in English in 1995, "The solar Chimney : Electricity from the sun"ⁱⁱ, a reference book even if its aim was mainly popularization, and which is the basis of a large part of what follows here. Three sizes are discussed : ①, a 5 MW nominal power for a 445 m high tower, a 13.9 GWh annual production and a 5800 €/kW cost ; ②, 30 MW for 750 m and 87.4 GWh/y ; ③, 100 MW for 950 m, 305 GWh/y and 3000 €/kW (600 million DM) of construction costs.

For the highest one, the thermodynamic efficiency is about 1%², which, in Jörg Schlaich's mind, is not a great problem as soon as we are in a desert and the economical efficiency is not too bad, especially if the temporal horizon is far enough. The solar chimneys could be qualified as "the poor man's solar energy" (more precisely, the urban poor) : on purpose, the chosen technologies are not very sophisticated, so that they can easily be implemented by the developing countries themselves.

On the basis of this book, a private society, Enviromission, was set up. In August 2002, the Australian ministry of industry approved a project of a 1000 m high tower and a 7 km diameter solar collector³. The 200 MW power is enough to provide a 200 000 people town with electricity. The inner air will be 30 ° warmer than the ambient air and its velocity should be at least 15 m/s inside the tower.

Various newspapers announced the Australian governmental approval by the end of August and during the fall 2002. Much information can be found on the internet sites enviromission.com.au and sbp.de, notably the annual electricity production, i.e. 750 GWh, or 17,000 times more than for the Manzanares prototype. 800 million Australian \$ (441 M€ at that time) are to be spent for the investment (2200 €/kW). From this, the kWh price can be estimated around 6 euro cents⁴, under realistic financial conditions (depreciation period, interest rate)⁵.

From this prototype to the present project, with the intermediate steps of the various options which are described in "The solar Chimney", the power is considerably increasing, without any new prototype. Why ?

² This efficiency is calculated with respect to the incident solar power which, at midday and in the sunniest regions, is classically about 1000 W/m². As we'll see later with more details, this 1% is the result of a 3% theoretical efficiency (proportional to the tower height) and of various losses (light reflection and reemission by the collector, thermal losses, air turbulence, losses in the turbo-alternator).

³ Slightly older documents show a 5 km diameter, but with the same peak power (200 MW). The tower's diameter has a comparable uncertainty : 160 m today, 130 m previously.

⁴ This price is not far from the wind turbines power cost (and its government-fixed sale price in Europe), which is one of the cheapest "new" energies. However, this price remains around twice the nuclear or fossil electricity's. This isn't enough to exactly appreciate its competitiveness with respect to fossil fuels (including uranium) plants, because we must take into account the transport conditions, the grid connection, how well the supply matches the peak hours, etc., but such figures show that competitiveness is not out of reach.

⁵ "The solar Chimney" (page 44) announces 0.18 DM/kWh, i.e. 0.09 €/kWh, for a 100 MW tower, a 40 years depreciation period and a 8 % nominal interest rate. To extrapolate it to the 200 MW project, we must multiply this figure by (441 M€ / 750 GWh) / (600 millions DM / 305 GWh), i.e. 0.6.

A first reason is that, even if some of the physical principles underlying this project are complex (turbulent fluid mechanics), there should not remain big surprises (and, if any, a positive one), as the changes in sizes don't lead to changes in the nature of the phenomena. The important thing is that, apparently, the prototype has effectively delivered the information it was designed to give. And models built with precision and common sense can predict rather correctly the behaviour of such structures.

But, overall, there exists a strong rationale for this unique leap, as the solar chimney profits by scale economies (Cf. the kW costs fall, shown by the previously quoted figures) in its very principle.

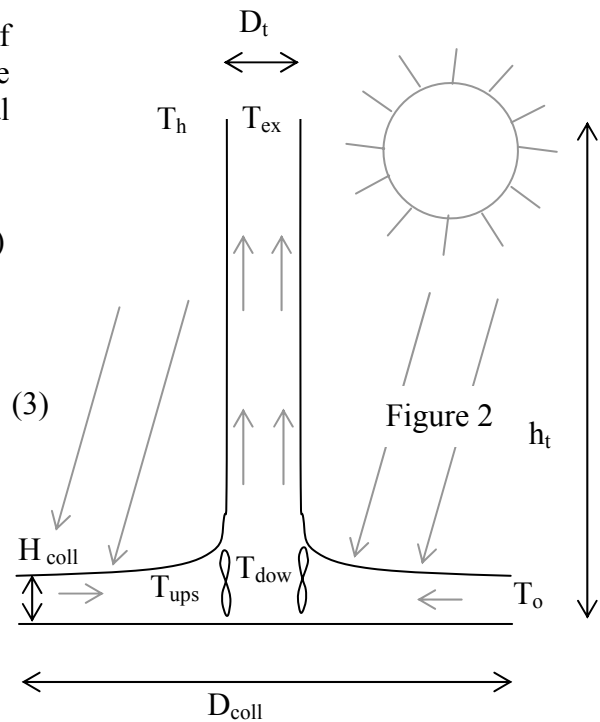
Indeed, from a thermodynamic analysis of figure 2 aside, and under some hypotheses, it can be proved (Cf. Appendix 1) that the tower's theoretical efficiency is equal to :

$$\eta = 1 - (T_{\text{ex}}/T_{\text{ups}}) \quad (1) \quad \text{with} \quad T_{\text{ex}} = T_{\text{dow}} - \lambda h_t \quad (2)$$

where :

$$\lambda = \frac{gM}{(7/2)R} = \frac{9.81 \text{ m/s}^2 * 0.029 \text{ kg/mol}}{8.32 \text{ J/mol.K} * (7/2)} \approx 10^\circ/\text{km} \quad (3)$$

provided that the outer air's temperature should also obey the adiabatic lapse rate law : $T = \text{cte} - \lambda z$. It isn't impossible, but the temperature gradient is often lower than $10^\circ/\text{km}$, which reduces the solar chimney's efficiency (and the lower $T_{\text{ups}} - T_o$ is, the more η is reduced).



This maximum theoretical efficiency, $\eta = 1 - (T_s/T_{\text{am}})$, is equal to the Carnot's efficiency⁶ which we'd get with a thermal machine whose heat source would be at the collector heated air temperature, upstream of the turbine, and whose heat sink would be at the temperature of the same air when it goes out of the tower (and not the one of the ambient air at zero altitude).

It can also be found that $\eta = \lambda h_t / T_o$ (4) . The tower's efficiency is

proportional (\propto) to its height, therefore the power output is : $P_{\text{elec}} \propto h_t \cdot D_{\text{coll}}^2$ (5) .

⁶ For a thermal engine receiving heat from a heat source at a T_{source} temperature (in $^\circ\text{K}$) and being cooled by a heat sink T_{sink} , the maximum efficiency (the electricity which is produced, divided by the heat given by the heat source) is, by compliance to the 2nd law of thermodynamics, equal to $(T_{\text{source}} - T_{\text{sink}})/T_{\text{source}}$: it is Carnot's efficiency. The lower irreversibility causes we endure (non-perfect heat or electricity conduction, friction, air turbulence, mixing of fluids with different temperatures, etc.), the closer we can get from this theoretical limit.

Also in appendix 1, it is demonstrated that under two more conditions, this result remains true even if we take into account the mechanical losses resulting from the air turbulent friction under the collector and inside the tower. These two conditions are :

$$D_t \propto D_{\text{coll}}^{0.8} \quad (6) \quad \text{and} \quad H_{\text{coll}} \propto D_{\text{coll}} \cdot h_t^{-1/3} \quad (7).$$

So, the quantity of electricity that the tower can produce is, in 1st approximation⁷, both proportional to the sunny area and to the tower's height. But, on the contrary, its cost is the sum of a part which is only proportional to the area, and of another which varies only with respect to the height (more than proportionally, but it will be taken into account). Assume that when doubling the tower height, we multiply the cost by n . Then we can multiply the collector's area⁸, and therefore its cost, by n . Of course, the cost of the whole lot will be multiplied by n as well. But the production is multiplied by $2n$. Therefore, we divide the price of each kWh by 2 !

Said differently, each tower additional metre enhances the collector's financial yield ; and each collector additional m² enhances the tower's yield ! Such a win-win cycle is an incentive to go on, and to target ever larger and higher sizes, hoping to reach what is, in the field of renewable energies, the Holy Grail : competitiveness, by comparison with fossil fuels.

I.A.2 The resources and the selling market

This solar chimney project's goal is to substitute all the fossil energy sources (including uranium) of centralized electricity production (photovoltaic solar energy remains the best solution to bring power to isolated villages without paying for a grid connection).

Clearly, like all the projects based on the same idea of a low physical efficiency but a high economical efficiency, this can be realized only in deserts, first because land has quite no value, and also because solar light is most abundant and regular there.

At a first stage, solar chimneys could bring to the neighbouring developing countries the low cost energy their development requires, without increasing worldwide greenhouse effect gases emissions. The simplicity of the used materials and techniques, could help them to build the towers and collectors by themselves, without jeopardizing their trade accounts.

⁷ Cf. the problem of the temperature lapse rate outside the tower.

⁸ To be perfectly precise, we should then considerer that more air will have to pass through the tower, therefore that its diameter must be wider, and that its cost will be multiplied more than by n . However, from a general point of view, the result won't be very different.

Later, and if energy transport costs aren't too high, they might export electricity to developed country, most of them having no deserts near them. Such an export prospect may be based, either on high tension (maybe direct current) electricity transport, or on more ambitious but yet uncertain techniques (hydrogen or aluminium electrolysis, without excluding the hope of a new unexpected breakthrough in relatively high temperature supra-conduction, which might benefit from the same scale economies as the solar chimneys).

About 700,000 km² (a circle with a 950 km diameter) of Saharan desert could supply Europe ; for the U.S.A., about one million km² should be found near the New and old Mexicos ; China and Japan would depend on the deserts north of Tibet ; as a lot, for the whole world, the equivalent of a circle, 2000 km in diameter, would be necessary.

The project to be realized in Australia in the next years is sort of a 2nd prototype, more than 20 years after the Spanish one. Anyway, it didn't appear by chance : it is based on some advantages and artfulness, which will now be briefly described.

I.A.3 The materials used to produce "industrial wind"

The first advantages, which offset the gigantism drawback, are the principles simplicity (Jörg Schlaich presents them as the gathering and adaptation of three classical technologies : the greenhouse, the chimney and the windmill), and the materials low cost. In addition to sun light, quasi-free "input" which is naturally the basis of the system, the project requires :

- glass, and possibly polycarbonate, materials that the truck farmers and gardeners use to build greenhouses, and which are used here in the same goal,
- reinforced concrete to build the tower, as for nuclear plants cooling towers (it could have been steel),
- water and plastic, for heat storage from day to night,
- air, as the operating fluid, and nothing, as a cooling fluid, as previously noticed.

The choice of glass for the collector may seem strange, because of its weight and apparent brittleness. It has indeed important advantages : it resists very well to wear, especially as far as transparency, which is a main parameter for a light collector, is concerned (at the time of the prototype, there existed no plastic able to resist so well). Set on posts arranged in a rigid array with cables tightened from one top to another, it resists also very well to bad weather. And, to cover hundreds or thousands of km² in a sand desert, we could think about producing it on the spot.

In the current Australian project, glass might be partially substituted by polycarbonate, a material recently appeared for greenhouses. But, at the collector centre, where the air temperature may reach 80 °C, glass could be kept, because it is a more efficient shield against infrared reemission towards the sky.

The air flow must be converted to electric power by turbines, a well-established technology. Here, there is a necessary question : in their principle, these turbines don't seem very different from the "naked" wind turbines which are already very successful for converting natural wind to renewable electricity. If a wind turbine is quite the same thing as a solar chimney from which we'd remove the collector and the tower, this is an idea for cost reduction !

However, there are important differences justifying the collector's and the tower's usefulness. First, the air flow which is created here is much more regular than the natural wind. This is useful to avoid calm weather and zero-kW production risk, but also the storms which oblige wind turbines to be designed so that to endure very severe stresses.

Besides, wind energy favourable locations without Nimby syndrome become rarer and rarer, so that most of its future developments could come from costly offshore facilities. And, to satisfy mankind's energy needs, it would be necessary to exploit wind energy all around our planet. Solar energy is much more abundant, even with a 1 % efficiency.

And finally, if we intend to use a wind turbine to catch the greatest part of the wind's energy by strongly opposing to its passing through, it will simply bypass the turbine ! That's why wind turbines only have thin blades, often three, even two, which allow the wind a large through-passing. The same reason explains that they rotate with majesty, i.e. rather slowly, which is a good thing for the wind's energy harvesting efficiency, but isn't very economic for the following conversions.

A low speed near the axis indeed lessens the alternator's efficiency. Thus, it is necessary to have a gearing box, in order to increase the number of rotations per minute. But the cogs of the first gears, which have to transmit a great power under a low speed, are submitted to very high forces, and this has an important cost.

For the solar chimney's turbines, it's the opposite : the wind can't bypass them, so it is possible to design blades opposing it frontally and efficiently. Such a design let them rotate rapidly : 105 rotations per minute in spite of a 10 m radius for the 100 MW tower described in "The solar Chimney". Then, no gear is needed, the alternator rotates at the same speed, and there is no great problem for the conversion into electricity.

In the same book, the turbines cost was important, and, moreover, didn't seem to benefit from scale economies. For the 100 MW tower, the mechanical components represented 26.6 % of the total cost, and, as the tower and the collector mutually lower their costs, the turbines are at a risk to account for a larger, and difficult to reduce, part.

However, we can read that "costs for the mechanical components were estimated very high, between 1600 and 2000 DM/kW, in other words the same as current wind power stations exposed to ambient, gusty wind conditions". It seems that, since 1995, a data research more directly focused on adequate turbines for solar chimneys, helped come back to more reasonable costs, which probably explains a great part of the drop in the kW global cost, that I noticed in page 3.

I.A.4 The egg and the bicycle wheel

As Jörg Schlaich, who is an architect, wrote in "The Solar Chimney", "chimneys 1000 m high can be built without difficulty ... serious plans are being made for 2000 metre skyscrapers in earthquake-ridden Japan. But all that is needed for a solar chimney is a simple, large diameter hollow cylinder, not particularly slender, and subject to very few demands in comparison with inhabited buildings."

The 1 km high tower will be constituted by concrete walls, 25 cm thick for all their upper half, and thicker at their bottom. This is, at the same time, much, because the whole tower will be heavy (about 1 million tons), compared to possible alternative solutions which will be discussed further, but also relatively few with respect to the tower diameter : 160 m. Hence, the question is : how do we know that it will resist various stresses ?

25 cm compared to 160 m, is like an egg shell, and it is indeed an egg shell, if we consider that when a pressure, even a strong one, is exerted all around an egg, it resists surprisingly well, and doesn't collapse. It's the same here : the aspiration created by the tower in order to drive the turbines means that there is a low pressure inside, with respect to the ambient air. This outer air compresses the tower, but, as it has the shape of a cylinder with a constant curvature, this pressure spreads regularly into the whole wall, which resists very well.

But this pressure is no longer uniform when the wind is blowing, and the cylinder could oval, which, in the long run, could damage the concrete. Here comes the bicycle wheel.

A cyclist's weight is supported by the saddle, the pedal, and, eventually, the frame. What is the frame put over ? The hubs. And them ? At first glance, they stand on the road, through the spokes which, one after another, take place between the hubs and the ground. But it is clear that bicycle spokes, fixed vertically on the ground, are too thin to support a bicycle, not to speak of the cyclist himself : they would buckle (any aside shift of a spoke element enables the hub to obey the gravity, and this generates an instability : even if the first shift was very small, the gravity gives it a positive retroaction, so it will be amplified, and the spoke will buckle). So, the hubs don't stand on the spokes located just under them.

But this buckling disappears if an element is submitted to tension. If a mass is hanging to a cable, the same aside shift of a cable element would raise the mass upwards, contrarily to the gravity. Therefore, there will be a negative retroaction, and the cable's linear shape is stable.

If a hub doesn't stand on the spokes under it, it may hang to the spokes over it, which should themselves hang to the part of the rim which, at this time, is just under the mudguard.

And this rim, how does it transmit the cyclist's weight to the road ? Of course, it is thicker than the spokes, but the cyclist is heavy, so it could oval, at least a little. Here come all the other spokes we haven't talked about, which are oblique, and horizontal, forward or backward. They all work in tension, to prevent any diameter of the rim from being longer than twice a radius. Then, the rim is obliged, by the tension of most of its spokes, to keep its perfect circular shape. In fact, to help us to stay on our bicycle, all the spokes work, except those situated between the hub and the ground.

Jörg Schlaich uses the same principle to prevent his 1 km tower from ovaling. But radial cables directly drawing the concrete could damage it. Therefore, he puts rims inside it, stiffened by their spokes, and which will oppose any ovaling of the vertical cylinder, due to the wind.

This is a very interesting idea, which probably enables us to trust the computer models used to determine the tower's parameters. Of course, they have a reasonable security interval : from "The solar Chimney", published in 1995, to a 1999 articleⁱⁱⁱ describing more precisely this bicycle wheel spokes principle, the upper walls thickness has increased from 16 to 25 cm (this latter value is also used for the current Australian project).

Only this upper part has such a low thickness. At its base, the wall becomes thicker, until one metre. Three reasons can explain this : thick walls may be necessary to support the weight of all the concrete above them ; it's useful to make the base heavier to help the tower resist the wind, whose stopping creates a pressure to be multiplied by a 160,000 m² area (the problem of its stiffness has been solved, but not the question of the tower falling aside in one piece) ; and the danger of earthquakes is also stressed in "The solar Chimney"⁹.

I.A.5 Current state of the reflection about the collector operating

A solar chimney collector efficiency is lower than 100 % because it loses part of its energy :

- by direct light reflection on its transparent canopy. This reflection varies with the number of dioptries (2 for single glazing, 4 for double glazing), the refractive index (higher for glass than for polycarbonate), and the incidence angle¹⁰ ;

- by immediate reemission by the ground (or dust lying over the collector itself), which would be equal to zero if it were perfectly black, equal to 100 % if it were perfectly white, and intermediate with respect of the darkening effort we agree to make ;

- by conduction : the collector's warm air transmits its heat to the glass which transmits it to the free air above ;

- by conduction within the ground. In the long run, the ground will get warmer because of this and of the geothermal heat flow, and this phenomenon will disappear, or even get inverted. But in the short run, it could lead to underestimated collector efficiency measures by comparison to the long run value ;

⁹ The need to reinforce the walls because the inner pressure is lower than the outer air's, proves negligible by comparison with these three points.

¹⁰ But, even for glass, for the first 45 degrees, the reflection ratio is remarkably stable, because with one polarization the reflection begins with a decrease and will have a zero, which compensates the growth of the reflection by the perpendicular polarization.

- by infrared reemission : the ground, for the part of its behaviour which obeys the black body's theory, emits infrared radiation. The warmer it is, the closer their wavelength will be, with the higher cumulated intensity (T^4 Wien's law). As for a greenhouse, a large part of these infrareds will be absorbed by the glass and a half will be reemitted downwards, but this must be combined with the previous point (conduction), which explains why double glazing are interesting.

Even if not conceptually very complex, a precise modelling of all of these phenomena requires a methodical organisation. The thermal interaction between the air (the operating fluid), and the parts of the collector which have to communicate their heat to it, varies as the air moves from the collector's periphery (where it is still cool and moves slowly) to its centre (where it is warmer and where its convergence movement accelerates). A very recent article^{iv} gives a good example of such a model, synthesized by the figure 3 below :

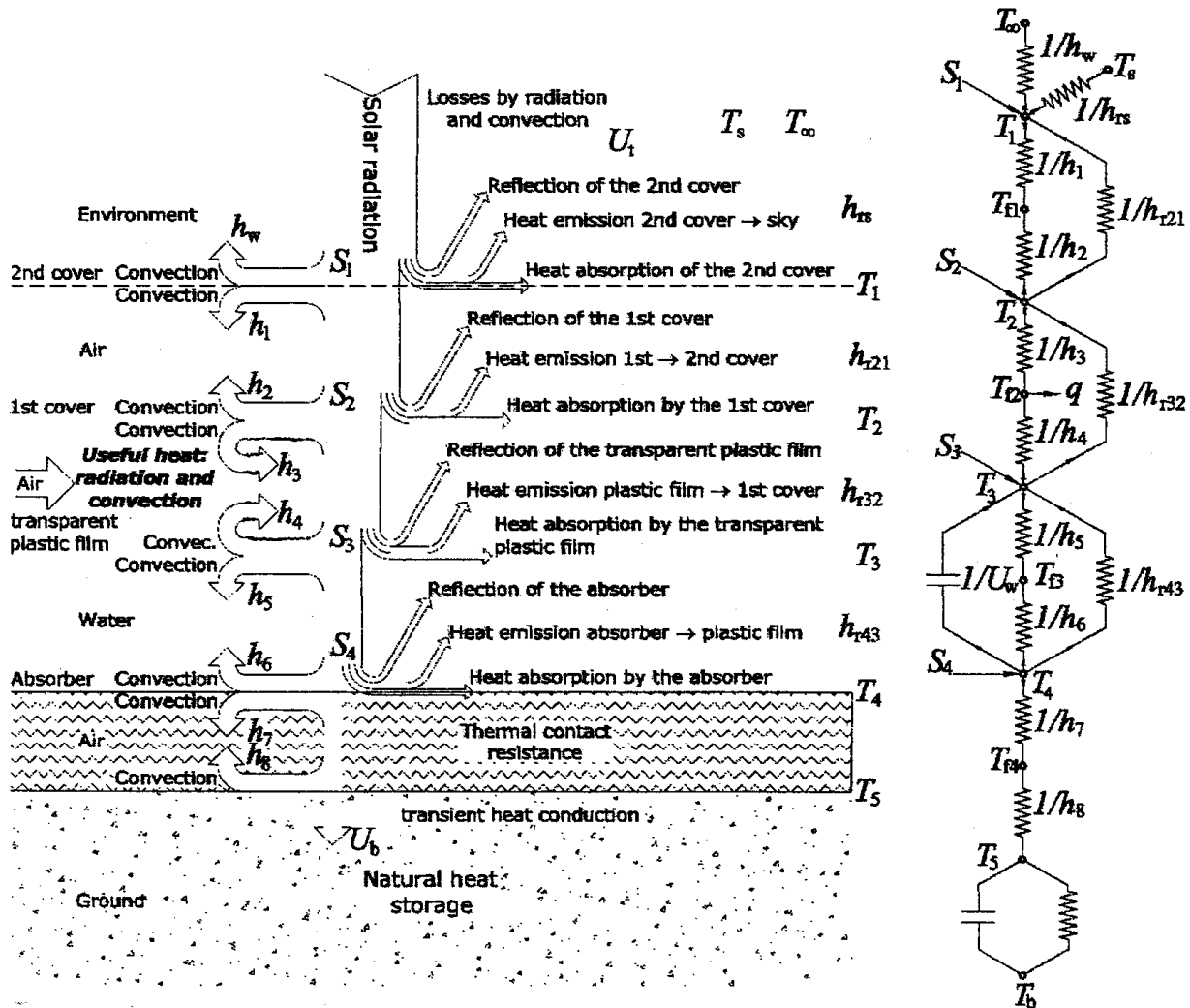


Fig. 3. Thermal network for the collector of solar chimneys.

This is a "maximum" model, as we've got at the same time a double glazing (the "2nd cover" and "1st cover" layers to which the subscripts ₁ and ₂ refer), a heat storage ("water" layer, the notions of storage and therefore of thermal inertia lie in the electrical symbol of a condenser - or "capacity", U_w) on the right hand diagram ; and even an insulating air layer between this water layer and the ground. Of course, if we want to study the behaviour of a more simple facility, we just have to eliminate the exceeding elements.

The right hand diagram is useful for a good analysis : being constructed in analogy with the electrical notions of resistance and capacity, it allows us to verify rather simply whether we forget anything, and which are the model's underlying hypotheses (notably of linearity) ; it helps to write down relations between heat flows (analogous to the intensity I) and temperature differences (analogues of the potential difference ΔV , or voltage U) between two knots of the network, so it is useful to set up a system of n equations in n unknowns (whose right hand members are in particular the heat converted light flows, S_1 to S_4), and to solve it by constituting a $n \times n$ matrix, letting a computer invert it, and multiplying the right hand $n \times 1$ matrix with this inverted $n \times n$ matrix. That's in fact what the authors do.

The older documents bore much less details. Although, since the beginning, the heat losses towards the ground (maybe responsible for part of the low electrical production in Manzanares) had been considered as a "long run heat storage", the idea of a water heat storage, enabling a night use of a daily collected heat, hadn't been mentioned even in the book "The Solar Chimney" ⁱⁱ, and appeared only in the 1999 article, "Tension structures for solar electricity generation" ⁱⁱⁱ.

However, a thorough reflection about the thermal exchanges had already taken place. This book indicated that the temperature rise between the collector's inlet and outlet should increase for more powerful towers (25.6° for 5 MW, 31° for 30 MW, 35.7° for 100 MW)¹¹, leading to a decrease in the collector's annual mean efficiency (respectively 56.24 ; 54.72 and 52.62 %). A higher temperature when the power increases can indeed be justified :

- because the outer air temperature frequently diminishes more slowly with respect to the altitude than the inner air temperature¹², and this reduces the inner air buoyancy, and hence the power output ; thus, as the higher the tower is, the more important this effect is, it is preferable to have in this case a large initial temperature gap, so that a greater part remains at the tower top ;

- because, for the same power, it allows the air to move slower in the collector and thus to avoid mechanical losses as its glass roof already reaches a height which might be difficult to increase (20 m at the centre for the 100 MW tower).

¹¹ It shows an evolution from the first ideas. We could read in the 1983 Haaf and alii article ⁱ : "there is an upper limit of temperature increase, above which there is no point in increasing the size of the collector, as the losses due to radiation, convection and friction then become excessive. This limit is $\Delta T_1 = 12 - 15$ K."

¹² That's why, in the first presentation of the scale economies which lies page 4, as well as for the energy towers 12 % ratio (formula 9, page 15), I write each time that my reasoning is only a 1st approximation, and must be checked against more detailed calculations.

Part of the modelling which is done further (notably in appendix 3) to evaluate the hypothesis of even higher towers, could have been based on the extrapolation of these evolutions, or on a liberty of speed control under the only condition that the thermal efficiency should keep on decreasing with respect to the air temperature ; however, to be prudent, in particular because infrared radiation losses grow very rapidly with respect to the temperature (the black body T^4 Wien's law), the figures for the 100 MW (950 m high) have been kept. And the announcement that the temperature rise in the Australian tower would be only 30 °, confirms such a prudence.

The Australian project, as it has been presented in 2002, includes a non negligible component of nightly electricity production. Part of the daily stored heat is easily given back to the even more cooler air which comes into the collector by night¹³. Such an idea was much less developed in "The solar Chimney". Indeed, with a power (200 MW) which is only twice than for the book's highest tower, the electricity production is multiplied by nearly 2.5 (750 GWh / 305). This enables to get a higher economical return from the tower, and thus to lower its part of the kWh cost¹⁴.

A 24 h quasi-constant power was even thought about in the 1999 articleⁱⁱⁱ, which explains that in order to store the daily received heat with a high efficiency and a low cost, it is possible to lay water-filled black plastic bags on the ground. The water is heated during the day, and gives its heat back to the cold neighbouring nightly moving air.

I.B The "Energy Towers"

Meteorologists, notably Israelis, have noticed that negatively buoyant air was sometimes "falling" from the sky, because it had been cooled down by the vaporisation of some rain coming from a cloud above it^v. After Ph. Carlson who, in 1975, issued a patent about this principle on behalf of the Lockheed company, these meteorologists, and a lot of scientists of the Technion Institute, in Haifa, drew from this a project of a turbines tower, producing renewable energy, but without a solar light collector : the idea is to put instead, at the tower's top, a water droplets spraying device, in order to mimic this natural phenomenon.

¹³ We could wonder whether this would happen with a higher efficiency than during the day, as the temperature difference between the incoming air and the collector's ground is at its maximum. However, as we saw it in formula (1), page 4, the efficiency doesn't vary as a function of *this* temperature difference, but of the difference between the inner air at the tower bottom, and the same air as it goes out from the same tower's top.

¹⁴ but not necessarily to enhance in the same proportions its global competitiveness. In the case of a coexistence with nuclear power, which can easily produce electricity by night, it is rather useless to produce solar energy at the same time. On the contrary, in a 100 % solar economy, being able to produce electricity even when the sun is hidden, would be a valuable asset.

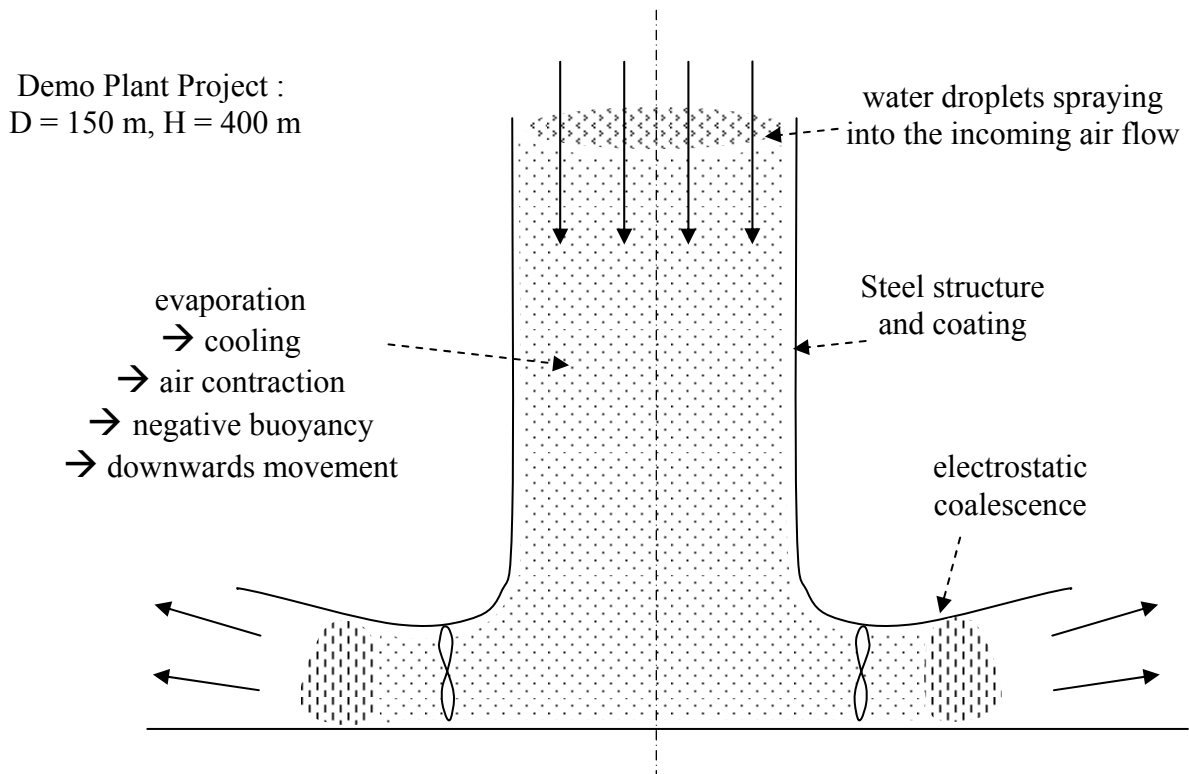


Figure 4

I.B.1 Air temperature decrease potential

The behaviour of a mix of air (either saturated by steam or not) and liquid water is well known. Therefore, the details of the following results are given in appendix 2. It is possible to work with diagrams like the following one, where we have :

- the exponential which results from Clapeyron's equation integration, and gives the saturating steam pressure with respect to the temperature.

- a line segment (arrow) which shows how the air gives the vaporisation latent heat. Evaporating a little quantity of water is enough to get a large temperature decrease, therefore this arrow's slope is low.

The temperature fall potential is equal to the abscissa decrease we get by following this arrow until it intersects the exponential.

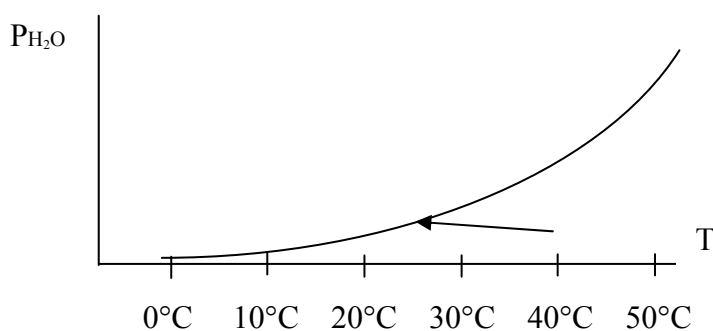


figure 5

If we want to cool a warm and partially moist air, the temperature we get is approximately the one at which the already present steam becomes saturating. And 10 or 12° are needed to multiply the saturating pressure by 2. Therefore, with a 50 % relative humidity, the temperature can fall, at best, by 12° ; with 25 %, by 24° ; etc..

If we want to cool down an air already so cold that Clapeyron's curve has a lower slope than the line we try to intersect, the cooling is much less efficient, and becomes twice more difficult each time we want to reach a 10° lower temperature. The limit between these two first cases lies around $T \approx 284\text{K}$, i.e. 11° C (Cf. Appendix 2, p. 143).

And if we want to cool down a warm and dry air, we get a large temperature fall which analyses first as in the 1st case above and, when the temperature gets lower, looks more like the 2nd.

These towers operate efficiently only if the air has enough temperature decrease potential, i.e. if it is warm and dry enough, hence only when the sun has risen enough. Therefore, we can ask the same question as for solar chimneys : wouldn't it be a better idea to remove the tower and the sprayers, and get the same result with natural wind ? But, another time, the same arguments can advocate the existence of a tower : the wind is more even, the turbine rotation is quicker and more powerful because the wind can't bypass it.

I.B.2 First theoretical feasibility ratio

To use this air's negative buoyancy, it must be generated at a rather high altitude, therefore we must pump large quantities of water up to considerable heights. Are we sure, at least from a theoretical point of view, that we won't spend more energy to pump the water up, than what we'll get back from the turbines ?

To calculate the corresponding ratio, we look for the negative buoyancy created by the vaporisation of one mole of water. It generates a cooling which equals, in Joules, to the vaporisation latent heat, L . If n air moles undergo this cooling, their enthalpy $H = 7nRT/2$ decreases by L , hence their Kelvin temperature T falls by $2L/7nR$.

Thus, as a percentage, T diminishes by $2L/7nRT$. As the air density is inversely proportional to T , the generated negative buoyancy equals, as a first approximation, this ratio $2L/7nRT$ multiplied by the air's weight, whose mass is, in grams, $29n$ (as the air's molar mass is around 29). This product of $2L/7nRT$ by $29n$ yields¹⁵ $29L/3.5RT$.

¹⁵ Simplification by n . Therefore, the result doesn't vary as a function of n : the ratio we're looking for will be the same if the water's vaporisation sharply cools down a little quantity of air, or slightly cools down a lot of air.

We get this weight's work, along a height h , by multiplying this "negative buoyancy mass" by the gravity acceleration g , and by h , but it is the same for the mole of water we pump up to the same height in the same gravity field. So, the ratio we look for will simply be got by dividing 18 grams (mass of the considered water mole) by the "negative buoyancy mass" we've just calculated :

$$\text{Ratio}_{\text{water pumping up energy / theoretical power output}} = 18 / (29L / 3.5.RT) \quad (8)$$

But Clapeyron's equation tells us that RT^2/L is equal to δT , i.e. the temperature difference for which the neperian logarithm of the maximum steam concentration in the air varies by 1, i.e. this saturating vapour concentration is multiplied by e ; δT is around 17° .

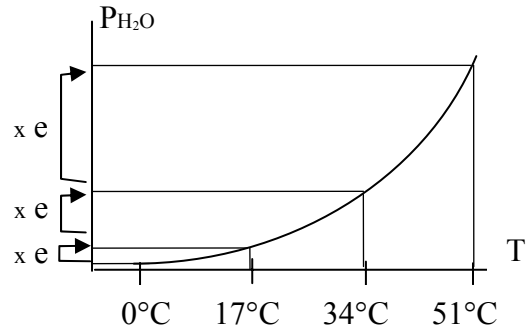


Figure 6

Thus, we finally get :

$$\begin{aligned} \text{Ratio}_{\text{water pumping up energy / theoretical power output}} \\ \approx (18 \text{ g} / 29 \text{ g}) \times 3.5 \times \delta T / T \approx (18 / 29) \times 3.5 \times 17 / 300 \approx 0.12 = 12 \% \quad (9) \end{aligned}$$

This ratio is widely lower than 1, so there is indeed a theoretical possibility to produce electricity from this principle.

I.B.3 The available resource

As for hydroelectric or wind energies, the electricity we could produce in an "energy tower" comes only indirectly from solar energy. It must only be a (more or less whether we're connected in parallel, in series in the same direction, or in series but in opposition) prudent taking off from a little pipe of the big thermal machine which is the biosphere as a whole, and which, at its level, is directly fed by the sun.

Therefore, we must wonder whether the available resource is limited. From a practical point of view, this question is about the water, especially if we must convey hundreds of thousands of m^3/s to the very centre of a desert. But, from a theoretical point of view, the resource is mainly dry air. It comes from the cycle which is known as Hadley's cell : some humid (equatorial or temperate) air loses its steam, as it rains, when it's cooled down during its travel towards high altitudes. Being dried, it migrates towards the tropical deserts, where it gets down, and therefore warms up. At that time, it is in a state where its steam concentration is widely lower than if it were saturated. It is then possible to operate energy towers.

From the rain quantity which creates this flow, we can estimate¹⁶ that about 1 or 2 10^{18} m³/y of dry air are produced in the high atmosphere and can be redistributed onto the subtropical deserts. The mean (night and day) corresponding electrical power is about some 10^4 GW.

To get the same power from a solar tower, from a mean light flow around 250 W/m², and an efficiency about 1 %, we'd need about 10^7 km². But, according to "The solar Chimney", the world's primary energy demand could be satisfied, from the same solar data, with only about $3 \cdot 10^6$ km². Therefore, the energy towers resources are higher than what would be required.

A comparable evaluation is given by this project's promoters, in a document^{vi} which is the present best basis for the possible decision to build a first demo plant.

This paper gives an estimate for the heat carried by Hadley's cells on the whole planet : between 2 and 4 10^{16} kWh/y, corresponding to a 1 cm/s mean downwards air velocity. With a 1 % efficiency for 1000 m high towers¹⁷, it yields a possible production of 2 or 4 10^{14} kWh/y (i.e. a mean value between 2 and 4 10^{13} W, in the same range than the previously calculated "some 10^4 GW"). Then, the authors divide this result by a figure of 5000 kWh/y corresponding to the energy which should be available to any human being, and this shows that the resource could be sufficient for 40 or 80 billion people.

However, although the air movements we get would rather reinforce, and not destabilise, the current atmospheric circulation, it would be prudent to exploit only part of this potential. So, we can't exclude the idea that it should be complementary with other sources of renewable electricity, even if they are more expensive.

I.B.4 The disposal of the salt dust the energy towers would produce

Direct water spraying into the air flow, resulting in a fog escaping from the facility, doesn't seem very environment-friendly : the fresh water is often scarce where the air is warm and dry enough for energy towers to have a good efficiency ; but using sea water would result in letting out into the environment, in large quantities, a salted fog which would soon be transformed by the sun's action into a rather irritant mix of air and tiny salt crystals (6.7 kg per electrical net kWh).

¹⁶ Take the equatorial zone as a 2,500 km wide and 40,000 km long strip, whose area would be 10^8 km² ; with a mean 2m/y annual rainfall, the corresponding water quantity is $2 \cdot 10^{14}$ m³/y. With a steam concentration equal to 10 g per air m³ (the same that the tower's top water sprayers can re-create), the relevant air volume is 10^{19} m³/y. Assuming that 5 % to 10 % are efficiently redistributed over tropical zones where towers could be built (and neglecting the dry air masses coming from the temperate zone), this yields 1 to 2 times 10^{18} m³/y, or, in m³/s, the same figure divided by $10^{7.5}$. If each m³ is cooled down, thanks to the water droplets vaporisation, by $12^\circ = 4\%$ of its Kelvin temperature, the created negative buoyancy will be equivalent to 4 % of its weight, which is about 12,5 N. These 0.5 N are to be multiplied by an approximately 1000 m downwards move, which yields, for each m³, 500 J of electricity convertible work. Therefore, the 1 or 2 $\cdot 10^{10.5}$ m³/s yield 1.5 or $3 \cdot 10^{13}$ J/s. This is, as announced, "some 10^4 GW". Divided by 1 % of 250 W/m², it is equivalent to 10^{13} m², or, as written, "about 10^7 km²".

¹⁷ It is the same figure as for solar chimneys, and this is not by chance : we start from the same maximum theoretical efficiency, i.e. 3 %, and we keep finally about one third of it because of various losses (up to 2/3 as we mainly look for an economical optimum rather than a physical theoretical one).

The project's promoters seem to have solved this problem. Their presentation paper^{vi} isn't very much detailed : it only mentions the words "enhanced coalescence". Coalescence is the phenomenon which occurs when little water droplets collide and result in one bigger drop. As it is heavier, it will then "fall" faster in the ambient air, and will meet other droplets on its way down. It will become a real rain drop, and eventually reach the ground.

What does "enhanced" mean ? It is a process, known in other industries, which consists in giving electrostatic charges to some droplets, in order to modify their relative movement to the other droplets, and generate the coalescence. An French company engineer has eye-witnessed it and says that an experiment in a 12 m high tower is rather convincing.

These towers would then reject sort of a cool and humid sea air. If it's mainly sea air, i.e. if, for example, the coalescence stops only 99 % of the salt, then we could have non negligible settlings : for a final goal of $3 \cdot 10^{13}$ kWh/y (Cf. previous page), 2 billion tons of salt each year. But if the "cool and humid" characteristics overcame this drawback, then it could be a useful help for irrigation which develops in some deserts, even very dry ones, and which generates a great evapotranspiration.

I.B.5 Possibility to operate near the maximum power point (mpp)

Knowing that we don't need first to collect the solar energy, so we're no longer dependent from an input we have to manage with economy (in the case of a solar chimney, we had to beware of the thermodynamic efficiency, i.e. the power output divided by the incoming solar energy ; for example, letting too large air flows move in the system, 1st, would rise the friction losses, and, 2nd, is rather useless, as we're anyway limited by the global efficiency, $\eta = \lambda h_t / T_o$, (4), page 4).

For energy towers, we can turn over the whole argumentation within the brackets : for a given tower, making it most profitable means producing the highest possible power, without any regard to its physical efficiency : we'd rather have 1 million m³/s pass through it with only a 50 % mechanical efficiency (38 % will remain after having subtracted the 12 % corresponding to the water pumping up), than 100 000 m³/s with a brilliant 90 % mechanical efficiency : $0.38 \times 1\,000\,000 > 0.78 \times 100\,000$. Such a reasoning is the maximum power point (mpp) theory.

It is detailed in the Indian-Israeli document which has already been quoted^{vi}. The authors name the tower section A_c , the turbine - alternator system's efficiency η_t , the air density ρ , a dimensionless losses coefficient resulting from the air movement, F . Last, E_{net} is the energy balance (expressed as a pressure difference between upstream and downstream the turbines) from the negative buoyancy we create and collect, minus the energetic cost of the water pumping up, noticing that this cost is partly offset by the fact that the water droplets reinforce the voluminal mass excess of the air they are mixed with¹⁸.

¹⁸ if they were totally static with respect to the air, this help would be 100 % net value, and we would only have to calculate the cold air's voluminal mass, including the remaining droplets. As they "fall" with regard to the air, there is viscosity in the air, then energy losses, and this help is lower than 100 %. Another way to look at the question is to consider that the droplets move downwards faster than the air ; thus, they stay a shorter time in the tower ; and their weight has got less time to push downwards ; therefore we must weight their action with a lower than 1 coefficient representing this shorter time they spend in the tower.

They get a power N (W), and a volume flow Q (m³/s), "very close" to the following results :

$$N_{\text{opt}} = A_c \eta_t \{(2E_{\text{net}}/3)^3/\rho F\}^{1/2} \quad (10) \quad \text{and} \quad Q_{\text{opt}} = A_c \{2E_{\text{net}}/3\rho F\}^{1/2} \quad (11)$$

They don't explain how they get such a result, but it is rather simple. The gross power output is : $N = Q E_{\text{net}}$. Then, we must subtract the air's friction : as a 1st approximation, it is proportional to the velocity (which mean value is Q/A_c), squared. To get a pressure loss (and compare it with E_{net}), we use the formula which, in fluid mechanics, often yields a pressure from a kinetic energy : $\frac{1}{2}\rho v^2$, and the F coefficient is here on purpose to give a friction-like result : $\frac{1}{2}\rho F v^2$, i.e. $\frac{1}{2}\rho F (Q/A_c)^2$. We subtract it from E_{net} , we multiply the whole lot by the Q flow and by the turbines and electrical generators efficiency η_t , and we get the power we want to maximize :

$$N = \eta_t Q \{E_{\text{net}} - \frac{1}{2}\rho F (Q/A_c)^2\} \quad (12).$$

For this maximisation, we must equate to zero this formula's derivative with respect to Q , which implies to derive Q and Q^3 functions, which yields : $\eta_t E_{\text{net}} - 3\eta_t \frac{1}{2}\rho F (Q/A_c)^2 = 0$. So, we get, as announced,

$$Q_{\text{opt}} = A_c \{2E_{\text{net}}/3\rho F\}^{1/2} \quad (11) \quad , \text{ hence : } \quad N_{\text{opt}} = A_c \eta_t \{(2E_{\text{net}}/3)^3/\rho F\}^{1/2} \quad (10).$$

We notice that, from the total power that the system generates at once, $\eta_t Q_{\text{opt}} E_{\text{net}}$, only 2/3 remain in the electrical power output, 1/3 being dissipated in the losses resulting from the air's movement. This result is very classical when we want to maximise a product which is mainly proportional to a variant, but with a proportionality coefficient which is subtracted with a loss factor proportional to this variant, squared.

However, why are these results only "very close" to the real optimum values ?

First, a precision : for the formula $N = \eta_t Q \{E_{\text{net}} - \frac{1}{2}\rho F (Q/A_c)^2\}$ (12) to be really the power we want to optimise, it is necessary to check that the water pumping power has been subtracted. The answer is that this subtraction is included in E_{net} . However, E_{net} is then multiplied by η_t . Therefore, in E_{net} , the water pumping power value must previously be divided by η_t . Equally, it will have to be divided by the pumping up efficiency, which is also lower than 100 %, first because the pumps are not ideal, but also because the water requires an additional pressure to inject the water jets (into the incoming air flow) with a high velocity, which is necessary to ensure a good scattering.

All this can perfectly be included in E_{net} , and thus be consistent with the maximisation calculation we've just made. But, oppositely, two other points modify, in theory, this calculation, because two parameters assumed to be constant in the derivation, depend in reality on Q . The first one is F : the turbulent friction losses are in fact slightly less than proportional to v^2 , therefore F is slightly decreasing with respect to Q . But we must also consider E_{net} . The droplets evaporation occurs after a delay during which the air is not yet totally cooled down, and not much heavier than the ambient air. The higher the air velocity, the taller the part of the tower where we must take this effect into account, therefore the lower E_{net} .

I.B.6 Elements of economical comparison with other renewable energies

a) Comparison with solar chimneys

The previous page's demonstration is not far from truth, but it neglects the cost (not the energetic cost, but the financial one) of a facility able to pump up and spray large quantities of water. To take it into account, a useful comparison is between the heat captured by a solar collector, and the coldness quantity that water evaporation produces in a dry air. This process might be competitive if it can evaporate, at a 1000 or 2000 m altitude (where the air is cooler), 6 litres of water per day as an annual mean value, for a lower price than 1 m² of collector¹⁹.

However, this conclusion, probably favourable to the energy towers, depends on a number of hypotheses which may be questioned. Notably, we assume that we use similar towers, or at least towers with identical costs per electrical kWh, which is far from being obvious.

The solar chimneys are generally rather slender (because if they were very wide, they'd need a gigantic collector to feed them with warm air). Besides, contrarily to the energy towers, they operate rather far from the mpp, because we can't afford to waste, as turbulent losses, 1/3 of the warm air the costly collector produces. For both reasons, a solar chimney air flow is much lower than for a regular energy tower (noticing that none of both have ever been really built up).

On the other hand, from a thermodynamic point of view, a very tall energy tower would not be very well justified, because water vaporisation can't efficiently cool down high altitude air, which is already rather cold, while a solar chimney's efficiency remains more or less proportional to its height up to several thousand metres.

In addition, all the energy towers projects include at their base an additional element, called a diffuser, which canalises the air flow until it is far enough from the tower and is scattered on a sufficient perimeter. So, this air can go out without having too high a velocity, and the exit opening can be low enough so that not to waste a great part of the cool air altitude difference between top and exit, which is the energy tower's engine. This additional building has a much lower area than a solar collector, but its cost isn't negligible, compared to the tower's.

Finally, the building principles of these two competing projects are rather different. We've seen that for the solar chimney, the chosen material is the reinforced concrete. For the energy towers, it is a much lighter structure, a steel tetrahedrons (or other triangle-based rigid structure) lattice. But this seems to come much more from the various promoter's architectural preferences, rather than from logical operating principles oppositions between both types of towers.

¹⁹ The water vaporisation latent heat is 43.5 kJ/mol, i.e. 2417 J/g, which may be lowered to 1800 J/g to take into account the -12 % of formula (9) page 15, a comparable -8 % ratio (formula 25, page 52), and the fact that the mechanical losses will be important if we operate closely to the maximum power point. A solar collector operating from a 2200 kWh/y/m² incident solar flow, with a 52 % efficiency, will transmit, each day, 11.3 MJ/m². So, 11.3 / 1.8, i.e. 6.2 water kilograms are necessary to get the same result from energy towers.

b) Comparison with hydroelectric power

Being so far the most developed and cheapest source of renewable electricity, the hydroelectric power is an interesting point of comparison, which "The solar Chimney" often refers to.

The energy towers principles can also be implemented if we replace the tower by a dam ^{vii}. This option's thermodynamic interest will be described further. However, it already brings a possibility to make a first comparison with hydroelectric power : it seems easiest to build a dam able to be filled with cold air, than with the same volume of water ; and its place can be chosen only with respect to its topography, without needing a neighbouring river.

I.B.7 Forecast structure and sizes

At first glance, nothing would prevent us from building energy towers according to the same principle than the solar chimneys, i.e. in reinforced concrete, with Schlaich's "bicycle wheels". In the document describing this project ^{vi}, there is an option of a concrete building in case a huge water reservoir should be set up, at the top, in order to store gravitational energy and finely tune the power supply with respect to the demand, regardless of the hours when electricity production from dry air is the easiest.

However, for their basis solution, the authors rely to a much lighter structure. The idea is to separate two functions that the reinforced concrete both fills :

- the function of isolating the inner space from the outer atmosphere, which can be realised by a 1 or 2 mm thick sheet-steel as well as by a 100 times thicker concrete wall ;

- and the structural rigidity function, i.e. mainly the resistance against buckling, which is quite realised as well, in a hundred-feet crane, by a correctly designed (with enough triangles) steel bars lattice, as if it were a much heavier concrete column with the same outer size.

The authors imagine to use series-made standardised modules, and to let a robot put them into places and make the array grow from only easily programmable movements.

They deduce the following investment costs :

Table 1 - Total investment in towers (\$M) of different dimensions, for AR=2

		Height (m)											
		300	400	500	600	700	800	900	1000	1100	1200	1300	1400
Diameter (m)	100	21	26	32	38	46	56	67	80				
	150	42	51	60	71	83	97	113	131	149	168	192	220
	200		87	101	117	135	156	178	201	225	247	277	310
	250			156	179	205	234	264	295	325	352	388	428
	300				260	296	335	375	415	452	485	530	579
	350				359	407	458	511	562	609	648	705	763
	400				483	546	613	680	745	803	851	921	992
	450				636	717	801	886	966	1038	1097	1183	1268
	500				822	923	1028	1133	1231	1319	1392	1497	1598

Being able to calculate, for each couple of sizes and with respect to the climatic data of the forecast place (Israel's most southern point for a 1st prototype), the electrical power output, they get, for each table compartment, the cost per kWh, in \$ cents :

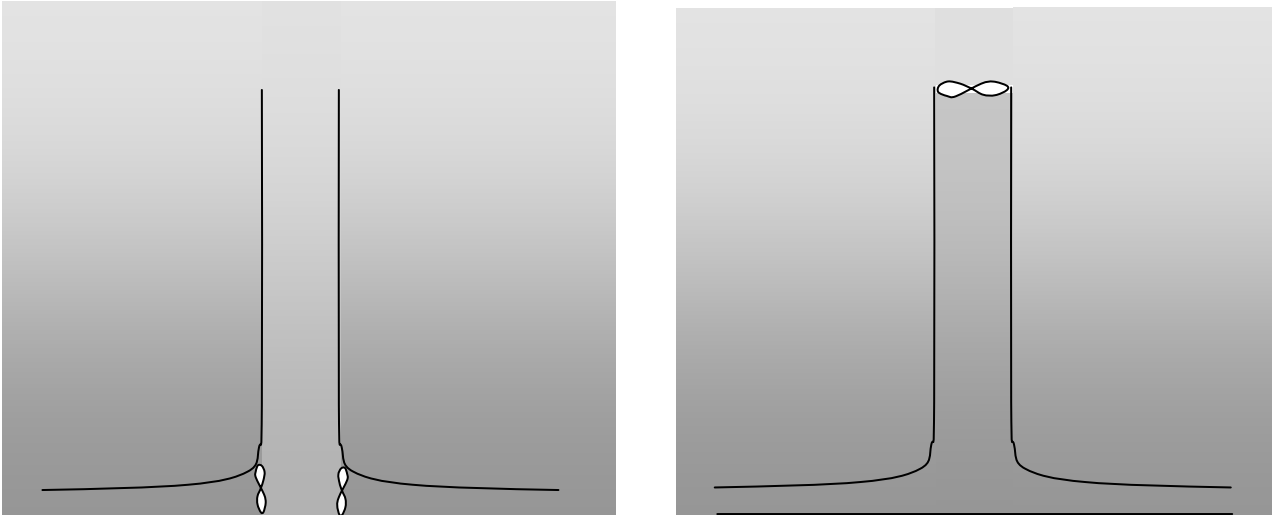
Table 2 - Cost of electricity production in Towers of different dimensions ; discount rate 10%; operation and maintenance taken as 0.556 ¢/kWh; construction time 4 years, with investment spread over 4 years: 20%, 20%, 30%, 30% ; project life 30 years

		Height (m)											
		300	400	500	600	700	800	900	1000	1100	1200	1300	1400
Diameter (m)	100	13.29	8.79	7.10	6.37	6.10	6.10	6.26	6.57				
	150	11.19	7.48	5.99	5.27	4.94	4.81	4.81	4.90	5.05	5.33	5.56	5.91
	200		7.02	5.60	4.90	4.54	4.36	4.29	4.30	4.35	4.48	4.59	4.80
	250			5.47	4.76	4.39	4.19	4.08	4.04	4.04	4.12	4.16	4.30
	300				4.74	4.35	4.13	4.01	3.94	3.92	3.95	3.96	4.06
	350					4.35	4.12	3.99	3.91	3.87	3.88	3.86	3.95
	400						4.18	4.04	3.94	3.89	3.88	3.85	3.93
	450							4.11	4.01	3.94	3.93	3.89	3.96
	500								4.10	4.03	4.01	3.96	4.03

The economical optimum, corresponding to the minimum kWh cost, lies with a height in the 1100 - 1300 m range, and a diameter between 350 and 400 m.

I.C Sorensen's principle

In 1983, J. O. Sorensen issued a patent ^{viii}, for a system which was thermodynamically similar to solar chimneys or energy towers, but with a different structure : the tower was no longer firmly fastened to foundations, but was hanging to a balloon filled with buoyant gas. Of course, this tower was no longer built, as for the Australian project, with one million tons of concrete, but was "inflatable", and therefore made with a much thinner and lighter material. However, this needed a 3rd modification, which, as shown in the following drawings, is related to the turbines location.



The difference between these two solar chimneys drawings lies in the structure of the gradual range of grey from top to bottom, but these greys, representing the air pressure, obey some common rules :

- outside the tower, the pressure lessens rapidly with the altitude, identically in both drawings : it's the reference atmospheric pressure.

- inside the towers, it also diminishes, in each drawing, from bottom to top, but more slowly. This is because the pressure corresponds to the weight of the air (or water, etc.) one has above him, so the pressure variation rate is equal to the fluid's density. In a solar chimney, the inner air is hotter than outside, and therefore lighter, so the variation in greys is slower inside.

- globally, the right tower's inside is darker (higher pressure) than for the left drawing. Why? Because, on the right (Sorensen's tower), the pressure equalization between inside and outside is done at the bottom, so the whole tower benefits from the high pressure of altitude zero, while pressure equalization is barred, at the top, by the turbine ²⁰.

On the left drawing, representing the standard solar tower, it's the opposite : pressure equalization takes place at the top of the tower, and the pressure gap takes place at the turbines level, at the bottom, thus the pressure is lower inside the tower than outside.

²⁰ To drive the turbine, the pressure must be lower downstream than upstream. Both diagrams comply to this.

That's why Sorensen can make its tower from a thin material : because, having placed the turbine at the top, he creates a positive pressure difference between inside and outside, and his tower is really "inflatable" : it keeps its shape only from the effect of the inner air's overpressure, its envelope working only in tension. And, as we saw it about the bicycle's spokes, thin materials can resist tensions²¹.

Sorensen's inflatable towers principle is used in none of the publications I found about this subject. As we'll see further, it has indeed a powerful enemy : the wind. However, for less radical projects than a very high tower only held by a buoyant balloon at its top and a punctual attachment at its base, some elements can be recycled, according to the following principles : it is a good idea to let some materials work in tension if the inner air has a pressure, either higher than outside, or slightly lower ; to have a higher pressure, this air must be situated between the system's inlet and the turbines, and, for a solar chimney, at a higher altitude than the inlet (the energy towers could benefit from the Sorensen's principle without modifying the turbines location).

I.D Solar ponds systems

This topic isn't in the mainstream of what is studied here, but it has some common points :

- if we remember the limits of the subject, as including all the massive renewable energy conversion methods having some common points with the thermal energy of the seas but not well known in France, then the solar ponds fit in pretty well ;

- one of the Israeli scientists who issued the patent about a dam used as an energy tower (G. Assaf)^{vii}, is also a co-discoverer of a solar pond based electricity production system^{ix} ; in fact, it may be that Pr. Zaslavsky's team, from the Technion institute, which works today on energy towers, was at once specialised in solar ponds, and has later shifted to energy towers, which they probably viewed as more interesting for power production (which, more modestly, was also my case) ;

- two remarks relating to solar ponds publications (one, in physics, about an electricity production system, and the other, in economics, about a solar ponds based sea water desalinisation plant), will be generalized to other subjects.

I.D.1 Solar ponds principle

The basis idea of a solar pond is that water, as well as air, is a good thermal insulator.

Our daily experience seems to prove the contrary : we can use a moist sponge to get refreshed in summer, boil food in a pan, water is used for a lot of domestic or industrial thermal exchanges.

²¹ Which is impossible in compression : A tower, whose turbines are at the bottom, can remain perfectly cylindrical only if it's rigidly built.

But, to describe correctly the latter function, we must say that water is carrying the heat, that it belongs to cold or hot water circuits : the heat transfer results from the water *movement*, from heat convection. It is the same for the pan, which is heated from under. When we boil food, boiling is both a thermodynamic transformation, and the creation of steam bubbles which generate a movement, as they're much lighter than liquid water. Both phenomena meet again when these light steam bubbles finally carry their heat very efficiently from the pan's bottom to the food.

But we can say that water is a good insulator, by assuming that if the pan were heated from above²², the heat would very slowly penetrate into the water. And this is true (as well as it is true that air is a good insulator if it's prevented from convecting ; that's why we imprison it inside wool, glass wool, expanded polystyrene or double glazing) : water thermal conductivity is 0.6 W/m.K. So, with a 1 m thick layer, which is the minimum order of magnitude for a solar pond, and a 75° temperature gap between the upper and the lower layers, the conduction heat loss will be only $75 \times 0.6 / 1 = 45 \text{ W/m}^2$, widely lower than the 250 W/m² (24 h mean value) a good sun can provide.

How is it possible to collect the solar energy and insulate the captor with water ? We've got not much choice : the sun is above us, therefore the captor must turn its blackened face upwards. We want to use water as an insulator, therefore, to prevent this heat from returning immediately into the atmosphere, the water must be above the captor. Therefore, we're in the same situation as in the pan : the heat source is at the bottom, the water above. Thus, how can we induce a different behaviour, so that the same cause won't produce the same effect ?

First, examine the reasons why the pan water was convecting. It's because its heating from below was dilating it, thus lightening it, so that it became buoyant. In a solar pond, the same phenomenon exists, but it is offset by a larger opposite feature : the water's salt concentration rises with regard to its depth. This stops the convection, and the bottom water temperature can rise with low thermal losses, to such an extent that one of the hazards is that it could start boiling.

How realise a progressive salt concentration gradient from the surface until the pond's bottom ? This is not very difficult, and in fact the solar ponds technique doesn't result from the invention of a renewable energies genius, but from a natural observation : solar ponds can appear spontaneously, and be stable. All is needed is that, by the shore of a salted water pond, the wind and the sun evaporate so much water that the remaining becomes very salted, and sinks down. Thus, the salted bottom is naturally regenerated, and this is enough to offset the salt diffusion towards the low concentration zones (this diffusion also smoothens possible concentration gradient irregularities in the bottom - top interval ; last, the same diffusion could increase the upper layer's salt concentration, but the fresh water inputs (rain, rivers) which float upon the salted water, offset this effect).

More precisely, this major feature of creation and stabilisation of a salt concentration gradient must be completed by other behaviours by the two ends of the water column :

- at the bottom, where a large part of the solar energy is received on a very thin surface, if the water were perfectly stratified, hence much insulating, we'd have a very strong temperature gradient, and thus a density gradient which could overcome the salt concentration gradient. So, a convection zone may appear (LCZ, lower convecting zone) ;

²² and with the help of a not too hot heat source, in order to limit the infrared radiation heat transfers.

- at the top, surface evaporation increases the salt concentration, so that the surface water periodically becomes slightly heavier than immediately lower layers. This creates the upper convection zone (UCZ).

Inside each of both convection zones, the temperature and salt concentration are homogeneous. In the central zone (NCZ, non convecting zone), they have an approximately regular gradient, but not exactly, especially for the temperature. Indeed, water is not perfectly transparent, notably in the red and infrared ranges ; light absorption takes place, and results in heat creation at every level. Only the remaining bluer light is absorbed at the bottom.

One of the main advantages of the solar ponds is that they allow heat storage over one year (as we'll see further, it can take 2 or 3 years to reach its nominal operating point, like a dam which is progressively filled : this shows that there is a thermal inertia with a time constant of at least one year). And, as this heat is stored in a liquid, it can rather easily be exchanged with other systems.

I.D.2 Electricity production from a solar pond

a) General issues

Every solar pond provides a heat source (the LCZ) and a heat sink (the UCZ). Therefore, we can use it not only for central heating, but also for thermodynamically more sophisticated processes, and first of all power production. The quasi-null cost of the solar energy will have to offset a great capital cost, due to the relatively low temperature of the heat source²³, because of the following :

① When the gap between the heat sink and heat source temperatures decreases, the thermal machine's theoretical efficiency, which is equal to $(T_{\text{source}} - T_{\text{sink}}) / T_{\text{source}}$, falls. Therefore, to produce the same electrical power, we need to take more heat from the heat source and give back more to the heat sink, thus have a greater solar pond, but also larger water flows and wider pipes.

② It is not possible, as we do in ordinary power plants, to produce overheated steam with a widely higher than 100° temperature, therefore with a pressure $\gg 1$ atm, and driving turbines with a great energy density (the steam incorporates vaporisation latent heat without having such a low density as gases under atmospheric pressure). We have only a choice between two solutions who both have drawbacks :

- to have high pressures again, we can substitute water by another liquid with a lower boiling temperature^{24,x}. This results in relatively high investment and maintenance costs (and it's out of our subject which includes only systems using, as operating fluids, the cheapest ones, water or air).

²³ Not more than 100°C, in order to prevent the LCZ from boiling. Theoretically, it could be a little hotter, because salted water, at a higher pressure than by the surface, boils at a higher temperature.

²⁴ " 134a Refrigerant ".

- or we try to do with turbines designed for pressures lower than 1 atm, which is not impossible, as the Australian solar chimney will operate with an even lower pressure gap between upstream and downstream, and wind turbines even even lower. However, the economical efficiency is necessarily reduced.

b) A particular device

An interesting device which illustrates the latter option is described in a patent ^{ix} showing the links between solar ponds and energy towers, as one of its authors had also issued a patent for an energy tower - like system ^{vii}. Here, the idea is to condensate the steam by a contact with the UCZ cold water, which is sprayed as droplets in a "shower" that the steam flow crosses through.

This is based on the idea that spraying the water into plenty of droplets enhances the thermal contact and thus the condensation efficiency. But, in an ordinary power plant, this thermal contact isn't specially difficult : one steam volume element condensates, the next one takes its place and comes directly to the heat sink's surface, where it also condensates, etc.

The problem is that here, such a condenser wouldn't operate, because the steam we use is produced by the evaporation of the solar pond's hot water ; and, contrarily to the pure water which is operated in closed circuits between a boiler, a turbine and a condenser, this water (as well as the "heat sink" droplets) contains various impurities, the most embarrassing being ... air : it mixes with steam, but can't condensate and will therefore accumulate, and impede the mechanism which made any steam element to come, one after the other, perfectly at the condenser's contact. This question is lengthily discussed in the patent, the droplets' diameter being adjusted so that to limit the cost of the vacuum pump which is necessary to eliminate this "incondensable" air.

Why vaporise directly the solar pond water in the system ? Probably for two reasons. 1st, because introducing a thermal exchange would have even reduced the temperature difference between the heat source and sink, with the low efficiency drawbacks we've noticed previously. 2nd, because it allows to very much simplify the heat introduction mechanism : the hot water comes up, from the solar pond's bottom, into the "boiler" ; the steam production cools it down and increases its salt concentration ; these two effects weigh it down, and it naturally goes down back to the pond bottom : this upwards and then downwards flow is self-maintained.

I.D.3 Sea water desalination

As the solar ponds can concentrate, with a low cost, the sun's heat into a liquid (the pond's water) which may easily transfer its heat to other liquids (for instance, sea water we want to desalinate), this is a rather logical track to follow. This has been done, through a two part article^{xi}, whose interest is that one part is about the thermodynamic and technical description of the process, and the other about its economical assessment, which is rare enough to be mentioned.

They get good efficiencies because a gap of a few degrees²⁵ may be enough for the heat (given by the heat source and absorbed by the heat sink) to evaporate a given quantity of salted water, condensate it, and return it as fresh water. So, with some dozens of degrees of difference between the heat source and sink, we can get more distillation, by one order of magnitude, than what we could imagine from dividing the heat quantity we bring, by the vaporisation latent heat.

Such a theoretical principle can be translated with no problem to a technical device (Cf. diagrams 8 and 9 hereunder) containing nearly 20 distillation stages. The various water circulations can be organised so that to ensure that the heat exchanges occur at the right temperatures, as it can be seen by reading K. R. Agha and allii's article. Various ratios seem rather classical in the desalination business, which allows us to suppose that there aren't much technological hazards in using solar ponds like this.

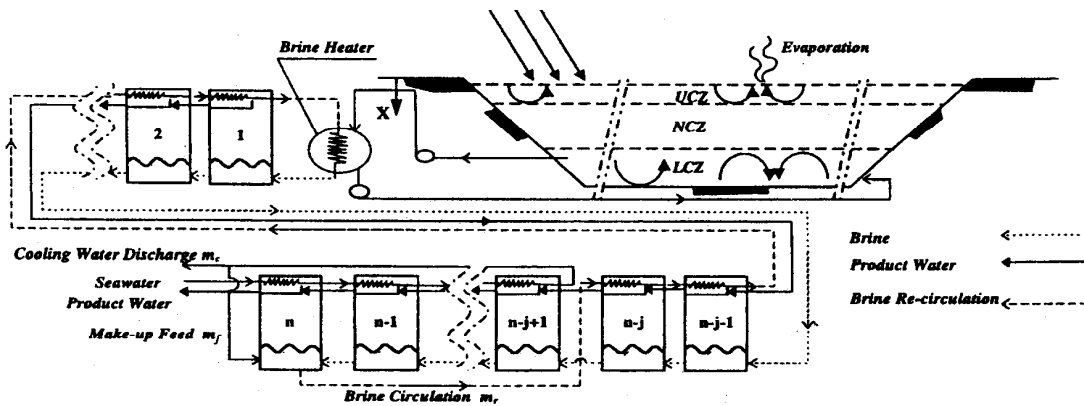


figure 8 A solar pond coupled MSF desalination system.

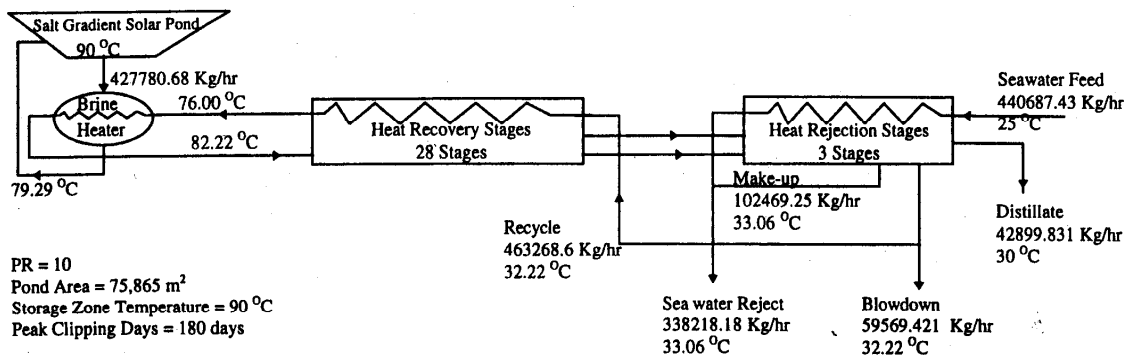


figure 9 Matching a salt gradient solar pond with an MSF desalination plant at performance ratio of 10 and storage zone temperature of 90°C.

²⁵ At least 0.3°, Cf. footnote n° 73, page 82, and not some thousandths of a degree. There is a practical reason (which such a low gradient, the thermal exchanges would be very slow) but also a theoretical reason : salted water evaporates with more difficulties than fresh water, so, with the same saturating steam pressure, it must be warmer. Mixing salt and water is irreversible, therefore it is logical, considering the thermodynamics 2nd law, that the opposite operation can't be realized with no cost.

II A CRITICAL ANALYSIS OF THESE PAPERS

II.A *Solar chimneys : what we don't know, but we try to imagine*

As it is normal, academic publications don't mention all the useful details to check the calculations. And this is even more true when it comes to books intended to be sold to the largest number of people.

Therefore, I'll stress the elements which are still missing in the jigsaw puzzle, the consequences this has had as far as my studies are concerned, and in some cases the approximations I have used to bypass these gaps.

II.A.1 Distinction between turbulent friction losses in the collector and the tower

Trying to optimize some solar chimney parameters, requires that we know their effects on the mechanical losses, notably as the tower diameter and the collector roof height are concerned, because their effect on the power output is only driven by the turbulent losses which occur from the air way's narrowness.

In "The solar Chimney", tables, like the following one, give a lot of data. The turbulent losses in the collector and the tower, which are similar in their nature and which vary in the same manner with respect to the air's velocity, are added up, and only their sum, ΔP_{fr} , is given for the three sizes examples. There is also an other category of mechanical losses, ΔP_{top} , which will be discussed thoroughly later, and which corresponds to the idea that, at the tower's top, the air's kinetic energy can't be recovered.

Table 3

Power		MW	5	30	100
Collector diameter	D_{coll}	m	1110	2200	3600
Chimney height	H_t	m	445	750	950
Chimney diameter	D_t	m	54	84	115
Glass roof height (external)	$H_{coll,e}$	m	2	4.5	6.5
Glass roof height (internal)	$H_{coll,i}$	m	10	15.5	20.5
Total pressure difference	ΔP_{tot}	Pa	383	767	1100
Pressure loss at chimney top	ΔP_{top}	Pa	40.4	75.1	117.5
Pressure loss by friction (collector and chimney)	ΔP_{fr}	Pa	28.6	62.9	80.6

We can see that for 30 MW, ΔP_{fr} is 31 % higher than the geometrical mean of its values for 5 and 100 MW, whilst for ΔP_{tot} (pressure difference which is produced by the air buoyancy), the same difference is only 18 %²⁶ : the 62.9 Pa for 30 MW look strangely high, by comparison with

²⁶ For ΔP_{top} this overvalue is only 9 %.

the 28.6 and 80.6 Pa in the same line. Part of the explanation could be that the 30 MW chimney is rather slender, but overall we don't have all the parameters, and notably the curve representing the collector's roof height for all the values of the variant r (radius).

The problem is that it makes it more difficult to build up a model : this ΔP_{fr} is the sum of the air frictions in the collector and in the chimney, and we need to model both separately. When we do it, with reasonable physical laws but by adjusting the parameters on these data (28.6, 62.9 and 80.6 Pa), all the attempts lead to a sharp overestimate of the pressure drop in the chimney and to an underestimate in the collector, which lowers the economical reliability of our future calculations.

Finally, despite the criticism such a method would attract, the less absurd results are given by an ad hoc solution : swapping the data from the two lines ΔP_{fr} and ΔP_{top} ! Thanks to ΔP_{top} more regular profile, which we assume to be equal to the sum of the losses in the tower and the collector, a classical adjustment rapidly gives a likely distribution among both groups of losses ; the profile anomaly migrates to the tower top's losses, which of course gives a poor adjustment quality, but probably with a lower prejudice for the calculation of likely modelling parameters.

II.A.2 Limiting factor for the wind resistance, and concrete resistance limit

Several risks are mentioned in the 1999 article "Tension structures for solar electricity generation" ⁱⁱⁱ, or can be imagined : wind²⁷, earthquakes, risk that the tower could crush under its own weight, etc. The solution this article describes isn't probably very different from the chimney to be built in Australia : bicycle spokes, profile of the tower thickness with respect to the distance from the top of the tower. After being constant²⁸ (25 cm) from the top (1000 m high) to the altitude of 600 m, this thickness increases regularly when we come closer to the ground. They add up, at each 100 m interval, the following numbers of cm :

7	9	12	15	19	12 (for ½ interval)
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We notice a 30 % rise for each step, which looks like an exponential law. It is indeed, as the following table shows. In the 1st column is the distance from the tower's top, 2nd the number of cm we can read in this article, and 3rd the product of a constant by a simple exponential of the 1st column figure divided by 400 m, with an approximation to the nearest mm :

Table 4	400 m	25	25.0	800 m	68	67.9
	500 m	32	32.1	900 m	87	87.2
	600 m	41	41.2	950 m	99	98.8
	700 m	53	52.9			

²⁷ We can again imagine several effects : tower's ovaling (this is what the bicycle spokes fight against), or toppling of the whole tower, whose foundations are only some metres deep.

²⁸ Most of the "bicycle wheels" which guarantee the tower's stiffness are set in this zone.

Such a coincidence, with an always better than 5 % precision and with a hundred-multiple as exponential parameter, can't be here by chance. More, this 400 m value is the distance from the top to the series beginning point, where the thickness stops being constant and where the exponential law starts.

This behaviour can be explained as follows :

① At 400 m, the wall thickness is 25 cm and every concrete segment with such a length, bears a cross-section whose area is : $25 \text{ cm} \times 400 \text{ m} = 100 \text{ m}^2$;

② A z_1 m lower segment is longer :

$$l_1 = 25 * \exp (z_1 / 400) \quad (13)$$

The integral of the thickness it bears will be :

$$100 \text{ m}^2 \text{ (as previously)} + \int 25 \exp (z/400) \quad (14)$$

The integral is to take from $z = 0$ to $z = z_1$, and the primitive of $25 \text{ cm} \exp (z/400 \text{ m})$ is : $25 \text{ cm} * 400 \text{ m} \exp (z/400 \text{ m})$, so it will be equal to :

$$100 \text{ m}^2 \{ \exp (z_1 / 400) - \exp (0) \} \quad (15)$$

The total concrete cross-section area above the segment we consider will be :

$$100 \text{ m}^2 + 100 \text{ m}^2 \{ \exp (z_1 / 400) - 1 \} \quad (16)$$

$$\text{i.e., very simply : } 100 \text{ m}^2 \exp (z_1 / 400) \quad (17)$$

which is exactly the product of (13) $l_1 = 25 \text{ cm} * \exp (z_1/400)$ by the 400 m coefficient ;

③ said differently, all the remarkable features we have noticed, can be summed up in the fact that, wherever a segment is (but farther than 400 m from the tower's top), the area of the cross-section above this segment is equal to 400 m times this segment's length. Therefore, the series of the thicknesses with respect to the altitude, which is given in the 1999 article, has been built up from a very simple principle : that no concrete element must bear a bigger mass than a 400 m high column with the same thickness (and also that the wall must never be thinner than 25 cm).

This looks like the answer we were looking for : the resistance of the concrete, against the risk that it could crush under its own weight, is the main factor that helped to choose the tower size, and this resistance implies to multiply the wall thickness by e each time we want to increase its height by 400 m.

However, the best concretes can bear 10 000 t/m² stresses, which, divided by a 2.5 t/m³ density, should yield a 4000 m pace^{xiii}. A safety factor is required (in particular because of the lateral wind's action), but a multiplication by 10 (from 400 to 4000 m) seems a lot, as the concrete thickness increase law with respect to the tower height, has a most important effect on possible scale economies, which are the solar chimneys' main asset. Therefore, we only can notice a very embarrassing incertitude for any precise economical appraisal.

II.A.3 Collector cost variation with respect to the glass roof height

When discussing the collector thermal efficiency, we saw that, in order to limit both the air velocity and the collector's glass roof height, we could have to accept, for bigger facilities, a rise of the air temperature, and thus more thermal losses. This would be based on the hypothesis that the collector m² cost notably rises with respect to its roof height. Indeed, in "The solar Chimney", this cost is regularly growing, from 24.4 DM/m² for the 5 MW tower, whose roof height varies between 2 and 10 m, until 26.54 DM/m² for the 100 MW one, with heights between 6.5 and 20.5 m.

If, as mentioned in appendix 3, we blend these two variants (the inlet and outlet heights) into a single one, we can model these data as a cost function with three adjustable parameters. But what kind of function ? From data ranging in less than a 10 % interval, the results could be very different if we take a polynomial, n-power, or exponential function, overall if we want to know how it behaves for very high roofs, which is legitimate if the corresponding cost isn't huge.

Without knowing it²⁹, and therefore to be prudent about the advantage we could yield from a simple enlarging of the Australian tower sizes, we'll choose a rapidly growing cost function when it comes to arrange glass plates 40 m above the ground. And we'll discuss a solution avoiding this hypothesis of just making an identical system's sizes simply grow.

Naturally, a very rapidly growing cost function handicaps the 1st hypothesis, and thus favours the 2nd solution. For further studies, this should be kept in mind : prudence is not only to be sceptical about possibly too optimistic cost functions, it also implies to fairly compare two options which are, at first glance, both interesting. Therefore, we shouldn't exclude that the simple enlargement of the same structure could finally be the best economical solution.

²⁹ Of course, "The solar Chimney" 's authors know with what cost function they got the figures they published, which probably result from optimisation calculations. At least, we can see that this height regularly grows with respect to the power, so that, for each size, the frictional losses remain a limited percentage, neither too great as it would lower the power output, nor too low as the roof would have to be too high, hence too expensive.

Our interest is to know whether it is possible to extrapolate such a discussion towards even larger collectors, in order to continue to profit with scale economies. There is no reason to extrapolate it towards smaller sizes, whose economical interest is null. More, under a 2 m roof height, the collector's cost would increase instead of decreasing, as the workers wouldn't walk under it. Therefore, the authors had probably been too theoretical when they write, in "The solar Chimney", about their Manzanares prototype: "the lowest realistic height for a collector roof for large-scale technical use, 2 metres, was selected for the small Manzanares plant. *For output a roof height of 50 cm would in fact have been ideal.* Thus *only* 50 kW could be achieved". Clearly, a higher collector's roof can't lower the electrical power.

II.B Many uncertainties about operating fluids energy balances

For thermodynamic (avoid to have a heat sink) and economical (use of very cheap fluids, such as air) reasons, a lot of the processes we examine here are open cycles. In the publications I read, this has resulted in much imprecision about this fluid's energy balance. This has to be thoroughly investigated because, in the most important cases, this energy balance has a major influence over the output power calculation.

When the operating fluid is the air, it is always, because of its low viscosity ν and of the system's size, in a turbulent state, whose study is more difficult than for a laminar flow. In order to progressively enter this issue, we'll begin with a liquid flow which may more easily behave in a laminar way.

II.B.1 The simple case of a probably laminar flow

Any mechanical transformation can be described with an energy balance (which, for a fluid, may be converted to pressure). A child on a skate board, or even a water flow on a perfectly even way, can accumulate kinetic energy when diminishing its altitude, and, afterwards, make the opposite exchange when mounting another slope.

Equally, below a hydroelectric plant, we can often see the water's level being very low just after passing the turbine, where its velocity is high, and then coming back up when it slows down, and finally being adjusted to the downstream canal's level. It is a classical application of Bernoulli's equation, which we also see in Venturi's effect : where a fluid moves faster (pinching), its pressure decreases, but recovers a higher value afterwards. There are indeed two successive conversions, in both directions, between kinetic energy and "pressure energy".

Therefore, at least for a laminar flow, we shouldn't consider an energy which, at some time, had been converted into kinetic energy, as being lost (i.e. being subtracted from an energy balance).

In the hydroelectric plant example, the resource is the gravity potential energy difference corresponding to the altitude difference between the dam surface and the downstream canal. In each of both extreme states, the kinetic energy is low and can be neglected.

Assume we're not pleased with such a description, and we want to subtract, from the energy balance, what has been temporarily transformed into kinetic energy (at least when the water has just passed the turbine, and can't push its blades any more). I can agree, but only if we consider a point just downstream the turbine, therefore where the water level is still even lower than in the canal.

Then, we must take, as an income in the energy balance, the altitude difference between the dam level and this "just after the turbine" level, which is greater than the global altitude difference, between the dam and the canal. This larger income creates an "altitude difference benefit", thus an energy benefit, which offsets much of what we thought we had to subtract in order to take the turbine outgoing water's kinetic energy into account.

In the patent ^{ix} where electricity was produced from a solar pond and where turbine steam condensation was made with UCZ water droplets, the incoming hot salted water flow is calculated. Correctly, this calculation is based on the fact that the cause of the water movement is the density difference between the relatively less salted and hotter water which comes up into the system, and the more salted and cooler water which goes back down to the pond. But it uses this resource to equate it to this water's kinetic energy value just when it passes in the "boiler".

This energy balance doesn't obey the principle we've just seen : they should have taken into account that the water's acceleration was temporary, and that (unless the creation of swirls and foam at the boiler's exit) its kinetic energy could be recovered during the following deceleration. Therefore, it mustn't be negatively counted. What should have been equated to the movement's "engine" (the density difference), were the mechanical losses, which have no reason to be identical to the kinetic energy, especially in a laminar flow.

A good model is an electrical circuit analogy, where we equate the sum of the potential electromotive force of all the circuit components, to all the dissipative tension losses (resistors, etc.).

II.B.2 Inadequate energy balances with warm air as the operating fluid

In a great number of studies in the field of the present thesis, we can find similar inadequacies to what we've just criticized. In some papers (and many patents ^{xiii}), the authors seem to calculate the kinetic energy that the air could naturally get during a meteorological-type transformation (warm air rises, cold air falls), and then implicitly assume that such a movement can be tamed and produce the same kinetic energy, which can be harvested without any other question.

Their power is calculated by multiplying the energy (work) one air m³ yields when it passes through the turbine, by the air flow (Φ , m³/s). Therefore, it is important to calculate this flow, which is the product of the cross-section and the velocity. But, without any discussion, the velocity is very often found as follows : for a mass m element, they assume that its kinetic energy $\frac{1}{2} m v^2$ directly yields the velocity v from the energy balance. If K is the movement's cause (generally including a temperature difference, the gravity acceleration g , and a height h), they find that v is proportional to $K^{1/2}$ (as $v^2 \propto K$) and therefore that the power $P \propto K \cdot \Phi \propto K \cdot v \propto K \cdot K^{1/2} \propto K^{3/2}$.

Such a $K^{3/2}$ law can be found in an article ^{xiv} which I'll more thoroughly criticize further, but where we can notice that it says, as if it were obvious, that the power must be $\propto H^{3/2}$. ³⁰

This demonstration, which consists in calculating a matter flow by solving the equation which is supposed to link this matter's kinetic energy with the work which is produced by the cause of a convection movement, and finally to multiply this flow by the kinetic energy which any mass or volume element has acquired, is criticisable for several reasons.

³⁰ "Since the power produced is proportional to v^3 or $H_c^{3/2}$, one has to take a very tall chimney for any substantial amount of power production".

First of all, it needs to think that we can convert all this kinetic energy to electricity, which, according to the most widespread mind that I describe in the present thesis³¹, implies that after this conversion, the air has no more energy, and therefore, that its velocity is null. But, for a continuously operating system, this air must be disposed of, which can occur only with a positive velocity.

Some authors think that it is really necessary to transform the cause of the phenomenon which interests us, into kinetic energy, and, afterwards, to convert it into a turbine's movement, then into electricity. But this consists in starting with a cause which can be expressed as a pressure difference, to convert it into kinetic energy, and finally to convert it back into pressure (the only phenomenon which is able to create a force on a turbine's blade).

This roundabout way³², and even more a 100 % conversion into kinetic energy and then the opposite conversion, aren't justified (even if it can be useful to have a fast enough movement just when the air passes through the turbine, so that the air flow cross-section isn't too large). Without having, at any time, the operating fluid move very fast, it is perfectly possible to convert efficiently the phenomenon's cause into electrical power, by letting the upstream pressure be much higher than downstream the turbine (Cf. fig. 7, p. 22). In a turbulent flow, this avoids high mechanical losses to be caused by this turbulence, which origin is the destabilisation, and thus the loss, of a large part of the current kinetic energy.

In reality, we should find a $P \propto K^{3/2}$ type law, only if we decide to use, from conscious economical reasons, to use the maximum power point (mpp) theory. But even this use, which may be either justified (I.B.5, p. 17-18, energy towers), or not (II.F.1, p. 72-78, solar chimneys), gives different results than what is criticized here : it leads to an air friction losses ratio which is equal to 1/3 of the theoretical potential, the electricity production comes from a pressure difference (without introducing the kinetic energy) between upstream and downstream the turbine, and the air reaches only a $3^{1/2}$ lower velocity than if we'd let it freely accelerate.

The Haaf and alii (including Schlaich) articleⁱ which, in 1983, presented the Manzanares solar chimney prototype, combines both approaches. The 1st one : "the chimney generates an air mass flow rate $\phi = \rho_i \cdot v \cdot F$, depending on ΔT , in accordance with : $v = \{2 \Delta p / \rho_i\}^{1/2} = \{2g H_T \Delta T / T_a\}^{1/2} \dots$ since power is proportional to the 3rd power of the upwind velocity $N \propto v^3 \dots N_{pk} \propto H_T^{3/2}$ ". And, then, the mpp theory (not called by its name, and in fact inadequate, Cf. further, II.F.1.c, p. 77-78) : " Δp_T is the pressure drop at the turbine ; the optimal proportion of the total pressure difference Δp is calculated at 2/3".

³¹ We could imagine that these authors were conscious that the air can have a velocity just downstream the turbine, as the water in the II.B.1 example, p. 32, but that the corresponding kinetic energy shouldn't be subtracted from the energy balance because it is recovered afterwards thanks to the little increase of the downstream pressure (see a little further, II.B.3, p. 36). However, this would require a great accurateness in physics, while even among those who elaborate rather sophisticated models, some make serious mistakes (Cf. further, II.B.5) ; and such a demonstration, which is globally valid for a laminar flow, is falser for a turbulent flow, for which a fluid's kinetic energy recovery from its downstream slowdown is, if not equal to zero, probably lower than 100 %.

³² which we can find even in a very recent article (dos S. Bernades and alii^{iv}), corresponding to the rather precise description of the solar towers, which I took as an introduction of the collector's thermal behaviour (fig. 3, p. 10). We can read : "The chimney converts the thermal energy produced by the solar collector into kinetic energy", which is followed by a formula : $w = \{(2/\rho) \cdot [\int (\rho_o - \rho) g dz - \Delta p_{friction}]\}^{1/2}$, which yields the velocity w according to this mistaken principle. Yet, this is corrected by other principles which are presented afterwards, and notably an equation with an adjustable coefficient x : $w = w_{tot} (1 - x)^{1/2}$, which we will discuss again later, but we can see that it seems difficult to get rid of ideas which are probably very deeply anchored in the minds of the people who work on these subjects.

II.B.3 Some similar uncertainties in "The solar Chimney"

By comparison, the results tables that we can find in the main part of "The solar Chimney" ⁱⁱ reflect a correct view of the various involved phenomena and could only be criticized because of an easily understandable excess of prudence. In the book's appendix tables, the annual production figures (in GWh/y) are consistent with the collector's area, the annual solar flow (2300 kWh/m².y) and the different useful efficiencies (of the tower, theoretically computable, Cf. formula (1) p. 4, and of the collector and turbines, read in other tables). Only episodic remains of the mpp theory, in particular in the physical principles appendix, will be examined further (p. 76, ©).

But the losses calculations are based on the idea that all the tower outgoing air's kinetic energy is lost for the energy balance. Said differently, the authors don't imagine that, as for what we saw previously below the hydroelectric turbine (II-B-1, p. 32), the air slowdown could be accompanied, according to Bernouilli's equation, with a pressure rise, hence an energy recovery.

Yet, we're no longer in laminar fluid mechanics, the flow is turbulent, and an initially purely translation movement rapidly tends to disperse into various swirls whose kinetic energy will be irrecoverable. However, four remarks :

- just from the impulse conservation principle, the translation movement doesn't disappear just like that, it requires that an opposing pressure field be here to slow the air down ;

- if a fluid flows in a pipe, turbulent losses can be computed. Their value is around its kinetic energy if the pipe length is equal to its diameter divided by a coefficient C which is lower than 1/10 for very turbulent systems (with very high Reynolds's numbers), as here. Is it obvious that, coming out from a chimney, the air will be as much slowed down, and its kinetic energy as much lost, than if it were to go on, in a ten times longer than wide pipe ?

- to a large extent, the swirls which will accompany the air when it comes out of the chimney, are already present in the air column just before the tower's opening. And, if the tower is long enough, we could consider that these swirls are taken into account in this tower air's turbulent friction, which the authors have already included in their energy balance. To add up additional kinetic energy losses at the chimney top, we'd assume that the friction with the envioning air masses creates *new* swirls whose dissipative effect should be at least equal to those which the tower itself, as a pipe, generates.

- for these first remarks, I assume that the outgoing air will indeed be slowed down as it can spread into a much wider cross-section. You could argue that, as it is buoyant, it will keep on rising rather quickly, and thus that Bernouilli's equation won't give it back anything. Maybe. But buoyancy means aspiration, i.e. depression. It would at least be paradoxical (paradoxes are possible in such topics), that an aspiration feature would result in less aspiration at the turbines level than if such a buoyancy would vanish just as the air goes out the tower ! (The link between energy balances at the tower top and turbines aspiration, in detailed in Fig. 10, next page).

Indeed, this discussion directly commands the pressure difference we get between upstream and downstream the turbines, therefore the mechanical power we can produce. Assume the outgoing air velocity is : $v = 13 \text{ m/s}$, which yields a "dynamic pressure" : $\frac{1}{2} \rho v^2 \approx 1 \text{ hPa}$.

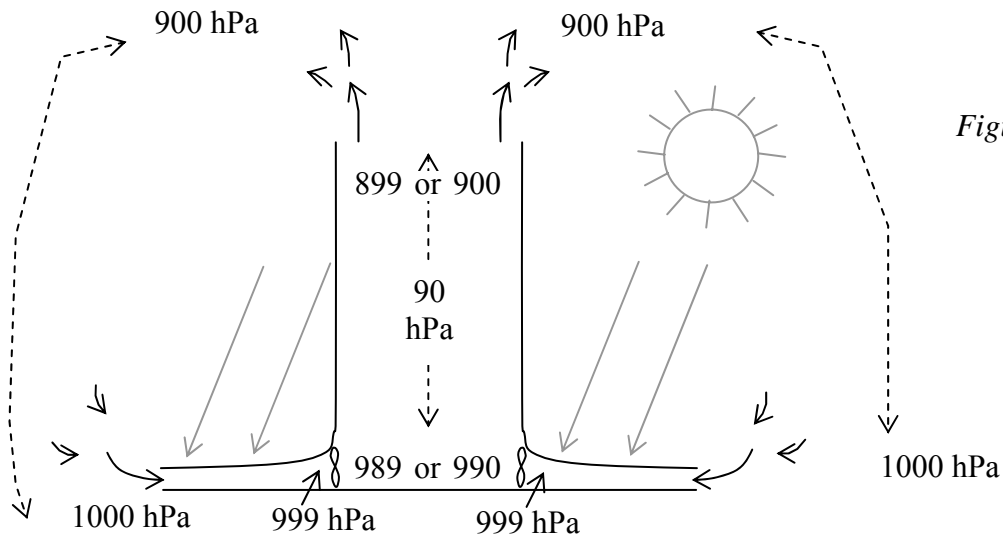


Figure 10

The various friction losses are neglected, to focus on a pure comparison between two simple theories : left of the figure, at the top, this dynamic pressure can be recovered ; right : it can't. In both cases, the outer air column pressure is 100 hPa, and 90 hPa for the inner column. At the tower's top, but slightly aside in order to have a negligible kinetic energy, the air pressure is : $1000 - 100 = 900 \text{ hPa}$. Also in both cases, we assume, to simplify the figure, that all the air acceleration takes place in the collector, which gives a 999 hPa pressure upstream the turbines, from a 1000 hPa ambient pressure.

On the left, where we assume that this transformation of pressure to kinetic energy is reversible, the pressure by the tower's opening is $900 - 1 = 899 \text{ hPa}$; on the right, if this energy is irrecoverable, we stick to our 900 hPa. This difference spreads down to downstream the turbines, where, with a 90 hPa shift corresponding to the inner air column's weight, we find the same difference again : 989 hPa on the left, 990 on the right.

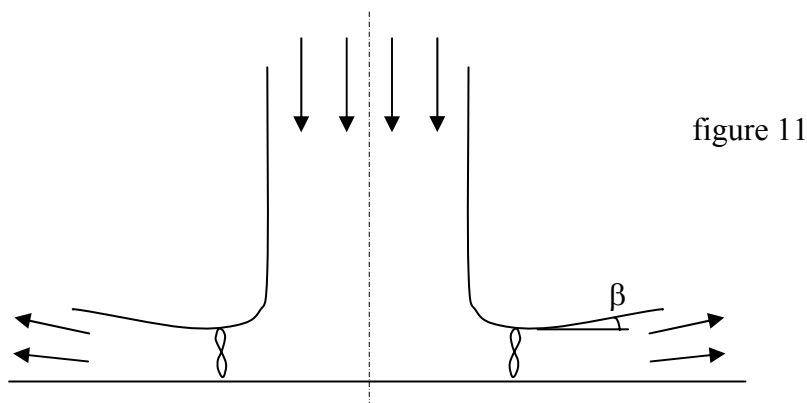
This directly modifies the turbines driving pressure difference : left, $999 - 989 = 10 \text{ hPa}$, i.e. the theoretical buoyancy $100 - 90 = 10$, which isn't surprising as we assume that the kinetic energy transformation is reversible ; opposite, on the right, $999 - 990 = 9 \text{ hPa}$, i.e. 10 % off.

What is the interest of such a discussion ? Not only to forecast with a great precision the tower's power in order to decide whether to build it or not. But also to adjust some parameters. If the kinetic energy loss at the top is lower than we thought previously, it means that we can, without risking too heavy losses, increase the air's velocity, i.e. either slightly reduce the tower diameter (sparing), or increase the collector area (additional power). On the contrary, if it's impossible to recover this kinetic energy when the air has gone out of the tower, there are perhaps more opportunities to do it just before, with a bell-mouthed profile (with a constant cross-section, the air accelerates as its density diminishes with respect to the altitude : it is indeed near the tower's top that there are the highest risks of kinetic energy - related losses).

The solar chimney promoters don't seem to be interested in such questions, as they write in an article project ^{xv} : " $\Delta p_{\text{chimney}} = \Delta p_{\text{turbine}} + \Delta p_{\text{friction}} + \Delta p_{\text{dyn}}$, using the standard definition for dynamic pressure $\Delta p_{\text{dyn}} = \frac{1}{2} \rho v^2$ " : this notion, which deserves to be examined with precision, is here considered as a "standard" (or even automatic) use tool.

II.B.4 Energy towers : why a diffuser ?

Figure 4 can be schematized as follows :



The diffuser is the annulus which, around the tower's base, is 100 or 150 m high, covers the turbines, but extends farther from the axis to accompany the outgoing air movement towards the system's periphery. It is often shown with a positive slope in this movement's direction (β angle).

Such a diffuser is justified nowhere. Therefore, we can wonder whether, for its creators, its existence goes without saying. This would in particular be the case if, as we've seen at the previous point, we'd consider all the kinetic energy associated to the outgoing air as naturally lost. The diffuser would then help to reduce this loss with a good efficiency. By enlarging the radius of the circle where the air goes out, we increase its perimeter. A positive β angle rises the exit height, and, again, the cross-section area. All this allows a proportional air velocity reduction, hence a very sharp diminution of the supposed losses, as they are $\propto v^2$.

However, as we've just seen it, it isn't obvious that this kinetic energy is irrecoverable. In such conditions, are the proposed diffusers uselessly big and costly, or even totally useless ?

If the commonly admitted justification is only the previously mentioned one, then the issue deserves to be totally rebuilt from zero and new foundations. Would there be any drawback in getting rid of (or shorten) the diffuser ? Instead of being guided by a rigid and even ceiling, the outgoing air would recover its freedom to spread into all the space being in front of it. Will it actually do it ? From a frictionless point of view, it is under-pressured (because of its velocity) with regard to the air both above it, and horizontally in front of it. This doesn't determine a privileged direction, so the fact that it is heavier could lead it to spread horizontally.

If we look at the friction, it will compete with this mechanism, and it is not easy to forecast which one will overcome. If this friction were laminar, we'd just observe that the dry air above the tower outgoing air would be dragged along. This would be a good thing because, as we'll see further, anything that helps to renew, from time to time, the tower's outer air, is useful. But this friction may also be turbulent³³. We'll get the same dragging along effect, but also a mixing effect of the outgoing cool air layer and the outer air, which is bad news for two reasons :

① - at the tower's base but above the outgoing cool air layer, a rather cool air torus will appear. It could reduce, by several hundred metres, the inner air's negative buoyancy with respect to the outer air, which is precisely the tower's engine ;

② - the more these airs mix together, the less negatively buoyant is the outgoing air with regard to the air just above it, the lower is the effect which is described in the footnote n° 33 hereunder, the more difficult it will be to fight against Kelvin-Helmoltz's instability, hence the more we'll risk to keep turbulent mixing. Therefore, the turbulence could be self-maintained (or at least it'd be hard to prove that it wouldn't) unless if, initially, the outer air were warm and light. The problem is that, every morning, the initial conditions are rather cold, especially in a desert.

Therefore, the tower could rather slowly reach full speed operating, i.e. with an outer air as warm as it is naturally (without a tower, the sun quickly warms the ground up and, by convection or thermal radiation, this heat can be passed on to the immediately higher air layers ; with an energy tower, the ground will always be cooled down by the outgoing air, so, even a beautiful sun won't easily maintain identical outer air conditions as without the tower - Cf. further, II.D.4.b, p. 67-68).

So, a diffuser is perhaps very necessary, not in order to avoid subtracting a great outgoing kinetic energy from the energy balance, but to avoid handicap even more, by a mixing effect, the tower's engine, which is the inner air negative buoyancy with regard to the outer air. Finally, this diffuser should perhaps be even larger than what is generally forecast ?

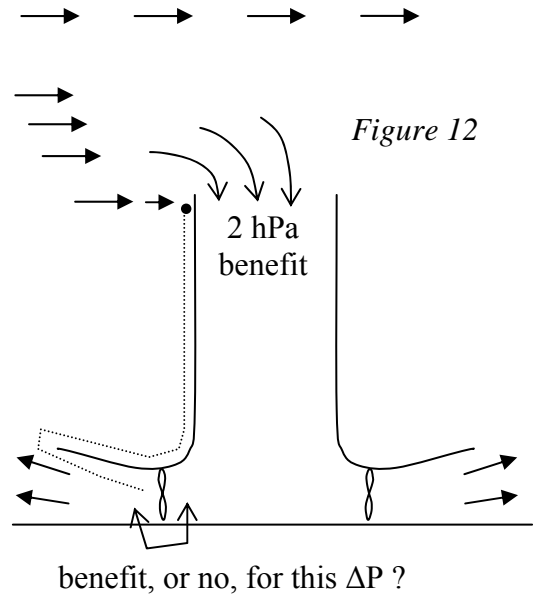
A large β angle is interesting only to reduce the outgoing kinetic energy, but in the analysis we've just done, it is rather prejudicial, as it drives the outgoing air upwards, and helps creating a thick cool mixed air torus all around the tower. In fact, while the diagrams are often, as fig. 11, drawn with such a $\beta > 0$ angle, the computations and modelling are sometimes made with $\beta = 0$, which is rather heartening.

However, there is another problem with this project and energy balances, which is that the tower is supposed to produce more power when there is a fast horizontal wind around its top.

³³ Theoretically, the friction is turbulent if Reynolds's number, which depends on the air velocity, on the width of the room it can fill, and on its viscosity low value, is high enough. However, this turbulence consists in instabilities (here, of Kelvin-Helmoltz), which attract the lower layer's air upwards, and vice-versa. These instabilities fight against the stratification in which the outgoing air, which is cooler than the outer air, should spread horizontally. It is difficult to determine precisely which one of both effects overcomes, and how the frontier between these two possible behaviours depends on the system's various parameters.

This can be discussed in the same way as for the problem of the possible recovery of the kinetic energy at a solar chimney's top exit. Between a windless situation and a situation with a $v = 19 \text{ m/s}$ wind, corresponding to $\frac{1}{2} \rho v^2 \approx 2 \text{ hPa}$, there will be a 2 hPa benefit for the incoming air ; but the immediately neighbouring air which must stop just outside the tower's top will effectively do it only if it finds, in front of it, a high pressure.

The pressure difference, which is also equal to 2 hPa, could be transmitted through the hydrostatic equilibrium (integration way in dotted line) down to the tower's base and finally oppose the turbines rotation. Therefore, it isn't sure that the system's global balance is $+2 \text{ hPa}$: if I'm not mislead, it could only be 0.



II.B.5 A very criticisable modelling of the energy towers

While energy towers are mainly studied by scientists from the Haifa Technion Institute, under D. Zaslavsky's and R. Guetta's direction, the publication which I first read about this idea was from a Tel-Aviv University competing team^{xvi}.

After an abstract where we can read that a 800 m high tower with a 200 m radius could produce as much as 4500 MW, this article begins by some arduous physical formulas, but keeps on with graphical results which makes it much easier to criticize.

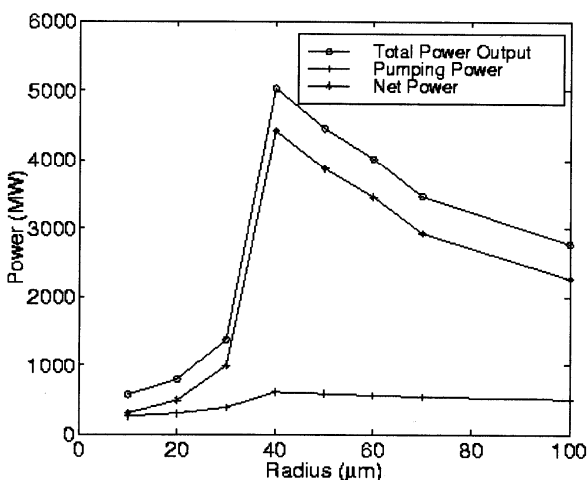
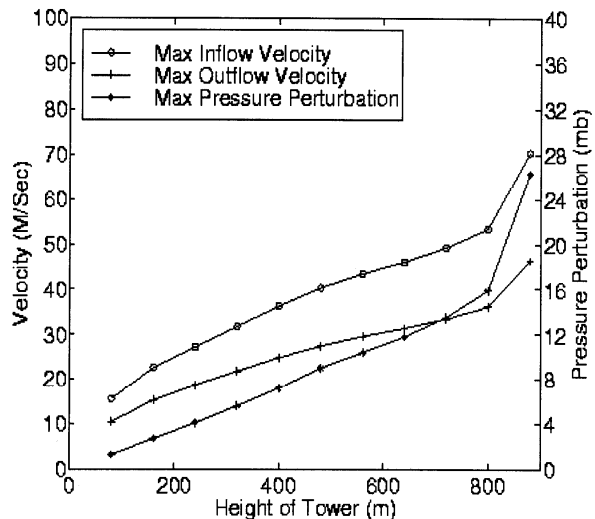


Figure 13

In the right hand part of the graph, the gross power output rises when the drop-lets radius decreases, which is normal (they evaporate faster, then contribute earlier to the air's negative buoyancy, thus the air flow is bigger).

But, from 40 μm to 30 μm , the power is divided by 3 (and again by 2 for 10 μm), which no common sense demonstration can possibly explain.

Figure 14 aside is equally strange : when the tower's height varies from 800 m to 880 m, the velocity suddenly increases by 30 %, while, with the same intervals, this rise had never been higher than 10 % in the whole range from 500 m to 800 m.



A likely understanding of these strange features is the following :

- ① There are again major uncertainties in the operating fluid energy balance.

The authors computer calculations consist, from a cell with various physical parameters (velocities, pressure, temperature, hygrometry, number of droplets with various diameters), in deducing the values of the same parameters at the next time, either for the same cell if the air speed is low, or for the lower cells if it flows downwards quickly. Here, nothing odd.

But this doesn't tell us where the parameters relating to the incoming air come from. For some of them (temperature, hygrometry, number of droplets), no problem : scientists may legitimately choose their assumed values. For the velocity's vertical component, a continuity equation must be obeyed : there can't come more or less air in, than what can be computed, a little lower, from the cell's whose behaviour is perfectly known.

The last one is the pressure, or, to be precise, its perturbation value (π) from a static distribution with regard to altitude. Here again, the authors assume that they can choose the boundary condition by themselves, and, without any other idea, they take the simplest one : $\pi = 0$ for $z = H_T$.

But this is undue : in fact, air can come to the tower inlet with a velocity around 60 m/s, only if it has been strongly attracted there. In fluid mechanics, only a depression can create such an attraction. By assuming that $\pi = 0$, the authors suppose that the incoming air has, with no cost, a large kinetic energy.

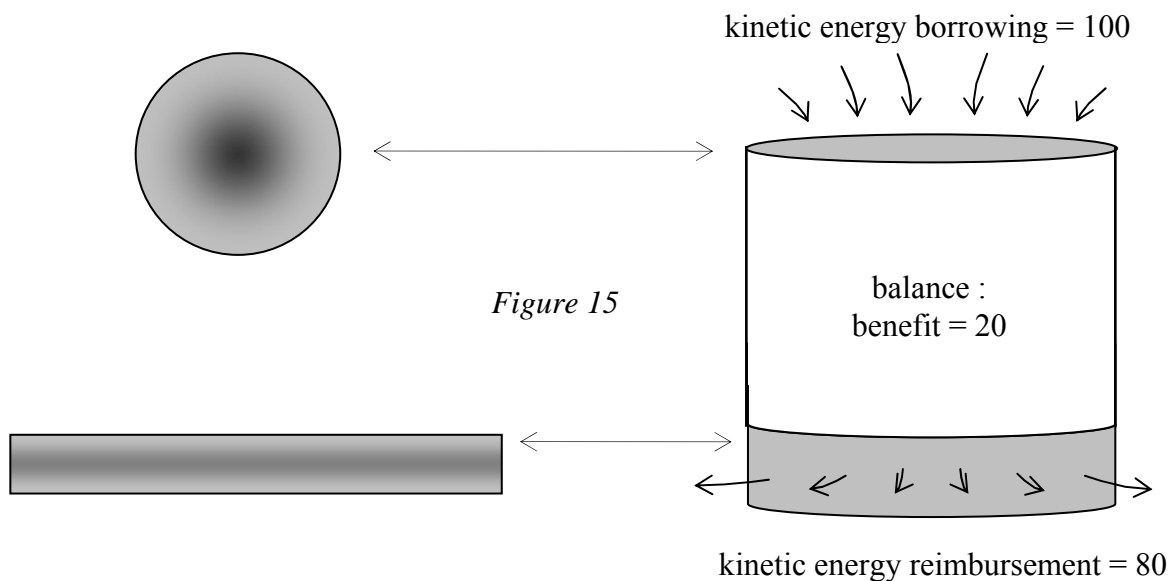
Fortunately, they give it back at the exit, as there is the same boundary condition at the diffuser which, here, is just a lateral opening at the tower's base. But three strong remarks remain :

- even if I've previously criticized those who think that, when outgoing from a pipe, air would lost all its kinetic energy without any counterpart, it may, symmetrically, be too simple to assume, without any other explanation, that all this kinetic energy is automatically recoverable : because of the turbulence in and after the diffuser, it is probably partially unrecoverable ;

- even if they give this energy back with the same $\pi = 0$ boundary condition, they keep it in a way, as, through the computation of this kinetic energy, they get the value of the electrical power they expect to produce with this diffuser's turbines ;

- and what they hand back is not exactly equal to what they had borrowed. The inlet area is exactly equal to the outlet area³⁴, but their shapes are different (plane circle / cylinder slice). At the outlet, the velocities profile is approximately parabolic with respect to the altitude z ; if we call the highest 40 % "the parabola's top", they fill 40 % of the cylindrical diffuser's area.

At the inlet, there is a comparable parabolic profile, but with respect to the radius r . So, the central 40 % top of the {velocity / horizontal co-ordinate} curve, obeys the πr^2 law, and it accounts only for $(40\%)^2 = 16\%$ of the cross-section's area. As we've got such maximum velocities only through a lower fraction of this area, they must be faster, for the total flow to be the same. That's what can be seen on figure 14 (previous page), with around 50 % higher inlet maximum velocities than outlet ones.



This modifies the energy balances that we can make, among entrance and exit, for the same total air flow, but with volume elements contributions which are now weighted by $\frac{1}{2}mv^2$: in the integral calculations, where v is low, the result is even lower than for the air flow, i.e. still near to 0,

³⁴ The tower's radius is half its height. As, in addition, the diffuser's height is constantly assumed to be half this radius, the inlet has exactly the same area as the outlet (simple comparison of a circle's area and a cylinder's).

Clearly, if the outlet area were smaller, the outgoing velocities would be higher, and the system would have to hand back a lot of kinetic energy, thus the air flow would be much lower ; if the outlet area were larger, the benefit from the inlet gift and the outlet reimbursement would be so high that the numerical simulation would probably show an unlimited acceleration, and never get stabilized. That's probably why, without any logical reason, as various parameters are tested, the inlet to outlet area ratio is always kept equal to 1.

thus not very different ; but, where it is higher, this difference is amplified by this integration. So, the inlet's freely borrowed energy will be higher than what is handed back at the outlet. With perfect parabolic profiles, they're in a 35/27 ratio (Cf. Appendix 5, pages 164-165).

This energy profit will result in an increase of the air velocity inside the tower, then an increasing air flow at in- and outlet, and eventually an even higher energy profit. The modelled system operates like an amplifier automatically reintroducing into the inlet a little more than what it measures at the outlet. Such a situation has a name in physics : Larsen's effect.

② Of course, if there were only this Larsen's effect, the system would never reach a steady state, and the authors couldn't publish apparently satisfying results. In fact, we have three contributions to the energy balance :

- the cooling and negative buoyancy effect which, even much smaller than Larsen's effect, still exists. In a situation of a quasi-equilibrium between the two following effects, it can even be the last straw, able to make this very sensitive system fall towards either stability, or instability ;

- Larsen's effect ;

- and a braking effect, with an ad hoc operator representing the turbulent energy losses.

This operator introduces a " turbulent viscosity" $\nu_{d,q} = (C_{t,d,q} \Delta)^2 \left| \nabla \left[(u^2 + w^2)^{0.5} \right] \right|$ (15)

which will afterwards play a similar role to the "true viscosity" in Navier-Stokes type movement equations. The article tells us, without other precision, that " C_t is constant and Δ is the analogue of mixing length".

About C_t , we can notice that this year 2000 article reproduces, for all the modelling part, the principles and probably the algorithms of a three articles series, published from 1988 to 1991^v and signed by three scientists including two in common with the most recent article.

These articles deal with the natural phenomenon which is the energy towers analogue : sudden falls of great air masses, cooled by the evaporation of water droplets from a cloud. In the 1991 article, we can read : "computational stability is also achieved by choosing the correct value of the turbulent coefficient C_t . Reisin and al. (1988)³⁵ showed that for ... a grid of $\Delta z = 300$ m and $\Delta r = 150$ m³⁶, computational stability is achieved for values of C_t within the range 0.95 - 1.15 ...".

C_t appears as an ad hoc constant, with no link with observation or theory (oppositely to the constant, also named C , which is used to estimate the turbulent friction in a pipe), but empirically determined, for a given computer grid (size of the cell where the computations are made), so that to fulfil the only condition that the computations shouldn't diverge.

³⁵ 1st of these three articles.

³⁶ Do these two sizes, one being vertical and the other radial, correspond to the unique parameter Δ lying in the turbulent viscosity ν expression ? Yes, as, in the same 1991 article's appendix A, we can read : $\Delta = (\Delta r \Delta z)^{0.5}$ with the same commentary : "an analogue of mixing length".

No doubt that this "brake" was adjusted so that it precisely compensated Larsen's effect, even if the authors may not have been conscious that they were hiding an artefact, and giving the appearance of scientific work to something which had no longer any link with the physical reality.

Noticeably, the model was operating quite well over a rather large range of heights, hence of velocities : indeed, Larsen's effect gives the air an approximately constant kinetic energy profit, thus proportional to v^2 , while the turbulent losses, thanks to v which varies as a function of the velocity to the power 1, vary with regard to v not to the power 1 as for laminar friction, but to the power 2, which is a correct approximation of real turbulence.

However, Larsen's effect was slightly depending on the tower's height : at a higher altitude, air is lighter, so, for the same mass flow, the inlet velocities must be slightly greater. Therefore, in addition to the shape effect (circle vs. cylinder slice) we've yet examined, we had another effect, slightly proportional to the tower's height, and which could help the results to grow rapidly.

(Besides, such a feature isn't surprising for a system based on the idea of operating at the maximum power point (mpp), thus with an approximately $h^{3/2}$ law, which is quoted (and judged as poorly justified) by the authors in their introduction.

A comparable effect was also taking place because of the evaporation cooling effect : the heavier outlet air didn't need very great velocities to represent the same mass flow ; therefore, it was handing back less kinetic energy, and Larsen's effect was stronger).

③ Can this explain the angular point we can see on figure 14 for $h = 800$ m ? Probably not. However, a solution lies in the article. A formula gives the grid sizes Δr and Δz , for tower's heights lower than 800 m : in this case, Δr and Δz are chosen so as to grow proportionally to the tower's height, up to, respectively, 20 and 30 m ; but, beyond 800 m, they're kept constant, which corresponds to an angular point with a downwards curvature. As the v brake was proportional to these grid sizes, it will equally have an angular point in the same direction. But the weaker the brake, the higher the velocity. So, it fully explains why, in figure 14, the velocity curves get an angular point upwards³⁷.

④ Same question for the sudden fall in the power output when the droplets radius becomes smaller than 40 μm ?

Without any other hypothesis, we only can assume that in this case, the vaporisation becomes so efficient and the cooling down so fast (which, as we saw previously, enhances Larsen's effect), that the "brake" proves insufficient, and that the software can't insure any longer the "computational stability" a correct value of the C_t constant was supposed to bring. This could have lead the authors to slightly raise its value in order to come back to convergent computational iterations. Such an additional brake, for radii of or under 30 μm , may then have generated a large reduction of the stabilization velocities, thus the power output fall.

³⁷ Strongly amplified as, from an equilibrium between two very intense and antagonist forces (C_t brake / Larsen), a small imbalance in favour of one or the other may have great effects, which makes the system very sensitive to small perturbations.

We can also see that no simulation is mentioned for a 960 m height (the next one after the 880 m item for which the results were the most spectacular), which let us suppose that, here as well, the computational program was unable to converge to a stable solution.

Most of these remarks have been submitted to this article's authors. They didn't wish to make any comment in response.

II.B.6 Conclusion

Most of the examined publications face more or less difficulties when it comes to make a correct energy balance between the far upstream (quasi-motionless operating fluid), the inlet (if it occurs with a high speed), the turbine (the modifications it introduces by comparison with a system which would freely evolve), the system's outlet, and the far downstream.

About the air as an operating fluid, the documentation of the Israeli-Indian project^{vi} is too much summed up and it can't be critically examined, even though this project's main lines don't seem to include fundamental mistakes like those which have just been described. The last documents relating to solar towers^{iv, xv}, or even the main part of the book "The solar Chimney"ⁱⁱ, aren't much criticisable, even if they consider perhaps too quickly that the tower outgoing air's kinetic is irrecoverable, while nothing proves that the depression generated by Bernouilli's equation is 100 % offset by the turbulent losses which are specifically associated with the tower's outlet.

Therefore, it would be useful that this question, which has perhaps already been studied by turbulent flows specialists, could be clearly settled, or seriously studied in order to base a consensus on precise arguments and facts.

II.C Other scientific remarks about the same publications

II.C.1 About the Australian-type solar towers

a) Correctly used, Carnot's efficiency concept can be useful to check other calculations

Other remarks must be made about M. Lohdi's already mentioned article^{xiv}, "Application of helio-aero-gravity concept in producing energy and suppressing pollution". First of all, as in other solar chimneys related papers, there is some confusion about the use of the air temperature value.

Indeed, in a table at the article end, a "Carnot's efficiency"³⁸ is estimated to be 14.2 %, probably from the comparison of the air temperature before and after its heating in the solar collector.

Table 5. "Rotor power production P_R and peak efficiency η for a location where the insolation is 1 kW/m²."

r_{tower} (m)	R_{coll} (m)	H_t (m)	H_{coll} (m)	P_R (MW)	η (%)
5	122	195	0.25	0.067	0.14
5	122	195	0.25	0.082	0.18
10	565	390	0.25	4.6	0.46
10	565	500	0.30	5.4	0.54
25	700	800	0.30	51.7	3.4
25	800	800	0.30	62.0	3.1
25	800	1000	0.30	84.1	4.2
25	800	1000	0.50	48.2	2.4
50	800	1000	0.50	132.1	6.6

A real Carnot's efficiency can be used as a reference, as it corresponds to the maximum efficiency of a system which would use a collector at a heat source, and then the ambient air as a heat sink. However, it seems very difficult to build such a system for reasonable cost and power.

If it's really just a simple reference, it means that in the author's mind, the fact that the solar chimneys operate an "open cycle" makes it impossible to set up a "Carnot's like" efficiency, adapted to solar chimneys ; but such a quantity is conceivable, as we saw in page 4 (see also appendix 1) that the theoretical maximum efficiency can, under some conditions, be written :

$$\eta = 1 - (T_{ex}/T_{ups}) = \lambda H_t / T_o \quad (1 \text{ and } 4),$$

where T_{ups} is the air temperature just upstream the turbines, T_{ex} the same air's temperature when it goes out of the tower, T_o the ambient temperature, and $\lambda = 10^\circ/\text{km}$.

And if M. Lohdi's idea were to set up its own indicator, then he does it in a wrong way, as he uses the air temperature variation between before and after its heating in the collector, which in fact has very little effect on the efficiency, and as he uses neither the temperature difference between the ground and the tower top, nor its height, both figures which the efficiency is proportional to (otherwise, even a "small" 200 m high tower could be substituted by a 10 m one).

By estimating a much higher "Carnot's efficiency" than $\lambda H_t / T_o$, M. Lohdi deprived himself from a verification element which would have been useful for his other calculations. For a 1 km chimney and a 300 °K ambient temperature, the true Carnot's efficiency is (10/300), i.e. 3.3 %. But his final table's last line shows, for this height, a 6.6 % efficiency. Therefore, there are necessarily other mistakes in this article.

³⁸ See footnote n° 6, page 4.

The first one is that, in his mechanical power calculation, M. Lohdi only considers the pressure difference between the chimney's top and bottom, calculated by an integration throughout the inner air column, as if it alone could be the cause of the solar chimney effect. Said differently, he totally forgets to take into account the pressure variation with respect to the altitude *outside* the tower. In reality, the cause of the warm air upwards aspiration in a tower, is the density difference between inside and outside (buoyancy means Archimedes force), but equations :

$$\Delta p = \frac{1}{2} \rho_m v^2 \quad (19) \quad \text{et} \quad \Delta p = (\rho_t - \rho_m) g H_c \quad (20)$$

make no reference to any distinction between inner and outer variables : the only subscripts t and m correspond to "top" and "bottom".

This results in a 2nd inconsistency : equation (20), giving the work which can be produced by the system, should be substituted by an integral, from 0 to H_c , of the difference between the outer specific weight and the inner one ; but, instead, we get the product of two figures, each one of them we can obtain through an integration with respect to z : $(\rho_t - \rho_m)$, and H_c ! The result of such a multiplication is proportional to z^2 , as the efficiency in the final table is more or less, although in reality we should only have a single proportionality.

These mistakes didn't come by chance, as it is possible to find others. For example, equation

$$\rho_t T_t = \rho_m T_m \quad (21)$$

is also mistaken, as, by application of the perfect gases fundamental law, $PV/T = \text{cst}$, we could demonstrate from this that the pressure doesn't vary as a function of altitude !

Such remarks aren't made only in order to gossip, but to show that the more sophisticated the calculations are (the article goes on with a series of formulas where we can find exponents like 15, 1/11, 7/3 or 19/2), the more useful it is to check them against basic principles and common sense.

b) The drawbacks of two Australian tower options

The 1999 articleⁱⁱⁱ, as well as a description of the Australian tower project in a French newspaper^{xii}, suggest that a cheap and efficient way to store the daytime received heat, return it by night, and thus spread the power output over a longer period than only during the maximum lighting hours, is to lay water-filled black plastic bags on the ground

But, as we saw about solar ponds, water has an unexpectedly low thermal conductivity, around 0.6 W/m.K (lower than for glass). Therefore, for a reasonable heat flow to be transferred downwards, e.g. 600 W/m², the temperature gradient must be equal to : $(600 \text{ W/m}^2)/(0.6 \text{ W/m.K}) = 1000 \text{ K/m}$. For a 10 cm thick layer, a 100 K temperature difference would be needed between the bag's top and bottom ! Water indeed behaves, in fact, as an insulator, if it's heated from above.

The solution is, as it was corrected by the article which will be examined at the next point, that these bags aren't totally black, but have a transparent upper side, only their bottom being black. During daytime, the water is indeed heated from the bottom, as in a pan, and convection can efficiently spread the heat ; by night, the above passing air cools the water down from its top, which is equally favourable to natural convection and to an efficient use of all the bags stored heat.

Another problem is that some illustrations published about the Australian tower project, as well as the same French newspaper's article, suggest that their promoters would like to consider the collector as a greenhouse, and to try to get additional income through agricultural use.

However, a desiccating wind will permanently pass through this greenhouse, and this will necessitate permanent irrigation. And we're supposed to be in a desert, where fresh water is scarce and expensive (fruit drying is also set forth, and is more rational from this point of view).

But, overall, this permanent introduction of water, which will evaporate until the air is steam saturated, will be a very efficient brake³⁹ against air temperature rising, and, therefore, against the solar chimney efficiency itself. If air passes from 30°C to 60°C in a moist atmosphere, the steam percentage can grow from 4 % to 20 %, which uses, for 1 m³, 300 kilojoules, i.e. 7.8 times more than dry air heating : the solar chimney's efficiency could be reduced in the same proportions (- 88 %) ! So, a classical solar chimney can operate correctly only in a dry environment.

This phenomenon could explain the Manzanares prototype's very low annual efficiency, in particular with respect to its peak power (Cf. footnote 1, where we noticed that the quotient of the annual work output and the peak power was 880 h, while there are 10 times more hours in a year). It may be that only the hottest summer day allowed a perfectly dry behaviour, thus with the hoped efficiency, while during spring and autumn, and after each rainy day, a large part of the collector's solar energy was in fact used to evaporate the water percolating up to the surface or to the plants roots (so, in its 1984 article, Haaf¹ was explaining the albedo variations by the fact that during the spring, there was vegetation in the collector, which got drier, and thus clearer, during the summer).

This shows a danger for solar chimneys : if we let the rain, even if it's scarce, penetrate into the collector, the ground drying heat will be as much wasted solar heat. Therefore, there would be a double interest to collect this rain water (anyway, it is necessary to let it flow down from the glass roof so that it periodically cleans its dust) and to store it apart : the collector ground remains dry in order to keep the highest chimney's efficiency ; and we gather fresh water, which, in a desert, is never useless (we could recover in this way the synergy with agriculture that was wrongly imagined through the idea of using the collector as an agricultural greenhouse).

³⁹ Which is the counterpart of the latent heat exchanges great efficiency, in particular through evaporation, as in the energy towers.

c) Recently developed model for the collector's thermal behaviour

We've already seen, page 10, the following diagram about the solar chimney's collector :

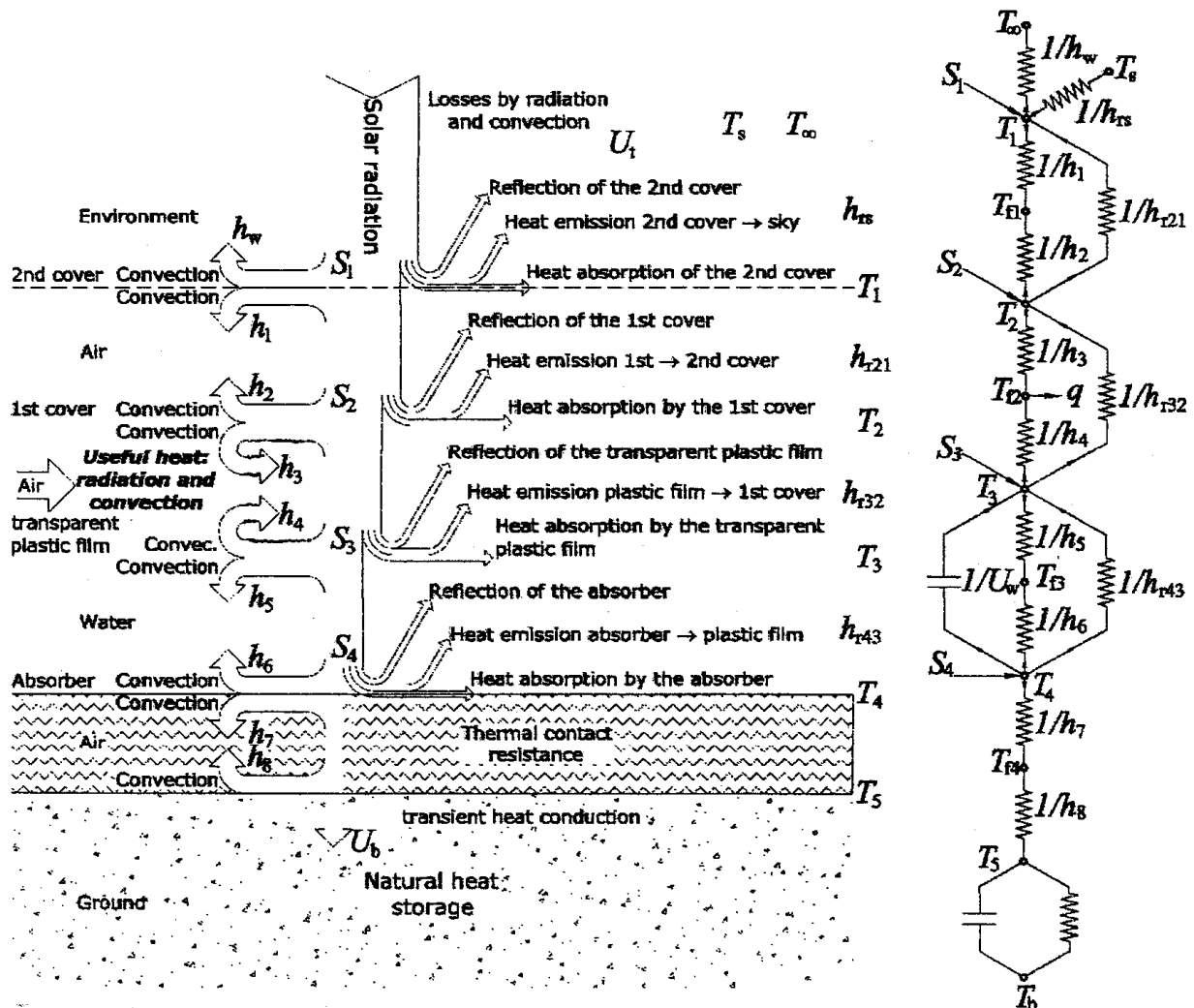


Fig. 3. Thermal network for the collector of solar chimneys.

It represents by itself an important modelling effort. More, this model is to be solved for each of 300 values of the distance r from the system's axis, and for 48 values of the time t . In previous publications, there was no model of the system's thermal behaviour under different conditions or control parameters : more or less black ground, more or less high velocities, more or less thick glazing, more or less oblique sunrays, more or less warm incoming air, etc.. Thus, we must warmly welcome the fact that such an article corrects this weakness.

Therefore, we won't too much criticize the fact that it could have been even more comprehensive, through describing the glass, water, etc. behaviour at different wavelengths, both for solar light (visible and close infrared) and thermal radiation (farther infrared, Wien's law) which are the basis for the modelling of radiation transfer coefficients (the h_r type terms).

We'll only make, instead, some common sense remarks, understandable by any physicist, and which however suggest that such a model can be improved.

The first one is about the light flow. Neither in the previous page diagram, nor in the article's mathematical formulas, can we understand that the upwards light, after a reflection or a reemission without wavelength change, may, before reaching the outer atmosphere, interact with the different collector elements, either by absorption, reflection or reemission (contrarily to what a little principle diagram at the article beginning was suggesting). Only the light flows transmitted by refraction from above are taken into account for such an interaction. (The left-hand diagram would bear the same critics about thermal infrared upwards emission, but the right-hand one is correct, provided that the transparent plastic film and both covers are totally opaque and "black" at such wavelengths, and that water is transparent).

Nothing more is said about how the transmission factors are calculated. We can suppose that the geometrical factors relating to the reflection and absorption of oblique sunrays have correctly been taken into account. However, in this case, to be perfectly precise, the transmitted light can't be only characterised by a single gross transmission factor, because reflection also has a polarization effect. When the light will reach the following dioptries, its part with a reflection-unfavourable polarization will reckon for more of 50%, thus, globally, this new flow will be slightly less reflected than at the 1st dioptry crossing. This effect is not huge but, when outgoing a double glazing, the dioptry is the 4th one, therefore this is not completely negligible.

More serious remarks concern the U_t , U_b and overall U_w terms, which, on the diagram, represent capacities. But, in the symbols table as well as in the matrix equations corresponding to the diagram, or even in the equation : $U_t = h_w + h_{rs}$, they have the same dimensions than thermal conductances by m^2 , as those named h : they are $W.m^2/K^{40}$. The capacities main features, i.e. their ability to store heat, which is most important here, seem to have disappeared from these two parts of the document : nowhere can we read that their received heat flow would be linked to the variation (derivative with respect to the time) of their temperature.

According to this article, the heat flow associated to the U_w and U_b coefficients calculates by $U.(T-T_0)$ formulas. The $T_{4,0}$ and $T_{5,0}$ that must be subtracted from T_4 and T_5 are defined nowhere. If they are the value of these temperatures, defined at the same point, one second before, there remains a possibility to end with something logical. However, with a 1800 s pace, and no formula to take it into account, it isn't sure. Conversely, there is a risk that the authors have taken in fact a 0-time which would be the beginning of the day they consider, i.e. 0 h.

At, for example, the hour when the water is hottest, its derived temperature with respect to t is null, thus the water neither gives nor receives any heat from the rest of the system. Therefore, $U_w.(T_4-T_{4,0})$ should be zero. But U_w is a constant, and $(T_4-T_{4,0})$ won't be null if T_4 is the water temperature maximum and $T_{4,0}$ its value at midnight.

The formulas yielding U_w and U_b should also be discussed.

⁴⁰ Nothing seems to allow us to suppose that they could be $Z = 1/jC\omega$ type "thermal impedances".

For U_b , the combination of equations : $U_b = 2b/(\pi t)^{1/2}$ (22) and : $b = (k\rho c_p)^{1/2}$ (23)

allows to introduce a calorific capacity ρc_p and a time t , but only to the power $1/2$. The other part of the formula (23), the k term, still means conduction. Their combination gives a parameter which plays a role in the heat diffusion into a plane-bordered half-space. However, the introduction of a time variant, used as $t^{1/2}$ without more precisions, is a new reason to fear that the authors refer to a model describing a transient response to a stair (ΔT discontinuity with $t = 0$ at 0 h)⁴¹, while a model describing a response to periodical outer conditions, with a 24 h period, would seem to better fit to a solar collector.

For U_w , we've got a formula :

$$U_w = \frac{1}{t} \sum_{k=0}^{\infty} \left[\frac{2 L_w \sin(\delta_k)^2}{\alpha \delta_k [\delta_k + \sin(\delta_k) \cos(\delta_k)]} e^{-\delta_k^2 \alpha \frac{t_1}{L_w^2}} \right] \quad (24) \quad \begin{array}{l} \text{(with } \delta_1 = \pi/2 \dots \\ \delta_k = (k - 1/2) \pi \end{array}$$

which is even more sophisticated, and probably results from a multi-harmonic analysis. The main parameters are the water layer thickness L_w and a number α which is the thermal diffusivity, in m^2/s . This would mean that the heat transport from the bag's bottom to the water itself is mainly the result of conduction.

But the model also includes a convection heat transport parameter ($h_5 \cdot h_6 / h_5 + h_6$) from the water layer bottom to its top. It would be illogical that the water would be a carrier for the heat transport between its two faces, but that for its role of heat storage, it wouldn't benefit from the same convection. Yet, it is what is shown by the comparison of the equation which, in order to determine h_w , uses Nusselt's number Nu (which is classical when convection takes place ; more precisely, Nu is a multiplying factor used to correct the thermal conductivity k), with equation (24), which uses α - which depends from k - but not Nu (nor any other term involved in the convection, as for example the water's dilatation coefficient) !

It seems that in reality, convection efficiently stirs the water. Thus, there's no reason not to make the simplifying hypothesis that the water layer temperature timelessly becomes quite homogeneous, and therefore that the heat flow it absorbs is simply the product of its calorific capacity (mass multiplied by 4.18 J/g.K) and its temperature derivative with respect to the time t , which, by example, seems to be the mathematical description of the operating fluid air layer above it.

The result of the calculations which are made about this water layer are in figure 16 (next page) which shows, for different values of this water layer's thickness, the curves representing the electrical power output at various hours of the day. We can notice that, according to this figure 16, the water layer has a much lower regulating effect than in figure 17, taken from the 1999 articleⁱⁱⁱ which, about the same question, had been produced by the same SBp cabinet.

⁴¹ In such a transient response model, $T_{5,0}$ could also be the temperature to which T_5 asymptotically tends. Having a power of t at the denominator supports this idea of a convergence to an asymptote. The same remark could be done for U_w which is studied just further in the present page.

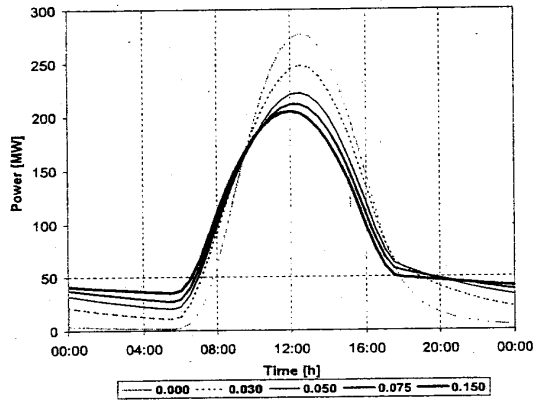


fig. 16 Effect of the water layer thickness of the on the power production.

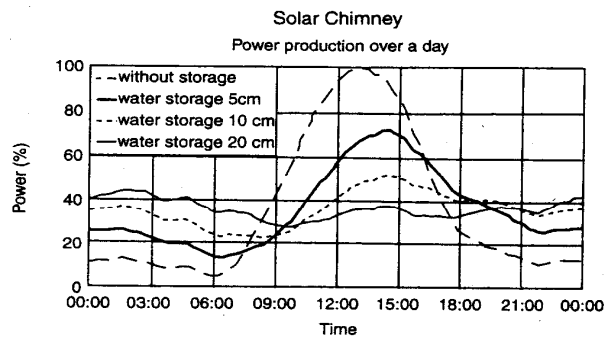


fig. 17 Electricity output during 24 h as a function of the thickness of the water layer.

Which one is closer to reality ? The right hand one shows some irregularities which probably reflect those of the model's data. But it has a big quality : the more water there is, the better regulated the curve is, but also the more delayed the midday luminosity peak is in the tower's output, which is a logical effect of all types of inertia, including thermal inertia. We don't find this characteristic in the left hand diagram, which is an additional sign of possible mistakes.

d) A calculation refinement which hasn't very deep consequences

Compared to M.A.K. Lohdi's article which I criticized previously, a recent article^{xvii}, from Th. von Backström, shows that some interested scientists correctly study this project. It implicitly underlines a phenomenon which is very often forgotten, including by me, and has a slight effect on the solar chimneys efficiency : the moving air energy balance must include the kinetic energy it has, in the tower, because of its velocity ; so, its pressure is lower than what it would be if the same air would rise more slowly ; but any adiabatic pressure fall has voluminal and thermal effects, which modify the air's buoyancy, and may finally influence the tower's electrical output.

However, two remarks :

- as we can read in any mechanical fluids book, it is necessary not to neglect the voluminal and thermal effects of a gas's movement, only if its velocity isn't negligible with respect to the sound's velocity in the same gas. This is confirmed in Th. von Backström's article, where this effect is involved through Mach's number, M , squared. M is equal to the air velocity divided by the sound's one. But, for a possible 15 m/s velocity, $M = 1/20$, and the effect Th. von Backström underlines will be less than 1 %, thus widely lower than a lot of other uncertainty sources.

- from intuitive thinking (Cf. the thermodynamics 2nd law), we could suppose that the result we got with formula (1), and which says that a solar chimney's equivalent Carnot's efficiency can be computed as a function of the air temperature at the tower's bottom (before any acceleration) and at its outlet (after being slowed down), is likely to remain true : it is possible that the balance of the energetic effects linked to an acceleration under relatively high temperature and pressure, and those from a deceleration when they're lower, would offset the column-high integral of the buoyancy modification. Under, of course, the hypothesis that the kinetic energy recovery at the tower top would take place, and with a 100 % efficiency. If not, the problem is still there - I mean, the problem of how much can be recovered from this kinetic energy, an issue whose consequences are at least as much important as those of Th. von Backström's M-precise calculations.

The difficulty is that it requires to work with turbulence, which isn't easy. More, it often leads to use heavy computational tools, which can be dangerous, as we'll see next point.

II.C.2 About the energy towers, studied by the same team as in II-B-5

a) A forgotten power output reducing coefficient

We saw in the energy towers presentation (p.14-15), that their energetic feasibility was insured by the fact that they require less energy to pump the water up to the tower top's sprayers, than what we hope to produce from the downwards wind we create. This is shown by the theoretical ratio, (9) :

$$\text{Ratio}_{\text{water pumping up energy / theoretical power output}} = (18 \text{ g} / 29 \text{ g}) \times 3.5 \times \delta T / T \approx 12 \%$$

However, this water will be pumped up, but then it will come back down, as steam. If it had been lighter to pump up, it would also be lighter during its way down. What does it mean that this steam is light ? In fact, it is lighter than air : each mole of water vapour weighs 18 g, each mole of air 29 g. Therefore, the air steam-enrichment creates an other upwards effect : a positive buoyancy from the steam's lightness.

Therefore, the desired downwards effect which is the air cooling down, must be corrected by two upwards effects : the steam's buoyancy, which is proportional to the molar masses difference between air and water (29 g - 18 g), and the need to pump the water up to the tower's top, which depends on the water molar mass : 18 g. These two effects are complementary : by adding to the formula (8), a new similar ratio :

$$\text{Ratio}_{\text{steam-caused buoyancy / thermal negative buoyancy}} = ((29 \text{ g} - 18 \text{ g}) / 29 \text{ g}) \times 3.5 \times \delta T / T \approx 8 \% \quad (25),$$

we could find, as a total ratio to be kept under 100 % unless the system could operate, a particularly simple result (independent from the water molar mass, but also from the air dryness, the tower height, the air flow, the temperature variation, etc.), as it writes :

$$\text{Ratio}_{\text{upwards/downwards}} = 3.5 \times \delta T / T \approx 3.5 \times 17 / 300 \approx 0.2 = 20 \% \quad (26).$$

In the three Tel-Aviv University scientists' article, we find no mention of the fact that the air in which the water is vaporised not only becomes heavier because it is cooled down, but also lighter because its steam concentration rises. Therefore, if there hadn't been more serious mistakes, its numerical results (power output), would have to be systematically multiplied by 0.92.

The same fact hasn't probably been ignored in the Technion Institute work. In the general presentation document, it isn't mentioned, but an article mainly focused on automatic regulation questions^{xviii} gives the system's main thermodynamic equations. One of them is accidentally missing (the one which gives the generalisation of the perfect gazes state equation with a variable number of moles because of the water vaporisation), but the mass continuity equation indeed uses the steam creation rate, thus the 18 g. Then, it is unlikely that the 11 g - linked effect could have been forgotten.

b) A strange parabolic profile

In the discussion about Larsen's effect, page 41-42, we used the fact that the authors' results were showing, both at the tower's inlet and outlet, velocities with a parabolic profile with respect to the current point's coordinate.

Such a profile is natural in the case of laminar friction forces. In a turbulent regime, the classical profile is very different : the velocities increase sharply when we first get away from the system's wall, and then, progressively, yield sort of a plateau when we're far enough.

This is because turbulence is the triggering of swirls which occurs when Reynolds's number becomes too big, i.e. when a product $D \times V$ becomes too much times greater than the dynamic viscosity. At the system's centre, the size D of the space where a swirl could develop is large, hence the velocity V difference between the different zones of this central space must remain very low. On the contrary, when we're stuck in the edges' very neighbourhood, D is low, so V can grow : that's where the velocities differences are the greatest (until we get so close to the edge, with so high velocity gradients, that the viscosity becomes the main driving force again).

This shows that, in order to model the turbulence, it is necessary to use different enough operators from those which describe a pure laminar regime. This condition isn't fulfilled by the operators the authors have used. The following formulas have been written down :

$$F_{d,q}(\phi) = \frac{1}{r} \frac{\partial}{\partial r} \left(v_{d,q} r \frac{\partial \phi}{\partial r} \right) + \frac{1}{\rho_0} \frac{\partial}{\partial z} \left(\rho_0 v_{d,q} \frac{\partial \phi}{\partial z} \right) \quad (27)$$

$$v_{d,q} = \left(C_{t,d,q} \Delta \right)^2 \left| \nabla \left[(u^2 + w^2)^{0.5} \right] \right|, \quad (28) \quad [\equiv (18), \text{ p. 42 }]$$

$$\text{where} \quad |\nabla(\phi)| = \left[\left(\frac{\partial \phi}{\partial r} \right)^2 + \left(\frac{\partial \phi}{\partial z} \right)^2 \right]^{0.5} \quad (29)$$

Their user-unfriendly appearance comes mainly from the cylindrical coordinates r and z which are used. In fact, they're based on rather classical gradient- or Laplacian- type operators. Formula 27 simply corresponds to a friction force, as the same formula is present in the article which had been published in 1991 in the Journal of Atmospheric Sciences by the same authors, and as formula 28 was also present there, but with an additional term which is simply ν_0 , the "laminar" air viscosity. As it's very low, it has been ripped off the most recent article, but its previous presence shows that $v_{d,q}$ plays here exactly the role of a viscosity, except that it isn't a constant.

Does its characteristics fit with what we're looking for ? We've seen that a turbulent movement must have a low velocity gradient in its central zone, which means that any velocities space differentiation would be opposed by powerful "turbulent friction" forces. Therefore, if we'd look for a "turbulent viscosity" to play the role of the "true viscosity" ν , it would have to be very high in this central zone where the (mean value for different times) velocity doesn't much vary from one point to another.

But what formulas 28 and 29 show, is exactly the opposite : there are as many Δ (Laplacian) and ∇ (gradient) operators than was needed to get a correct dimensional equation, but where the velocities don't depend much on space variants, these multiple derivatives will still yield very low results, while they should have given the greatest possible values.

Instead, the system probably reacted through the generation of a rather uniform behaviour : nowhere did these space derivatives yield null results because it would mean a null viscosity, and thus a possible computational divergence ; and nowhere did they yield very high values, for it would correspond to a strong viscosity, which in return would prevent the development of large mean velocities differences among neighbouring points.

Therefore, it isn't very surprising that the result is an almost parabolic profile, corresponding to what in the real life is a laminar flow, while here the Reynolds's number value is at the opposite of such an hypothesis.

c) An absolute confidence in computational tools

A lot of this article's characteristics can be explained by the fact that it uses a computational tool which had been set up 10 years before, in a different goal : thoroughly study the very complex interactions between turbulence and droplets sizes spectrum (the droplets evaporate and become smaller ; the biggest fall faster ; on their way, they can absorb smaller ones ("coalescence") ; etc.).

Such a refinement was adequate to model a natural phenomenon in the field of the atmospheric sciences ; but these scientists forgot that, here, they were free to choose all the system's parameters, and in particular that nothing forbade them to spray only droplets with a definite diameter. Having thus comparable behaviours, the coalescence risk could be strongly lowered (which eases their evaporation), and, from a computational point of view, they could have reduced by 31 the number of variants they had to compute in each cell.

Most defaults of this article can be explained by the authors' too great trust in computers, reducing the attention they paid to common sense questions such as the boundary conditions or energy balances⁴². Why such a dependence on this tool ? First of all, because it was there, and already programmed.

But a deeper reason can lie in a small 1995 Nature article^{xix} which, headed "Tower of Babel", presents the project, describes how it is managed by the Technion Institute in Haifa with the help of noticeable public subsidies, explains that its goal is to produce electricity at 0.7 \$ cents per kWh, etc. But, the article's end raises the question whether to realise a serious prototype (200 m, 50 MW, 30 M\$), or to jump directly to a theoretical economical optimum size (900 m), but with non negligible uncertainties.

We can imagine that this led to a debate about the possibility to make preliminary experiments in order to secure the towers principles. But, in fluid dynamics, in particular in the most turbulent (with very great Reynolds's numbers), no real experiment is possible, to such an extent that the experimentation idea automatically refers to the notion of numerical experiments, i.e. with big computers. The authors' willingness to reuse the tool they had designed for atmospheric sciences, in order to estimate the energy tower's power output, may come from this.

d) A lack of reaction in front of surprising results

We've got here, to put it to an extreme point, a psychological experiment about how people can get fascinated by a both necessary and extremely powerful tool. In particular, we notice the lack of reaction and of "handwriting" checks in front of rather surprising results.

⁴² On their behalf, few real physicists worked on this subject, maybe because producing electricity only from water and ambient air could seem unrealistic and contradictory with the thermodynamics 2nd law (in fact, it isn't, because we operate an open cycle, and because these media aren't in thermodynamic equilibrium : to be in such an equilibrium when there is water nearby, air must be saturated with steam, which isn't the case here, as we choose, on the contrary, to be in a desert so that it is as dry as possible). Scientists used to pay little attention to this 2nd law were more likely to be interested in such an idea, which can explain that they weren't much respectful of the 1st law !

Indeed, the power output dramatic fall in the case of small radius droplets (fig. 13 page 39) is explained as follows : *"the net energy dramatically decreases when the radii of the sprayed drops decrease below 30 μ m. This is because the smaller drops evaporate rapidly producing saturated air in the air tower and preventing further evaporation"*.

This demonstration is clearly wrong. If we reach the air saturation, it is :

- a good news, because it means that we have evaporated a maximum of water, proportionally cooled the air down, thus increased its voluminal mass, and greatly contributed, even in the tower highest part, to the downwards movement we look for ; the smaller the droplets, the sooner they evaporate, the greater the cumulated effect on the whole process ;

- something which can't be lost : even if the further evaporation is reduced, it means that the temperature decrease will be slower, but starting from a cooler value ; as long as we haven't reached the reference value, we're cooler, and it is profitable. If we reach it, we also reach the reference air saturation level, so the remaining water quantity is also the reference one, thus everything is ready to keep on in a way which can't be less favourable than what we're supposed to be compared to ;

- a provisory state : if, at any altitude, the air is saturated, the continuation of its downwards movement will make it receive energy from the air above it, which presses it harder and harder (the pressure increases when the altitude diminishes) ; this energy results in a temperature increase ; but the same steam concentration, able to saturate the air at a low temperature, no longer saturates it when its temperature rises ; therefore, the vaporisation process can easily restart, contrarily to what this article's authors say.

Clearly, they lost an opportunity to discover that their computer program was generating an artefact, and to correct its inadequacies to their study's current object.

We can observe the same lack of reaction in front of surprising results, about the power output steep rise when the tower height increases from 800 to 880 m.

Sometimes, they seem to be astonished by the water quantity they must pump up the tower. In other circumstances, they seem pleased by such a result, and they quote it in a conclusion sentence including the word "optimal"⁴⁴, but they don't seem to be curious enough to investigate whether keeping on increasing the tower height would even improve this result.

None of both attitudes is appropriate. They could be compared to a controlled nuclear fusion research team, discovering that when a parameter varies from 100 to 110, the neutrons flow rises by 200 % ; who would consequently be delighted, without saying what would occur for a value of 120 because its computer simulations wouldn't converge any more ; but who at other times would be worried by the tritium additional quantity needed to operate the system with a 110 parameter. Such a behaviour would be absurd : for controlled nuclear fusion specialists, getting a divergence is the ultimate goal ; and being worried that a treble fuel quantity would be needed to treble the energy output, doesn't make sense.

⁴⁴ *"a set of optimal geometrical and physical parameters is presented, for which the net energy could be larger than 4000 MW (value for 800 m) and in some cases may reach up to 11 500 MW" (value for 880 m).*

Here, we're not in the field of nuclear fusion, and we don't expect any divergence. Yet, the authors probably found one. Was it the best attitude to push it discreetly under the carpet while publishing all their other results, or shouldn't they have tried to understand its origin, and discover the Larsen's effect their too simple boundary conditions had generated ?

e) Conclusion

Their mistakes have various prejudicial consequences :

① They could let people believe that such towers can really produce a dozen GW. We saw that solar chimney power outputs like in M. Lohdi's article can rather easily be checked against Carnot's efficiency, which is a rather radical testing of their verisimilitude. Here, it's more difficult :

- with no collector, the logic is to look for the maximum power point (mpp), by mixing supposedly unlimited air and water quantities at the tower top, therefore the efficiency approach is less obvious⁴⁵ ;

- an energy balance in which we'd hand back at the outlet (analogy with the water level which gets up below a turbine) the same energy quantity that we'd have borrowed at the inlet, isn't falsier than what we often find in various publications ;

- then, in order to prevent the system from reaching a very high mpp, there only remains the air turbulent friction (with a very high Reynolds's number), and the fact that if the air falls very quickly and if the droplets are too big and thus too few, evaporation won't have enough time to be efficient before the air goes out through the diffuser ; however, on these two very technical topics, it seems logical to trust specialists, which meteorologists are.

② This article's goal is not only to estimate typical energy towers' power outputs, but also to be part of a debate about their silhouette. They oppose to other publications describing rather slender towers (which have at least the advantage to ease the droplets sprayers displaying), by a double authority argumentation : criticism against the other side ("*it is absolutely unclear, on which theoretical or experimental studies they obtain the expression for the power output*⁴⁶ or the relationship H_T/R_T "), and use of their own results as a reference. According to their calculations, the net power output would be negative for any height lower than 1000 m, if it is four times the radius. They get their own very powerful results with a cylinder whose height is only double the radius, i.e. equal to the diameter !

⁴⁵ However, we could notice for example that when the height varied from 800 to 880 m, the sprayed water quantity, which commands the air cooling down, was only varying from 78 to 120 m³/s, i.e. a hardly higher than 50 % increase, while the power output was soaring from 4500 to 11500 MW, i.e. + 150 %. This was clearly inconsistent with the idea of a simple causal relationship between the negative buoyancy and the power output.

⁴⁶ a rather common $h^{3/2}$ type formula, like we've already met a lot.

Once this article had been published, it was unlikely that its algorithms principles (which are probably 99 % correct) could be questioned. Then its authors can oppose to competing projects (maybe even the solar chimneys). And if a controversy would develop, every non-specialists would prefer to get away from it, which would be a pity, as it is precisely a non-specialist approach, such as the present one, which enables to prove that this team's results are seriously questionable.

③ This team is indeed directly competing with D. Zaslavsky's one, from the Technion Institute, who works much more seriously. The fact that I first heard about the studies which I just criticized, shows that their diffusion is not limited by their poor scientific quality. This competition is mentioned in the Zaslavsky team's papers, which precise that among quite a dozen reviewers, these authors are the only ones who find diverging results. Very concretely, this competition could interfere with European research subsidies applications. With two projects, each one being backed by scientific results, which are strongly divergent and uneasy to classify, one in the "true" category and the other in the "false" (which is yet the reality), such subsidies are at a serious risk not to be granted for a sufficient amount.

Isn't there any criticism to express about the Technion project ? Some points will be seen further (exaggerated use of the mpp theory, controversial approach of solar chimney projects). Appendix 6-a (pages 166-167) describes sophisticated but useful studies which I don't know whether they've been done yet. Among main topics, the most unclear issue is the electrostatic enhanced droplets coalescence, but the difficulty to get detailed information seems to result from an industrial secrecy logic : no publications, demonstration visits for potential business partners.

From a strictly physical point of view, the only remark I can do is that the following diagram bears a slight imprecision :

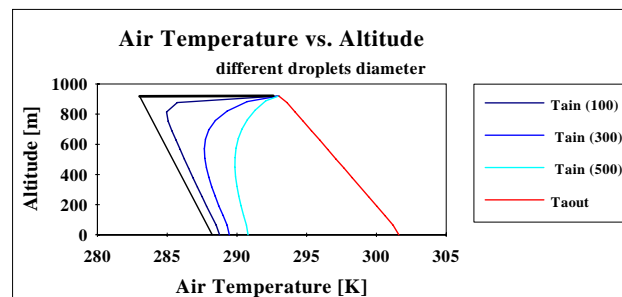


fig. 18

The smaller the droplets, the quicker they evaporate. Therefore, the first segment from the left, to which the central curves asymptotically converge, represents the characteristic of a permanent steam saturated air. Said differently, it is the " humid adiabatic gradient" curve (while the first from the right, "Ta_{out}", corresponds to the dry adiabatic gradient).

But a saturated curve is not a straight line : at a high temperature, the evaporation is very active, thus takes most of the work that the falling air receives because of its compression : the transformation quite occurs at a constant temperature, and the lower part of the curve should be quite vertical. Conversely, at a lower temperature, evaporation is less efficient, the falling air compression keeps some heating effect (temperature increase), therefore, in its upper part, the curve can be oblique. The presentation's authors admitted that, from this point of view, it was oversimplified.

II.D Technological and technical-economical difficulties

II.D.1 The catenary curve global elasticity

Very tall towers can be imagined either with a steel frame design, based on the triangles and tetrahedrons rigidity properties, and whose principle is to link compression-working segments by stiffening tension cables ; or like a reinforced concrete wall, with a homogeneous cylindrical surface, as for the Australian project.

However, we've seen ("the egg and the bicycle wheel") that, even in this case, the advantages of the tension structures justified to use cables. Their main advantage is that they only need to resist elongation, whilst a compression-working linear element must avoid to buckle, and thus must have an internal rigidity which requires a rather costly internal structure.

When we look at a stiffening cable in a metallic structure building, or at a bicycle wheel spoke, there's no doubt that, thanks to the fact that it works in tension, it's perfectly linear, and that the parameter designed to measure what we ask it to do (that its length vary as little as possible when we stretch it), thus its tightness coefficient, depends only on its constituent steel's elasticity.

However, the bicycle wheel spokes which are drawn in J. Schlaich's 1999 article ⁱⁱⁱ, are not exactly rectilinear⁴⁷. This can be explained by their weight's effect on a great span : any cable, with a finite T tension, and a non null λ lineal mass, takes the geometry of a catenary curve, as :

$$z = (T/\lambda g) \cdot \text{ch}(\lambda g x/T) \quad (26)$$

Therefore, a long stiffening cable's global elasticity is the sum of two terms, one resulting from the steel's mechanical properties, and one from the geometry : in formula (26), even if the steel were perfectly inelastic, we can see that the distance between two points linked by a constant length of cable, varies with respect to its tension.

For a stiffened enough cable, we can approximate this catenary curve by a parabola :

$$z = (T/\lambda g) \cdot (1 + (\lambda g x/T)^2/2) = \text{cte} + \lambda g x^2/2T. \quad (27)$$

A curvilinear abscissa calculation yields, for example, the cable length between two points at the same altitude, and whose abscissas are x_0 and $-x_0$:

$$dz = (\lambda g/T) \cdot x dx ; \quad \text{thus} \quad ds = (dz^2 + dx^2)^{1/2} = (1 + \frac{1}{2} (\lambda g x/T)^2) \cdot dx \quad (28)$$

and a final integration gives the total length : $L = 2 \{ x_0 + (\lambda g/T)^2 \cdot x_0^3/6 \}$, thus, if we put $2x_0 = L_0$,

⁴⁷ We can even more easily see it if we consider that it is the diameters which should oblige the distance between opposite points to remain constant, and that they clearly aren't rectilinear.

$$L = L_0 + (\lambda g/T)^2 \cdot L_0^3/24 \quad (29)$$

This length can be derived with respect to T, which yields the apparent elastic constant resulting from the catenary curve geometry :

$$(dL/dT)_{\text{caten}} = - \lambda^2 g^2 L_0^3 / 12 T^3 \quad (30)$$

(and we suppress the - sign because in fact, it is L which is constant and L_0 which varies with respect to the cable tension ; from now, we'll only use L).

This must be compared to the steel's intrinsic elasticity : with a cross-section S, a length L and a Young's modulus E, the elastic constant is : $(dL/dT)_{\text{intrins}} = L/ES$. Thus the ratio of the two elastic constants :

$$\alpha = (dL/dT)_{\text{caten}} / (dL/dT)_{\text{intrins}} = (\lambda^2 g^2 L^3 / 12 T^3) / (L/ES) \quad (31)$$

We can more efficiently simplify this expression by taking T from the purely elastic elongation ΔL : $\Delta L = LT/ES$, i.e. $T = ES \cdot \Delta L / L$, thus :

$$\alpha = (\lambda^2 g^2 L^3 / 12 (ES \cdot \Delta L / L)^3) / (L/ES) = \lambda^2 g^2 L^5 / 12 E^2 S^2 \Delta L^3 \quad (32)$$

The interest being naturally that the lineal mass λ is equal to the cross-section S, multiplied by the steel voluminal mass, ρ . We finally get :

$$\alpha = \rho^2 g^2 L^2 / 12 E^2 (\Delta L / L)^3 \quad (33)$$

This α coefficient (ratio of the two types of elasticity) could become higher than 1, and thus the catenary curve problem could overcome the steel intrinsic elasticity, when the length L is large (this isn't surprising, as usually sized stiffening cables don't encounter such problems), and when $\Delta L / L$ (which effect is cubed) is low. It is the case if we want to keep a fair safety factor against steel irreversible deformations, elastic limit but also creep. Therefore, if we want to keep a good tightness without being obliged to tight the stiffening cables every other year, we'd have to avoid very wide spans.

However, it is difficult to give a very precise numerical example, as different steels seem to have very different parameters. Young's moduli E are often slightly lower than 200 000 MPa^{xx}. For the elastic limit, we get for example, for a steel "316L", a 138 MPa value, while Young's modulus is rather low. This yields a slightly lower than 1‰ $\Delta L / L$. Formula (33) will then give, with a voluminal mass around 7000 kg/m³ :

$$\alpha \approx (7000)^2 \cdot (10)^2 \cdot L^2 / \{12 \cdot (150\,000 \cdot 10^6)^2 \cdot (0.9 \cdot 10^{-3})^3\} \approx 2.5 \cdot 10^9 \cdot L^2 / \{10^{14}\} \approx 2.5 \cdot 10^{-5} \cdot L^2 \quad (34)$$

α will become higher than 1 when L^2 becomes higher than around $4 \cdot 10^4$, i.e. for a length around 200 m. Therefore, the problem we've just described will probably appear for the same order of magnitude as for the Australian project, and will be the major issue if we want to go towards even wider spans.

However, for the Messine Strait suspension bridge project, 1800 MPa resistant cables are mentioned ^{xxi}. As well, the French skiing telepheric "Vanoise Express" ^{xxii}, with a 1800 m span, is made of two cables, weighing 55 tonnes each, thus a 30 kg/m lineal mass, and a cross-section area around $4 \cdot 10^{-3} \text{ m}^2$. They are stretched by 1000 t counterweights, i.e., for each of them, $5 \cdot 10^6 \text{ N}$. The used elastic limit is therefore $5 \cdot 10^6 \text{ N} / 4 \cdot 10^{-3} \text{ m}^2 \approx 1250 \text{ MPa}$. These 1800 or 1250 MPa will yield 10 times higher $\Delta L/L$ than the $0.9 \cdot 10^{-3}$ in (34). But the $\alpha = 1$ criterion gives an equation where we have, on one hand, $(\Delta L/L)^3$, and on the other, L^2 . Therefore the maximum span for which we're only limited by the intrinsic elasticity, would be multiplied by 30.

But these high performance steels are probably more expensive and, in order to build stiffening cables whose goal is to limit oscillations or warping, a high $\Delta L/L$ is not very good. Therefore, it's difficult to say whether this question is responsible, at least partly, of the fact that in the Australian tower project, wind is not fought by guy rods, whose span would be around thousand metres.

II.D.2 The wind's effects

a) Sorensen and the wind

Sorensen's patent, as I presented it previously (turbines at a tower top, creating an overpressure inside, and allowing this tower, made of a thin material, to hang to a buoyant gas filled balloon) is difficult to fully implement. We naturally think of the difficulty to let powerful turbo-alternators operate at an altitude of several km while being suspended to a balloon. But the greatest danger is probably the wind.

It seems indeed very difficult to fight at the same time against its various effects :

- very violent local gusts which would rapidly wear textile materials, so that it would be better to use semi-rigid materials (metal sheets, blown up from inside, therefore working in tension) ;
- possibilities that wind local overpressures exceed the internal overpressure (especially at the tower's base, where the latter is yet weak), and bump these metal sheets ;
- and the global push of the wind, on a several km x hm structure, fixed to the ground at only one point, and whose vertical orientation would only come from the hot air's and the buoyant gases' Archimedes's force.

b) The limit layer detachment outside the tower

For rigid towers, the same cross-section area, and the wind velocity, yield very high Reynolds's numbers⁴⁸, to such an extent that it often exceeds the curves we use to estimate its lateral drag.

Such a curve, similar to one which is shown in the Indian-Israeli project, is the following :

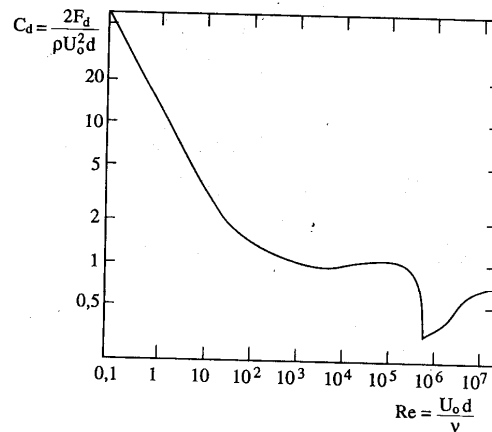


figure 19^{xxiii} : Drag crisis for a cylinder : for a Reynolds's number around 10^5 , the drag suddenly falls by around 50 %. This is a consequence of the limit layer transition from a laminar state to a turbulent state

Such an effect may be the background of a suggestion made in Le Monde's (French newspaper) 2002 solar chimneys presentation article^{xii}, where we can read : "the perfect circle induces ... aerodynamic effects (swirls) at the wind's passage. This is the reason why large industrial chimneys are surrounded by helical ribs, coiling on their outer face, in order to ease the air flows."

This technical artfulness may consist, for these "large chimneys" builders, to artificially trigger a local turbulence, and prevent a behaviour which would be locally laminar, but more turbulent at a global scale, because of the phenomenon of the "laminar limit layer detachment". If the limit layer is locally turbulent instead of laminar, it is less detached from the tower, and generates a smaller global swirl. That's exactly what happens in the diagram above : the Cd coefficient, thus the air drag, suddenly falls when Reynolds's number varies from 10^5 to 10^6 .

However, this suggestion could be useless for the gigantic towers we're speaking about : their Reynolds's number being around 10^8 or 10^9 , we're at a point in the figure (in fact, outside it) where this transition towards a turbulent limit layer has already taken place, where its effect has been consumed (the curve comes back up between 10^6 and 10^7), and where we can't expect much benefits from such an artfulness.

⁴⁸ Product of the velocity and the width, divided by the dynamical viscosity.

II.D.3 Solar towers : two questions about the neighbouring atmosphere

a) The solar chimneys low output in the beginning of the morning

Since the first studies for the Manzanares tower buildingⁱ, the heat leaks into the ground are not completely considered as losses, but also as a storage for a further utilisation : by giving back, by night, part of this heat to the air with which it is in contact, the ground allows a solar chimney nightly operating, with a low power output but a rather good efficiency (little turbulent losses). In the most recent publications^{iii, iv}, this storage effect is systematized : water-filled black bags are designed to realise this function. However, as these articles' curves show it, the most difficult time is the morning. The electricity demand is already high, the heat storage bags have been cooled down all night, and the lighting isn't yet favourable.

This can be understood by observing a landscape at dawn. Grass seems blue, whilst some hedge bushes look pale pink. This is because they face the red sun, when the ground is hardly skimmed by its horizontal rays. If the incidence angle is called i (with respect to the surface's perpendicular : $i = 90^\circ$ for a tangential ray), the received luminous power is proportional to $\cos(i)$.

But the fact that the ground is blue instead of black, proves that the sky is already rather luminous. Indeed, from a geometrical point of view, the air molecules reemitting the blue light towards the ground aren't on a surface, so that no $\cos(i)$ multiplies the power they receive.

The same with the solar heating : the direct atmosphere heating may already be efficient, while the ground heating is yet handicapped by the grazing direction of the sun rays (which, in addition to the $\cos(i)$ coefficient, increases the reflection on the glass, and thus lowers again the light power entering the collector). The tower air will hardly be warmer than at the end of the night, but the outer air will soon get warmer. As the electrical power varies sharply with respect of the temperature difference between inside and outside the tower, we understand that the power output curves with respect to the time, have a weakness at the morning beginning.

b) Will the ambient air condense, after being sent into the high atmosphere ?

The solar chimneys being designed for deserts, where the air is usually dry, we don't spontaneously imagine that they could generate clouds, or even storms. In fact, the following has been suggested to me by a scientist from Paris 7 University dynamic meteorology laboratory (Lmd in French) to which I was presenting my research.

The solar chimney air should be about 30° warmer than the ambient air, which creates a 10 % voluminal mass decrease. Therefore it will very rapidly⁴⁹, thus adiabatically, rise until this

⁴⁹ An important question is how much its turbulent interaction with the ambient air will create a mixing effect, and thus a reduction of the temperature differential. This is probably one of the points where the Manzanares experiment findings will be least transposable, as the air flow is to be multiplied by several thousands.

difference disappears. Assuming that the rising air gradient will keep on being "dry adiabatic", i.e. $10^\circ/\text{km}$, while it will only be $5^\circ/\text{km}$ around it, the temperatures equalisation will happen only around 6 km high, the "warm" air temperature having fallen by 60° and the ambient air being 30° colder than at the ground level. With a $7^\circ/\text{km}$ outer gradient, the same figures become respectively 10 km, 100° , and 70° .

But, if the operating air doesn't mix very efficiently with the ambient air, it can support a 30° temperature fall without condensation only if its initial steam concentration is 10 or 15 % of the saturating value. For 70° , this would be around 1 %. Yet, in a desert, the air is much drier than elsewhere, but there always remains some water vapour. So, it can hardly be as dry as the 1st of these two figures, and, for the 2nd one, it's clearly impossible.

Therefore, we must imagine a continuous air arrival, much differentiated from the ambient air, at altitudes where it could condense, either as liquid water, or more probably as ice⁵⁰. These are difficult cloud dynamics questions, but with options which all are unfavourable :

- either it spreads at an equilibrium altitude : the drawback is that it will generate a cloudy sheet which will shadow the solar collector, and sharply reduce the facility's power output ;

- or precipitations will bring back to the ground an equivalent water flow as what was sent up by the tower. In addition to the fact that we shouldn't let these precipitations come back into the collector (Cf. point II-C-1-b, page 47), we mustn't exclude, as the Lmd scientist told me, that they could be as violent as storms. Well localised rains have lesser shadows, but a violent and "artificial" storm could also include hail-stones, able to endanger the glass or polycarbonate collector's roof.

These hail-stones' size depends on the number of falls and rises they can undergo in the condensation generating upwards air flow. As this flow is turbulent, it will generally destabilize these hail-stones, letting them fall as rain drops, but we can't exclude that by chance, one day, it allows them to oscillate enough time to beautifully grow. Therefore, rather delicate statistics would be necessary to model the risk that, during all the tower's life, very destructive hail-stones damage the collector, and to estimate the corresponding maintenance costs.

If meteorologists' advice, or the Australian experiment, should confirm this risk, a solution could be to reduce the temperature difference between inside and outside the tower, so that the inner air wouldn't rise too high after outgoing from the tower. However, there are several potential drawbacks :

- this needs, in order to convert the same luminous power, to increase the air flow, thus to widen the tower, and probably to build, for the collector, the ribs which are further described (point III-A-2-f, p. 106-108 ; conversely, the fact that the collector ground and the inside air would be less warm, reduces the thermal losses) ;

⁵⁰ The solar tower promoters say "some hoar-frost". We can fear that less than 100 % of the steam condensation takes place at the tower upper edge, and that it could have more serious consequences.

- the efficiency could also fall as, if the outer lapse rate is lower than $10^\circ/\text{km}$, a reduced temperature gap between outside and inside will, in percentage, fall more rapidly. This particularly concerns the idea of building much higher than 1 km towers (see pages 98 to 105) ;

- and it doesn't totally exclude this risk, because if one day the lapse rate were close to $10^\circ/\text{km}$, the inner air could rise very high even with a low internal / external temperature gap.

II.D.4 Energy towers : two questions of energetic efficiency

a) The water droplets radius

We saw, as we presented this technology (p.15), that its feasibility depended on the :

Ratio water pumping up energy / theoretical power output

$$= (18 \text{ g} / 29 \text{ g}) \times 3.5 \times \delta T / T \approx (18 / 29) \times 3.5 \times 17 / 300 \approx 12 \% \quad (9)$$

Contrarily to the 8 % Ratio steam-caused buoyancy / thermal negative buoyancy (25) we saw p. 52 (to notice that the Tel-Aviv University scientists had simply missed it and that their results should be multiplied by 0.92), the 1st ratio can have real consequences well beyond its 12 % theoretical value.

First of all, neither the energy conversion by the turbines, nor the water pumping up to the tower's top, have a 100 % efficiency. Therefore, it will probably be necessary to deduct, in order to pump the water up, a notably higher than 12 % percentage of the effective electrical power output.

But overall, the Israeli project is based on the idea to have the best thermal contact between water and air, by spraying directly the water into the air flow. What falls inside the tower is in fact a moist fog. Therefore, we need to pump more water up than what will really evaporate and contribute to the air cooling down⁵¹. But, even if we can choose the droplets size, no solution is ideal :

⁵¹ Two remarks : ①, this method's interest is that the droplets evaporation goes on during all its fall, but a mid-height evaporated droplet will account only for a half in the air total cooling down which yields the total overpressure at the turbine level ; ②, even if the water droplet isn't entirely evaporated (which is the preferred solution in order to implement the electrostatic coalescence), its pumping up energy is not totally wasted, as its weight contributes to make the falling air-water mix heavier ; however, the percentage of this energy which undergoes the lower than 100 % efficiency at the turbines and pumps levels, will absolutely be lost, and burdens the final balance, which could in the worse cases use more electrical power than what is produced.

- a lot of sprayers are needed to spray well evaporating tiny droplets (because, even if we use a non negligible overpressure to eject them, small objects are quickly slowed down by the air friction, and the water jets range will be small). Besides, they will face an incrust risk because of their narrow diameter. All this could reduce the economical efficiency ;

- conversely, a larger radius reduces the evaporation, and this deteriorates the 12 % ratio (as well as the economical efficiency of a system whose pumps must be bigger). To limit this deterioration, we should let more time for the evaporation, i.e. lower the air velocity. But this reduces one of the main theoretical advantages of the energy towers : the fact that we can target to rise the power output up to the mpp (maximum power point) by letting the water and air flows increase without any other limit (notably : no limit about the input) than the one which results, proportionally to the air kinetic energy, from the turbulent losses inside the tower and after the air goes out of it.

The Technion Institute project, such as presented in the document which is most used here ^{vi}, seems to have found a correct compromise between these various dangers. However, they pay a price for it, through a droplets projection overpressure, about hundred metres of water pressure, which is non negligible in the global energy balance. Finally, the water pumping up losses are about 1/3 of the power output the mpp theory yielded.

Thus the interest, for some favourable topographies, of the solution exposed in the Assaf & Bronicki 1989 patent ^{vii}, which, without explicitly referring to the above dilemma, mentions an evaporation time order of magnitude (1000 s) adapted for droplets whose diameter (0.5 mm) seems large enough to help to improve the energy balance while saving some costs and reduce the sprayers incrust risk. Conciliating the use of not too small droplets, a sufficient time for their evaporation, and yet a mpp operating point, requires that the evaporation volume is equal to the product of this rather long time by this very high voluminal flow. This can be nothing else than a large "air dam".

Compared to a hydroelectric dam with the same volume and which, classically, is filled and emptied (sometimes very partially) only once a year, the cool air flow will here be equal to the volume divided by some minutes. This will offset the fact that the cool air negative buoyancy is much lower than the water's, and we'll find a comparable power output.

Knowing that it is easier to build a dam when it only has to hold cool air rather than the same volume of water, and that the location can be chosen only with respect to its topography without any necessity to be downstream of a river, the technical-economical comparison with hydroelectric energy, yet very profitable, seems rather promising.

b) The reference air characteristics and the risk of scale diseconomies

We saw at point II-B-4 (p. 37 to 39, diffuser) that an important risk is that the cooler and moister air which goes out from the tower bottom, could mix with the surrounding air. From meteorologists advice, it appears that this risk could be real in the afternoon (which is precisely the time when the energy towers could be most efficient), when the sun heated ground creates a turbulent air convection in the atmosphere's first kilometres.

Would there be a significant difference between the temperature profile (and therefore the density one) in the same desert, without and with towers ? If the surrounding air were mixing (in a possibly even thicker layer than the tower height) with the cool and moist air it releases, this tower's presence could have four effects :

- contribute to cool the outer air down, thus to raise its density, which reduces the inner air negative buoyancy ;

- contribute to increase the outer air steam concentration, thus to lower its density, which could attenuate the previous effect ;

- from the same cause (outer air steam concentration increase), raise the heat exchanges by far infrared radiation emission / absorption, with the ground as well as with the other atmospheric layers, or with the space (ultimate heat sink). If the ground mainly gets refreshed by convection, then these radiant exchanges main effect could be to cool the tower outer air down ;

- and, least probable but most important, to enrich the tower incoming air with steam, so that it would become more difficult to evaporate water droplets in it and to create a negative buoyancy. The system would be poisoned by its own waste, as it may happen in other industries, with the difference that here this waste disposal is very difficult to manage.

The more towers we'll build, the greater these effects could be. However, building few of them isn't very rational if we must dig a canal to bring sea water to a desert's middle : such a canal is very sensitive to scale economies, we'd better dig a canal with a fifty times bigger capacity if it enables us to produce fifty times more electrical power (or, by desalination, fifty times more fresh water). That's why it would be a real pity if the interaction between towers and the ambient atmosphere would generate scale *diseconomies*.

These questions seem very difficult to settle :

- There could be a competition between ① the possibility that the tower outgoing cool air could be dense enough to "crawl" by the ground and avoid to be mixed with the ambient air ; and ② the risk that the globally turbulent context could however enforce such a mixing, and suppress this air's density advantage and the stratification effect which resulted from it. But the suppression of this effect will positively retroact on the turbulence intensity, which makes the system even more difficult to model than an "ordinarily turbulent" system.

- all this modelling must be realised at various scales, at least :

① at the scale of the tower nearest environment (which already forbids to reason like in developed turbulence, and requires that we make approximations to model this turbulence, from a mechanical point of view as well as about its mixing effects) ;

② at the scale of a group of towers in order to correctly take into account the problem of scale diseconomies we've just mentioned ;

③ and at the scale of Hadley's cells, first because the action of a lot of humid air creating towers could marginally modify them, and also because, as D. Zaslavsky^{xxiv} argues on this issue, these cells cycle (corresponding, above a desert, to a downwards dry air movement) may keep the main influence on the towers surrounding air characteristics, as only some % of these cells world-wide dry air production, would be used by the energy towers.

II.D.5 Electricity production from solar ponds

The Technion Institute research team seems to have focused on this energy tower project after having studied the solar ponds and the possibilities to make them produce electricity. This idea is quite abandoned today. Therefore, the following remarks are just for historical interest.

The patent in which a low pressure steam (and incondensable gases) turbine system is fed by a solar pond bottom warm water spontaneous flow, whose dynamical analysis has been criticized previously, also shows, from the principle diagram which describes it, two particular uncertainties.

First, this warm water spontaneous flow advantage must be compared with the cost of the solar pond surface water "showers" which are supposed to ensure the steam condensation after its expansion in the turbine. But, on the diagram, these showers look like an accessory detail, as the warm water incoming device seems to be a much more massive part of the system.

If this hypothesis is true, it doesn't obey the thermodynamics principles : for quite every thermal machine, and even more if its heat source and sink have close temperatures, the heat quantity that the heat sink must absorb is close to what the heat source must provide. Thus, the diagram's small shower must have a comparable delivery as the big warm water flow⁵² in the drawing's centre, and these droplets fall, with a height around 1 m, will use up a widely higher power than the some centimetres of altitude difference we save, at the heat source, by avoiding to pump the water up to the facility centre (nevertheless, this pumless device remains artful).

A second imprecision is the following : on the drawing, we can see that it would be a small floating plant, just berthed at a quay. By analogy with the thermal energy of the seas, this allows the interesting prospect of "skimming" the ocean and converting, from place to place, the temperature difference between lower and upper layers. But the patent doesn't say whether it would operate in such a way, and, in the affirmative, how the power output would be transferred away.

⁵² unless we'd accept a wide gap between the cold water's temperature and the one corresponding to the pressure of the steam we have to condense (which could be the case, because, in order to work with very low pressure steam, the turbines must be designed for very large steam flows). This would make the thermodynamic efficiency fall, as the heat sink wasn't already very cold, and the heat source wasn't very hot.

II.E Environmental effects

Generally speaking, renewable energy conversion systems are rather environment-friendly, even if some hydroelectricity or wind power projects rouse real reserves. It could take 2.5 years for the Australian solar tower to save the CO₂ volume used up by the makers of its various components (steel, glass, concrete, turbines), which is, in my opinion, a proof that it is beneficent (by comparison with the tower's 60 years theoretical lifetime, and with its 20 or 30 years financial depreciation period), but some radical conservationist groups⁵³ estimate that this 2.5 years ratio is a reason to criticize this project.

However, the points that, I think, must be most thoroughly checked, are those which are directly linked to the towers operating.

II.E.1 The solar chimneys

Any macroeconomic human activity has an influence on the environment. Indeed, for the Lmd scientists, one of the solar chimneys effects will be that, if it is well insulated (and even more if there is a double glazing), a solar collector will behave, in its exchanges with the atmosphere, as a rather cool surface, probably giving to it, each afternoon, less heat than the equivalent naked desert it replaces. However, the tower outgoing warm air will probably have the most important effects.

a) Can we provide the world electricity needs from solar energy with a low physical efficiency ?

It makes sense to try to convert solar energy with a low physical efficiency, if the costs are even lower and if land is costless and unlimited, which seems to be the case for a desert. That's what justifies the present thesis, as well as other researches, for example about thin layers photovoltaic electricity⁵⁴ (amorphous silicon).

However, the available deserts aren't completely unlimited. We can read in "The solar Chimney" that 1 million km² would be required to provide the United States with all the primary energy they need ; the Thar desert, which seems interesting for India, could as well have a hardly sufficient area.

⁵³ the Friends of the Earth, quoted by the French magazine "Sciences et Avenir", October 2002.

⁵⁴ If this technology would reach really interesting power mass production costs, and the same for the solar towers, the only drawback being the large warm air quantity that each of both technologies would release into the deserts high atmosphere, a good idea would be to "recycle" this heat by combining them : we'd just have to set photovoltaic panels inside a solar tower collector. The solar power would first be converted through the photoelectrical effect, and the remaining part, i.e. what is converted to heat in the silicon if it behaves quite like a black body, would heat the collector's air and drive the solar tower turbines. Both efficiencies would be added up, and the necessary ground area, as well as the released warm air quantity, would be divided by two.

Besides, it could be prudent not to use too big a proportion of such deserts' area. Indeed, air is often dry there because it comes from a high altitude layer where the air is cold, and the water vapour concentration is low⁵⁵. But, conversely to these downwards flows, the solar energy production systems which collect a large part of the incident energy but convert only a lower part into electricity, release much heat, and create upwards air warm flows.

Therefore, especially if the solar collectors area is a large proportion of the available desert, there is a risk of perturbing the local exchange system between lower and higher atmospheres. If the air goes upwards instead of coming from the sky, this means that it comes from the ground level, with a risk that it could come from the sea and be moister. Clouds could appear, so that the collector could collect less heat : we would have created an astable system, an oscillator ! There is also a risk of perturbing the jet stream, which flies eastwards over the Sahara and Arabia, and seems to be important for the triggering of the Indian monsoon.

b) Application to the question of the solar chimney height

How, in order to reduce these environmental perturbations, can we boost the solar chimneys efficiency ? We saw (formulas 1 and 4, page 4) that their thermodynamic efficiency is equivalent to Carnot's efficiency with a heat source which would be the air when it has been heated in the collector and a heat sink which would be the same air at the tower top. So, it's approximately proportional to their height (we don't know whether the "The solar Chimney" area figures have been calculated with 445 m or 950 m towers, although the corresponding efficiencies are in a one to two ratio).

1 km, isn't it already very tall, and can we reasonably imagine something even higher ? This question's technical and economical issues will be examined further (naturally, the fact that a tower cost is more than proportional to its height, must be taken into account). But it isn't useless to try to take this problem from an opposite point of view.

In the global atmospheric circulation, after it goes out of the tower, the air will keep on rising, then generally become stable around 10 km up, where it will stay long enough to be cooled down through infrared radiation, as the earth does every night. And when it is as cool as other air masses at the same altitude, it will insert back into this global circulation.

If all this travel could be converted to power, the system's heat sink temperature would be the Everest top one, which would allow a pretty good efficiency⁵⁶. However, in reality, for the last

⁵⁵ Before being above these deserts, this air had come, always at a high altitude, from equatorial or temperate zones where, as it rose and thus was cooled down, it lost its steam, converted into clouds and rain. Therefore, the fact that it rains on the equator and in temperate regions, and that the weather is dry by the tropics, is linked to the fact, which interests us here, that in the deserts the air mainly comes down from the sky (and then goes back, by the ground, to the equatorial or temperate zones).

⁵⁶ Be more precise : it's interesting to build the highest possible tower only if, at every altitude, the inner air is warmer than the outer air, hence buoyant. With regard to altitude, the temperature decreases, outside the tower as well as inside. If both diminutions follow the same pace, which sometimes happens, the inner air keeps its buoyancy during all its rising, and the efficiency is really proportional to the tower height. If, conversely, the temperature falls slower outside, the inner air buoyancy progressively disappears, and it is less interesting to have very high towers. However, as the lapse rate is 10°/km inside the tower, and as this air should be 30 or 35° warmer than outside, there remains a non negligible interest to build higher than 1 km towers.

8 km, the fact that the tower outgoing air is warmer than the surrounding air, indeed makes it buoyant, but this only helps it to hustle the neighbouring air masses and reach the high atmosphere : it has no power to increase the tower's turbines aspiration. Only the tower inner air can drive them.

That's why the tallest possible tower is justified if we don't want to waste the greatest part of this rising air conversion potential. We've indeed reversed our point of view : limiting the tower's height at 1 km, is being happy with a much lower efficiency than the theoretical maximum. 1 km must no longer be a size which surprises us because of its gigantism, but, on the contrary, because of its low value.

II.E.2 The energy towers

If the problem of the salt rejects into the atmosphere is solved by the electrostatic coalescence technique (point I-B-4), the energy towers only reject cool and moist air, which seems rather neutral, or even a good thing, as such a desert would become less hostile. Irrigated agriculture could even develop, as the atmosphere would then be much less desiccating.

However, from a thermodynamic point of view, such an air is full of latent heat, quite as if it were floating just over the tropical oceans surface, in summer. But such an air can give birth to hurricanes. Without reaching the same intensity, as there never will be hundreds of hours of tornado amplification in succession, a similar phenomenon could be possible here : if this air starts to rise, the steam condensation will slow its temperature decrease down, therefore it will become buoyant, and could create a strong upwards aspiration.

We could think that the first km will be impassable, and that this mechanism can't begin as, from symmetry reasons, the air will be as negatively buoyant as it was in the energy tower at the same altitude. However, outside, this air will be in contact with the ground which, during daytime, is heated by the sun.

So, at some time of the day, the following phenomenon could happen : the ground air (maybe hundreds or a thousand km away from the towers) becomes warm and moist enough to be able, from the effects of dilatation and of the low water vapour molar mass, to move up, by one or two thousand metres, replacing the air above it ; then, it reaches an altitude where condensation is able to produce second stage buoyancy, as in cumuli ; and the final consequences could be benign or more serious, depending on whether the steam quantity is rather comparable to what we have in temperate regions, or to summer tropical oceans.

However, we must also take into account the catastrophe theory : as for earthquakes, the higher the barrier which, at once, prevents the phenomenon triggering, the more violent the same phenomenon when, at last, it manages to exist. Here, this barrier is a up to a dozen degrees gap between the ambient air and the tower outgoing air temperatures. This is much : a strong solar heating could be needed to overcome this barrier ; said otherwise, the accumulation of a large quantity of humid and finally warm air. This can generate differences with cumuli formation mechanisms in temperate countries, where we haven't such a stratification between an ambient desert air which globally obeys the dry adiabatic gradient law, and a much modified air which, when it rises, will rapidly generate a strong buoyancy.

II.F Examples of suboptimal optimizations

So far, the only mentioned economical discussions were about the kWh costs the various project promoters announce, or the possible offsetting of a low physical efficiency by a good economical one if the primary energy cost is extremely low (once the environmental externalities have been included).

However, economics must be used not only in order to choose one technology rather than another, but also to adjust various parameters of a same project, and to choose the values set which yields the best final result. This economical optimization principle is well known in general economics and in engineering sciences, but, here, it shows some particularities, as its insufficient application in some cases, and the importance of meteorological variants, both on electricity demand and supply sides.

II.F.1 The mpp (maximum power point)

a) Mpp general topics

There is no general reason that an economical optimum should coincide with a maximum of the physical production, or even of the physical efficiency. That's why, unless pathological cases⁵⁷, an investment's sizes and characteristics are never determined from a maximization of its power output, as it would mean neglecting the considerable cost rise such a maximization would generate.

However, once we consider these fixed assets parameters as being constant, we can still make some control parameters vary : at an energy tower top, we can spray more or less droplets ; at all types of towers bottom, there are turbines which can oppose more or less strongly to the air flow (by controlling the electrical generators they drive, and possibly their blades orientation) ; etc.

For the first example, we must take into account the water pumping up energetic cost, with very large quantities and an altitude around 1.3 km. For the last example, on the contrary, it seems logical to consider that all the options will be quite cost-identical, and therefore that nothing forbids us to limit ourselves to the basis problem : which control yields the highest power output ?

The next page diagram is probably well known in the renewable energies world, and is indeed a good theoretical reference. Choosing a photovoltaic cell best control⁵⁸ is choosing the best electrical receptor (here, the analogue is the turbine "strength"). As the photodiode voltage mainly depends on the semi-conductor nature ($V_o = 0.7$ V in the silicon), there's no point in trying to limit the current's intensity and hope to reduce the voltage internal losses. Symmetrically, the intensity,

⁵⁷ The energy towers "Larsen's effect" article, ^{xvi}

⁵⁸ We can read in Weinrebe - Schiel's article project "up-draught solar chimney and down-draught energy tower - a comparison" ^{xv}, p. 7, under equation (11) : "this is analogous to the maximum power point (MPP) found for PV-systems". The reference is supposed to be so obvious that the meaning of PV (PhotoVoltaic) isn't given.

i.e. the number of created electron-hole pairs, depends on the number of received photons, i.e. the luminous flow : it is useless again to define a receptor control strategy with the hope that we could offset a very low tension by a great intensity, as it is limited by the incident light flow.

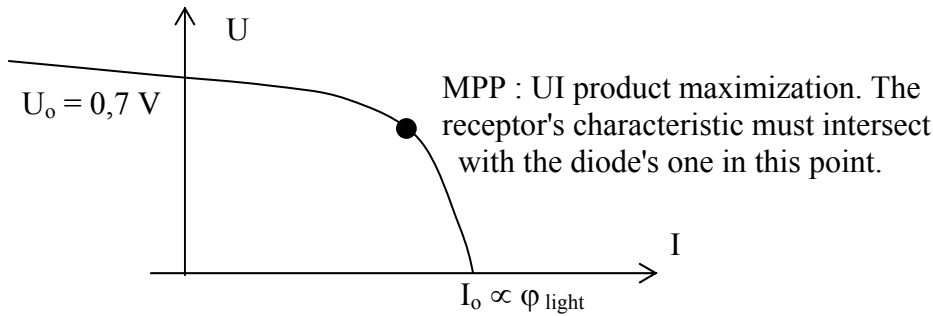


Figure 20

If we model this curve by a parabola ($U = U_0 \{1 - (I/I_0)^2\}$), then the UI product maximisation leads to :

$$I_1 = (1/3)^{1/2} I_0 \quad (35), \quad U = 2U_0/3 \quad \text{and} \quad P = 2U_0 I_1/3 = 2(1/3)^{1/2} U_0 I_0/3 \quad (36).$$

We'll see that this type of results is, sometimes correctly but often wrongly, very frequently reproduced in towers systems.

b) Mpp and energy towers

We saw (I-B-5, p. 18) an optimal flow yielding calculation $Q_{opt} = A_c \{2 E_{net}/3\rho F\}^{1/2}$ (11) and an optimal power $N_{opt} = A_c \eta_t \{(2 E_{net}/3)^3/\rho F\}^{1/2}$ (10) . These results are very analogous to formulas (35) and (36) above⁵⁹.

Therefore, there is nothing here we should criticize, except the already-mentioned precision (first made by the authors), about the droplets vaporization delay. However, the authors generalize this result (that only 2/3 of the gross power are kept in the electrical power output, 1/3 being lost because of the air movement), through a double one third subtraction from the theoretical product :

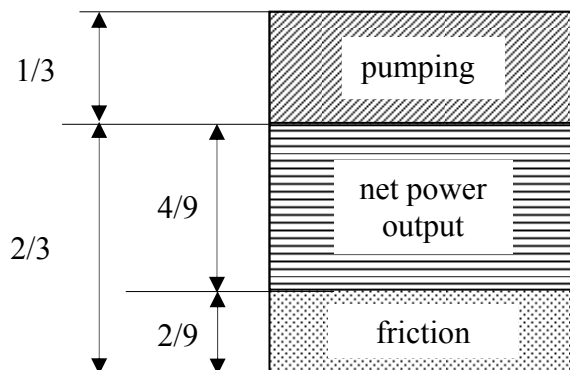


Figure 21

⁵⁹ with some differences about the figure "2", because the power we optimize contains a 1/2 term :

$$(12) N = \eta_t Q \{E_{net} - 1/2 \rho F (Q/A_c)^2\}$$

In reality, the 1st 1/3 / 2/3 splitting has no theoretical basis : we saw previously, from purely thermodynamic data, that the minimal water pumping up power ratio was 12 %. The further adjustment is mainly derived from environmental or economical arguments : which water droplets diameter enables to throw them at the right distance and best mix them with air (Cf. II-D-4-a, p. 66) ? Which percentage of non evaporated water must we get at the bottom so that the "enhanced coalescence" gives an effluent from which most of the salt has been eliminated ? etc.

(On the contrary, as we've just seen, the 2nd 1/3 / 2/3 splitting - the one which yields a 4/9 net power output after subtracting a 2/9 turbulent losses - indeed corresponds to a case where the classical mpp theory is applicable. However, as we saw at point I.B.3 that the worldwide dry air resource is not very much higher than the needs, and although we get a global atmospheric circulation reinforcement effect, it could be more prudent not to use too much of this dry air and not transform too great a quantity into moister and cooler air. So, choosing a point slightly under the theoretical optimum is probably preferable.)

c) Mpp and solar chimneys

A solar chimney is made of fixed assets and controllable equipments (mainly the turbines). Therefore, there is no principle reason to consider that the mpp theory wouldn't be applicable to the corresponding controls, i.e. to the optimal air flow calculations.

However, come back to the photovoltaic mpp presentation : the idea is simply that there are not much margins for either of both variants ($U_o = 0.7$ V limited voltage, $I_o \propto \varphi_{\text{light}}$ limited intensity), and that we only can minimize the drawback preventing us from having at the same time the maximum voltage U_o and the maximum intensity I_o .

Here, we can make an analogous reasoning : the power is the product of the collector absorbed heat, by the chimney efficiency. The collector heat is equal to the luminous flow, minus the losses from glass conduction, above air convection, and radiation (reflection, reemission due to the fact that the ground isn't perfectly black, and thermal infrared radiation). These losses' variable part quite linearly depends on the temperature we manage to transfer to the operating air. The tower efficiency is approximately proportional to its height, but with mechanical losses which are $\propto v^2$, therefore to the air flow, squared.

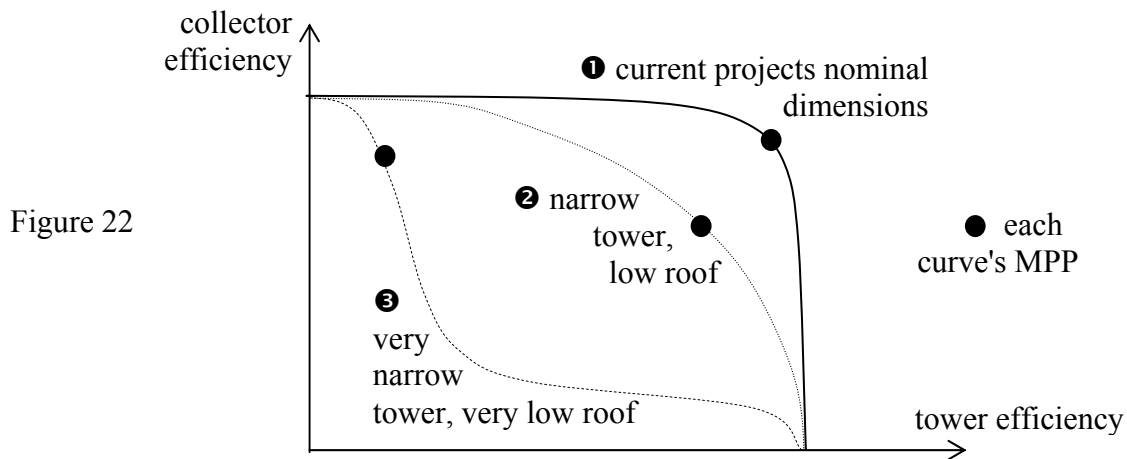
Is there the same type of a dilemma as we saw about photovoltaic energy (we can't completely avoid slight losses, from the voltage as well as from the intensity) or energy towers (raising the air flow increases a ΔP multiplying coefficient, but diminishes this ΔP itself) ?

Yes, but indirectly : in order not to have too much mechanical losses, we must limit the flow (and have neither too low a collector roof, nor too narrow a tower). But with too low a flow, the

collector heat could be carried away only by a very hot operating air, which means that the collector efficiency would have been reduced⁶⁰.

However, as it is indirect, there is no obligation to accept a 1/3 losses ratio, as in the previous examples. Here, there is enough margin, in particular with the investment parameters we've just mentioned : collector roof height, tower diameter, but also the collector thermal insulation. For the most studied projects sizes, a 30° air temperature rise from the collector inlet to the tower bottom, which doesn't make collector efficiency too sharply fall, is also consistent with air mechanical losses not higher than only some %.

In fact, we don't have one curve (which we move along with respect to the air flow value) whose maximum power point we must determine, but several, as a function of the fixed assets characteristics :



We can see that there is no fatality that a 2/3 coefficient must appear, at least not for the optimal flow determination in an already built facility. The choice is between reaching a 95 % "mpp coefficient" (❶) but paying a high price for the investments, or saving money from them and accept a mpp coefficient which, by chance, could be 2/3, or a little higher, or a little lower.

However, this 2/3 coefficient stubbornly appears in solar chimneys papers, somehow like the operating fluid energetic balance approximations we examined with a lot of details in the II-B. Just look at the following examples :

❶ 1983, in the Haaf and al. article¹, we can read (already quoted at the end of point II-B-2, p. 34) : " Δp_T is the pressure drop at the turbine ; the optimal proportion of the total pressure difference Δp is calculated at 2/3".

⁶⁰ This reasoning, based on the idea that the heat quantity the air can carry away must balance what is brought by the sun, is true for a steady-state regime. Transiently, we can accept that the air carries away more heat than the sun's contribution, notably by night and in the morning. Then, the air temperature depends on the velocity with which we can extract the previous daytime stored heat, and depends much less on the incident solar flow and on the efficiency with which we catch it. In this case, we can let the "air velocity" variant vary much more freely (Cf. further, II.F.5).

② in "The solar Chimney" ⁱⁱ physical appendix end, a formula expresses the power output as the product of three efficiencies (the collector's, the turbines', and the tower's, where we already take the air mechanical losses into account), and afterwards multiplies it by 2/3 (this is "justified" by an optimization argument from a similar curve as in figure 22, n° ②).

In reality, the losses are much lower (we're closer to curve ①). The 2/3 yielding optimization calculation would give an air velocity around a hundred m/s, while in fact it is lower by quite an order of magnitude.

This creates inconsistencies with the result tables in the main part of the book and which are, at a whole, quite correct ⁶¹. Indeed, by multiplying their values of the torques and angular velocities, we get higher powers than the nominal figures (5, 30 and 100 MW), because the latter are calculated from this appendix formula and the 2/3 coefficient it includes ⁶².

③ This appendix's author, W. Schiel, is, with G. Weinrebe, the author of the solar chimneys and energy towers comparison article project ^{xv}. The following quotation shows how difficult it is to become totally free from this 2/3 reference, even when we have all the required elements for it :

“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 x_{tm} 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 ⁶³. 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.”

⁶¹ In page 37 tables, the annual output figures (in GWh/y) are consistent with the collector area, the solar annual flow (2300 kWh/m².y) and the various previously mentioned efficiencies (collector's, turbines', and tower's).

⁶² As well, a "capacity factor" (quotient of the annual effective power and of the annual theoretical power corresponding to permanent full speed operating) around 1/3, is calculated from approximately 3000 h/y "annual operating hours". But a 26.3 % only "capacity factor" results from the comparison of the total annual solar flow (2300 kWh/(m².y)) and of its 1000 W/m² peak value which is used in the appendix last calculation (i.e. a 2300 h/y number of hours). This discrepancy can disappear only if the 1000 W/m² is multiplied back by the 2/3 coefficient !

⁶³ Notably because it diminishes the effect of a non dry adiabatic temperature lapse rate outside of the tower.

④ The same tendency to flirt with the 2/3 (or at least to keep it as an implicit reference for what we do) while finding results which progressively go away from it, can also be found in the "Thermal and technical analyses of solar chimneys" article^{iv}, whose authors include, as previously, G. Weinrebe).

Indeed, the system's dynamical behaviour is described by two formulas, which yield the power $P = \Delta p_{\text{tot}} A w_{\text{tot}} \eta_t x (1-x)^{1/2}$ (37) and the velocity $w = w_{\text{tot}} (1-x)^{1/2}$ (38),

"where x is the factor of pressure drop at the turbine and w_{tot} is the velocity obtained neglecting friction losses".

These formulas first seem appalling : $w = w_{\text{tot}}$ for $x = 0$ (free wheel turbines), and if in addition we neglect the friction losses, this velocity would become very high, as the one which, in the energy towers, we multiplied by $(1/3)^{1/2}$ to find the mpp, or as the 100 m/s which the ② mpp calculation was yielding.

The power formula ends by the function : $x(1-x)^{1/2}$ which is precisely the one whose maximum is obtained when x is 2/3. A lot of shrewdness is needed here to realise that, with a very high flow, the temperature difference will be low, so will Δp_{tot} , and that the global optimum must be looked for with other values of x .

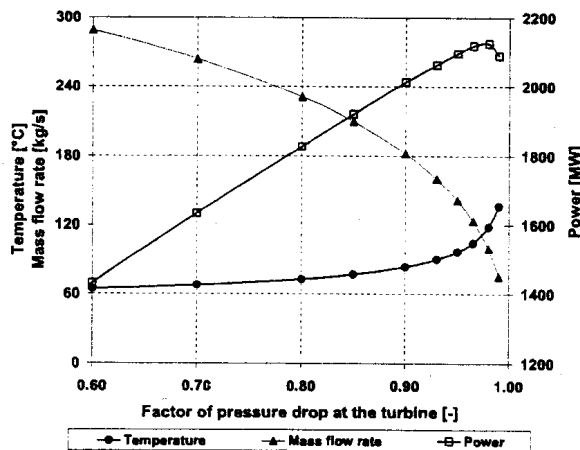


Fig. 23 Temperature and power output as function of the factor of pressure drop at the turbine.

Indeed, as shown by the above curve (the one with the small squares⁶⁵), the optimum is not for x (the abscissa variant) = 2/3, but rather for $x \approx 97\%$, which is much more reasonable.

Yet, the commentaries are disappointing : "In reality, a factor of pressure drop at the turbine equal to 0.97 is hard to be achieved. Thus, the use of a value between 0.80 and 0.90 is recommended". This is false : we're not speaking about turbines efficiency, etc.. We're simply speaking of being happy with a 15 m/s velocity, as in "The solar Chimney", instead of imagining to let the air flow at 40 m/s (144 km/h), which corresponds to an x between 0.80 and 0.90 : which one is the most reasonable ? The 2/3 mythology seems really difficult to abandon.

⁶⁵ Showing the total power, not in MW as the y-axis scale indicates wrongly, but in MWh/day, as can be corrected from the same page other diagrams. The left-hand scales (temperature and air flow in kg/s) seem equally mislead.

⑤ Such shilly-shallying gives a hold for criticism, particularly from competing projects promoters. So, in the energy towers Indo-Israeli project presentation^{vi}, solar chimneys are run down just after the 1/3 - 4/9 - 2/9 diagram, and the same efficiencies are applied to them. Starting with a tower "Carnot's efficiency" correct value, i.e. $H/30000$ (which correctly yields 3.3 % for 1000 m), the authors multiply (without very clear explanations, but this reduction could correspond to turbine losses) by 0.7, i.e. 2.8 % instead of 4 % for 1200 m high. Then they deduce a 1.2 % "efficiency to net deliverable electricity", i.e. 4/9 of 2.8 % after approximation (it's exactly 4/9 of 2.7 %). Finally, they apply the collector efficiency, i.e. 50 %, to find that a 1200 m tall solar chimney efficiency could only be, at best, 0.6 %.

But, in "The solar Chimney", it is estimated at 1.3 % for a 950 m height, thus, for 1200 m, we'd have at least 1.6 %, i.e. 2.6 times more than what the Indian-Israelis estimate. Where does this discrepancy come from ? From the 4/9 coefficient, which is globally quite justified for the energy towers, but not at all for solar chimneys. Obviously, there are no water pumping up losses (the first 1/3 losses in the balance which leads to these 4/9). And the air turbulent losses stay much lower than 1/3 of the remaining, if only we don't apply, from mere habit, a 2/3 coefficient, as did (and have much difficulties in stopping doing it) Haaf, Schlaich, Schiel and Weinrebe, which in fact gave ready arguments to be used against themselves.

Can we find a last argument to distinguish, on this point, the solar chimneys and the energy towers ? For the latter, a mpp goal seek by optimization of a $x(1-x^2)$ function was economically justified because the energy source (the interaction between the droplets and the sky-falling dry air) could be seen as costless (except the water pumping up energetic cost, taken into account besides).

But for a solar chimney, the energy source is the collector, which is the greatest cost factor : the heat we have to convert into electricity is limited and has a high cost, we can't afford to waste it from a 1/3 mechanical losses ratio, in order to increase the air flow, which would create quite neither additional heat, nor a greater theoretical η efficiency : $\eta = \lambda h_t / T_o$, (4).

Therefore, the economical logics are very different. For energy towers, the mpp air flow control is rather independent from the investment cost and the size choices : we always come back to a $x(1-x^2)$ control function, and a close to 2/3 coefficient. For solar chimneys, as we saw in fig. 22, the mpp theory application leads to place the operating point on a set of very variously shaped curves, and the building parameters are economically optimized through the choice of one of these curves. Hence, the air losses coefficient have no particular purely physical reason to be equal to 1/3.

*

The following shows various examples of insufficient use of all the existing margins which could help to reach the economical optimum. Although some of the previously described projects authors had many parameters at their disposal, they seem to have only varied those they were most used to consider.

II.F.2 The need to let all the system sizes vary together

An optimization point research amounts to equate a function derivative to zero. But when a system depends on a very great number of parameters and variants, we must theoretically turn to an optimization process in a n-dimension space, possibly with boundary conditions or other constraints, etc.. We can no longer talk about "one" derivative, unless we choose a synthesis variant, able to perfectly represent all these elements. In principle, the various authors are conscious of this need, as shown by the following diagram, from the oldest article we comment here (Haaf and alii, 1983, ¹).

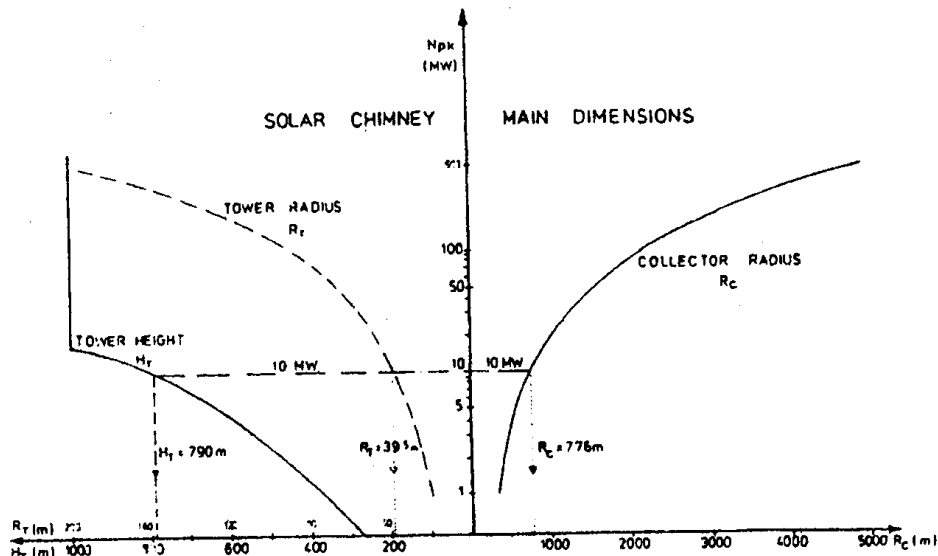


Figure 24 Main dimensions of solar chimneys in relation to installed capacity.

As we can see, the authors conclusion was that in order to multiply a solar chimney's power by 8 (from 1.25 to 10 MW), they had to approximately double its collector radius (thus multiply its area by 4, right-hand curve) and the tower height (450 to 800 m, last left-hand curve). The dotted left-hand curve corresponds to the tower radius, which, as the authors hadn't forgotten to look at, must widen to let a larger air flow pass through. For each power, i.e. on each horizontal line, we've theoretically got the values of these three parameters which enable to produce this power for the lowest cost, which is indeed the result of an optimization where we vary the implied parameters together.

But, often, this rule is forgotten, or incompletely carried out, as we'll see it about two more recent studies, whose quality seems, in other respects, globally good.

a) "The solar Chimney" : power estimate for very large collector areas

In the government recently approved Australian project, the collector diameter, compared to the example which, in "The solar Chimney", was the most adequate reference, is quasi twofold (7000 m instead of 3600), i.e. its area is multiplied by 4. The tower height is only slightly increased (1000 m instead of 950).

In 1st approximation, the power is proportional to the collector area and to the tower height : it should be multiplied by 4, but is only twofold (200 MW instead of 100).

Part of this gap can be explained by the fact that, if 24 h power regulation is implemented, more electricity is produced by night, but less at midday's peak. However, the annual electricity output should be multiplied par 4, and is only by 2.45 (750 GWh / 305).

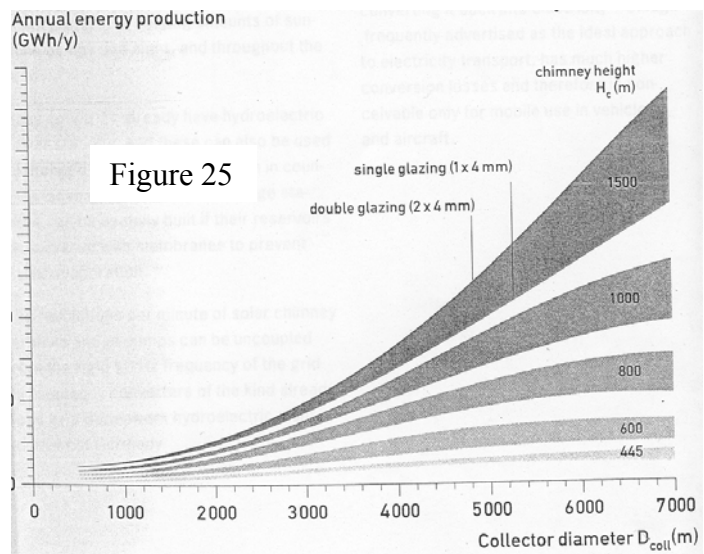
Why ? The chosen Australian location might receive less sun energy than "The solar Chimney" assumed. But the main difference seems to come from an efficiency drop resulting from an air large kinetic energy dissipation, particularly in the collector. This is confirmed by the following facts :

- a short calculation I've done (Cf. Appendix 3) gives, instead of 18 % as a reference figure, a 42 % loss rate, without having introduced aberrant physical values (collector's roof height) ;

- in the 1999 articleⁱⁱⁱ, for which a good power spreading over 24 h lessens the maximum air flow and therefore its kinetic energy, the annual electricity production increase (+ 400 %) is nearer to its theoretical value (+ 500 %) ;

- and, in "The solar Chimney" ii, there is a diagram representing the power with respect to the collector's diameter. Although, theoretically, this power is proportional to this diameter squared, we can see that, rather quickly, the curves stop being parabolas, and aren't steeper than straight lines, as if the power were only proportional to the diameter itself.

This can be understood if the collector's roof height is kept constant when vary its area⁶⁶. If we want more air to pass by the same way, it raises its velocity, thus the kinetic energy linked losses.



These diagram curves, which seem to be "with constant collector roof height", could have been "along an optimized path as concerns this height". If it were possible to raise the collector height without too much increasing its cost, we could have been much closer to maintain the curves parabolic shape. So, it may be that the book authors have neglected to vary this parameter, hence to have deprived themselves, without much reason, from more optimistic power prospects⁶⁷.

⁶⁶ As well, from the book to the Australian current project, the tower's diameter is up by only 40 % when the collector's one is quite twofold, so this question of the mechanical losses could explain its power weakness.

⁶⁷ In the opposite hypothesis, with a collector becoming too costly if its height exceeds a dozen of metres as a mean value, and about 20 m at the centre (values for the 100 MW tower of "The solar Chimney"), we'll see further (p. 106-108) that other solutions can be imagined to bypass this limitation.

b) Energy towers : a rapidly growing cost for large diameters

The energy towers Israeli-Indian project presentation ^{vi} includes a cost estimate for such towers, designed according to the principle of a steel lattice structure, as much "vacuum-filled" as it is possible while keeping a fair global stiffness :

Table 6 - Total investment in towers (M\$) of different dimensions

		Height (m)											
		300	400	500	600	700	800	900	1000	1100	1200	1300	1400
Diameter (m)	100	21	26	32	38	46	56	67	80				
	150	42	51	60	71	83	97	113	131	149	168	192	220
	200		87	101	117	135	156	178	201	225	247	277	310
	250			156	179	205	234	264	295	325	352	388	428
	300				260	296	335	375	415	452	485	530	579
	350				359	407	458	511	562	609	648	705	763
	400				483	546	613	680	745	803	851	921	992
	450				636	717	801	886	966	1038	1097	1183	1268
	500				822	923	1028	1133	1231	1319	1392	1497	1598

This table shows an odd feature : wide and low towers seem to be strangely expensive. For instance, with a 600 m height, the cost is multiplied by 11.5 when the diameter rises from 150 m to 500 m, while it is only multiplied by 7.3 if the same transformation occurs with a 1400 m height. And this latter multiplication starting point, 220 M\$ for a 150 m diameter and a 1400 m height, is probably not surprisingly high for a very high and narrow tower, which must face sever stresses.

Therefore, in comparison, the 822 M\$ for a 500 m diameter and a 600 m height, seem very expensive. Besides, this cost doesn't even double when the total height rises from 600 to 1400 m. A less than height proportional cost seems rather strange.

An explanation lies in the fact that these figures include the cost of the diffuser, a structure which guides the air from the tower bottom outside, and whose size only depends on the tower diameter : so, we get a constant term, whose relative weight is biggest for small but large towers. However, a more precise cost splitting up (non publicly quotable document) confirms that, even for the tower itself, the previously described cost anomaly partially remains.

This could be explained by the fact that the steel lattice structure which gives the tower its stiffness, is characterized by a parameter which is the "wall thickness", around a dozen metres. Compare it to the tower's radius of curvature : it may be enough to stiffen a 150 m diameter tower, but no longer if this diameter exceeds 400 m, which could necessitate to reinforce each steel element, and therefore raise the global cost.

If this explanation were correct, we could conclude that these results come from an ill-engaged optimization : for such sizes, 20 m thick walls instead of 10 would have little drawbacks such as a reduction of the tower internal diameter (operating air passage) with respect to its external diameter (wind drag), while upgrading the geometrical stiffness, hence without needing the steel quantity very large increase which these costs variations reveal.

II.F.3 Facility temporal management : the example of solar ponds

The previous examples didn't depend on time. Here, this question is approached from the analysis of an article^{xi} dealing with the use of solar ponds for sea water desalinisation.

Though this technology is finally rather marginal in the present thesis main topics, this article, which, besides, is well studied, is an excellent example of a lack of mind flexibility when it comes to an optimization with a great number of possible parameters and variants. That's why it is analysed here in detail, before seeing, at the following point (II-F-4), a general theoretical analysis of the method we should use for such an optimization, and the categories which we should fold these variants in.

a) First approach of the problem

K.R. Agha and alii's article^{xi}, "The thermal characteristics and economic analysis of a solar pond coupled low temperature multistage desalination plant", distinguishes two cases : either the solar pond alone provides the heat necessary to boil (under reduced pressure) the sea water we want to desalinate ; or we add, in winter, a fuel boiler, in order to get a constant transmitted heat all over the year⁶⁸ (this 2nd hypothesis disappears in the article 2nd part).

⁶⁸ More precisely, a little solar pond is associated to a mainly fuel-operating desalination plant : in their 1st article conclusion, the authors view as a good result that a "solar pond can supply more than 10 % of the total annual thermal energy requirements". We could be surprised that only two extreme hypotheses are studied (a solar pond which produces 115 % (Cf. further) of the needed heat, and a fuel boiler 0 % ; or 10 % from the solar pond and 90 % from fuel-oil), without any intermediate hypothesis (as : 60 % from the solar pond, and 40 % from the fuel boiler, just to back the solar pond in winter and avoid wasting part the summer produced heat).

For the first case, the authors write without much explanation that "due to the intermittent nature of the energy supplied by the solar pond and in order for the desalination plant to be fully utilised, some of the summer heat will have to be wasted"⁶⁹, and they confirm it through a diagram where we can clearly see that the curve named "thermal energy output from solar pond with N 'peak clipping days'" (figure 29, following page) is clipped : N is generally around 180 days/y, and the amount of energy which must so be wasted represents, graphically, about 15 % of the whole annual output.

Being so happy with the idea of not using part of the desalination plant thermal resource, implies that this plant's cost represents such a large part of the total cost that it would be necessary to submit all the options to the only goal of a maximum use of this plant. That's why we can be surprised to read, in the same article (page 257), that the main cost factor is energy⁷⁰.

Another reason to be surprised is that one of the characteristics of solar ponds is their large thermal inertia : in the same article (figures 26 and 27 hereunder), we can see that several years are needed before the solar pond operates at full power.

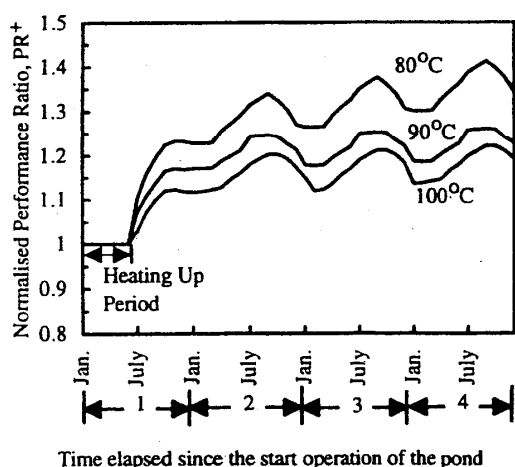


Figure 26 The effect of top brine temperature on the normalised performance ratio (PR^+).

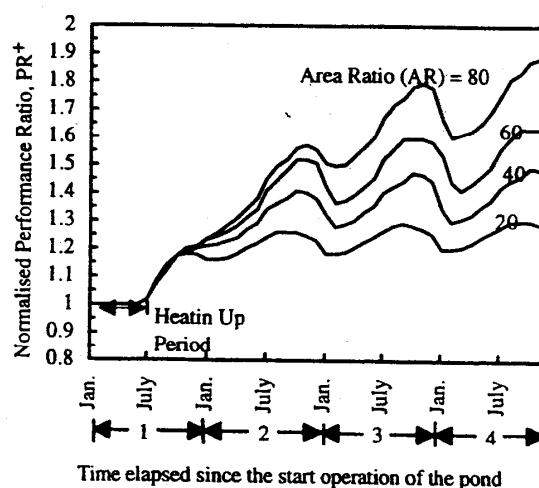


Figure 27 The effect of area ratio of pond area to the total MSF stages heat transfer area on the normalised performance ratio (PR^+).

⁶⁹ A problem about solar ponds is that if they're too much heated by the sun, their lower layer can boil, which could destabilize the whole pond's layers structure. Therefore, saying that we won't use part of this heat, requires to build a particular device to get rid of it, which has a cost. So, there must be very serious economical reasons to choose a smaller desalination plant than what could absorb all the summer available heat.

⁷⁰ "The cost arises from the fact that the systems of desalination require considerable energy input, usually as heat, and unless such energy is available as a by-product of other processes, *the energy cost is inevitably a limiting factor* on the applicability of such techniques. This means that such systems will have to be built in conjunction with thermal power plants (to use the waste energy)".

Contrarily to electricity which, as it can't be stored, requires that at any time the production is equal to the demand, this inertia should free the solar pond managers from such a rule : nothing forbids a solar pond to transmit a different heat quantity than what it receives from the sun at the same time or on the same day.

b) The position of the extracted heat extrema in the year

The curve (fig. 29 hereunder) which the authors think they must clip, and which is named "energy output", strongly looks like the seasonal variation of the incident solar energy, which is yet the solar pond energy input.

However, the heat quantity the desalination plant could extract from the solar pond depends on the intensity of the evaporation phenomenon due to take place in the plant. Therefore, it could vary as a function of the solar pond heated brine temperature, i.e. of the pond's LCZ temperature (this layer being where the sun heat is *stored*). So, a true energy output could easily be at its maximum when the solar pond is hottest, i.e. at the summer's end (August), and not at the 21st June solstice.

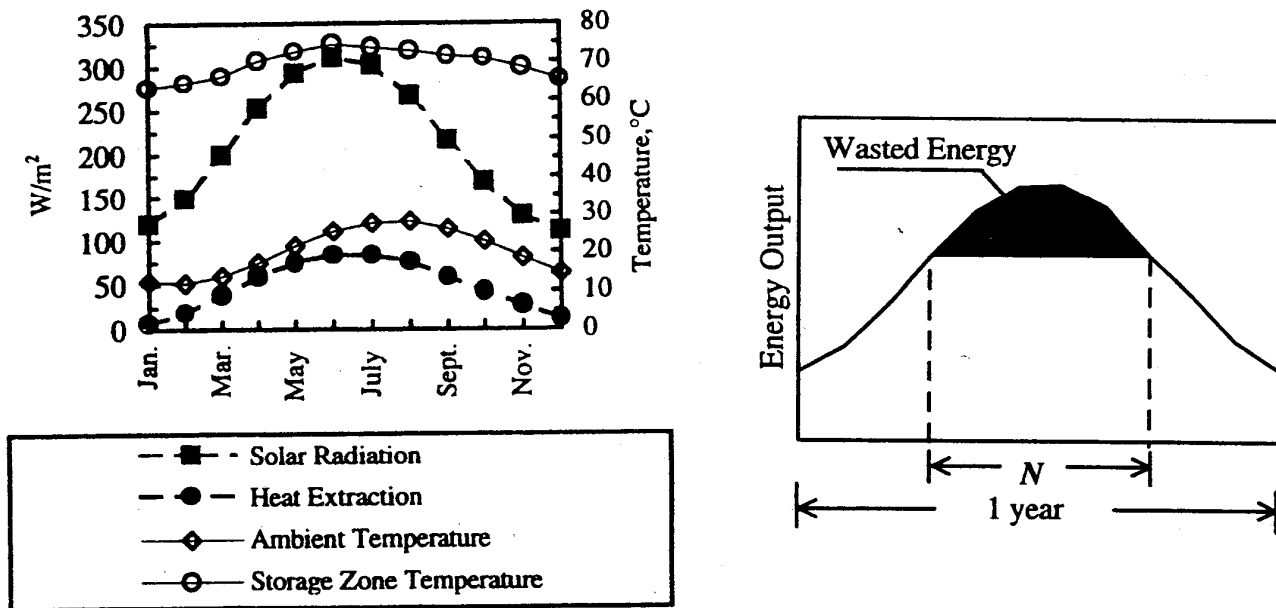


Figure 28 Energy extraction pattern of the reference solar pond for a constant storage zone temperature of $70 \pm 5^\circ\text{C}$.

Figure 29 Thermal energy output from solar pond with N 'peak clipping' days.

To be more precise, and in particular to take into account economical reasons and the cooling water characteristics, three possible principles could be imagined :

- ① (applicable if the plant's cost is not too high and if the solar pond produced heat is very costly). In order to get the best from the solar pond and avoid the peak clipping, we consider our most valuable asset is its thermal inertia : we're not afraid to let it get hotter all summer long (starting from low enough a temperature so that at the end it doesn't exceed 100°), which doesn't prevent us from exploiting it rationally, i.e. providing the plant with enough heat so that it operates at full load ; and, during the winter, we don't hesitate to pick up as much heat as the plant needs, even if it makes the storage zone temperature fall, which will precisely help to realise the following year required initial condition : start from low enough a temperature, etc. ...

- ② (applicable if the plant's cost is high, so that our main goal is to make it profitable) : it may be that for the plant to operate, as much as possible, at its nominal capacity, the temperature gap between its heat sink and its heat source must be quite constant. But the heat sink is the sea water (or the solar pond surface water) which, as we can see in figure 28 ("ambient temperature"), is season-sensitive, but has also got thermal inertia, and reacts to the sun input with a delay : maximum in August, minimum in February. Therefore, the heat source (solar pond lower layer) temperature is to be adjusted so that to have quite the same variations, with a rather constant gap.

- ③ (applicable if our goal is to keep the solar pond temperature within a narrow variation interval around a stable value, for example $70^\circ \pm 5^\circ$, with extrema at the solstices). In this case, the heat we should extract from the solar pond must be large in June-July, as the solar flow is maximum and we don't want to let the solar pond become even hotter. Symmetrically, in December-January, when the solar flow is low and if we don't want the solar pond to become even cooler, the heat we can extract from it is very low.

What can we think about these three principles ? That the first two are based on different costs hypotheses, but that, by sort of a coincidence, both converge towards an identical conclusion : that there is a strong rationale to let the solar pond temperature rise during the summer, with a maximum in August, and symmetrically fall during the winter, with a minimum in February. And that the third one, much different in its conclusion, doesn't seem to follow any economical logic, to such an extent that it may be hard to understand why we talk about it.

The only reason is in fact that such a principle is the simple paraphrase of figure 28 ! This looks like a religion of keeping the storage zone temperature as constant as possible, all over the year. And this is not by fear of exceeding the solar pond boiling temperature threshold : at $70^\circ \pm 5^\circ$, we're far from it. Besides, the 2nd article economical compares three possible operating modes : at $70^\circ \pm 5^\circ$, $80^\circ \pm 5^\circ$ and $90^\circ \pm 5^\circ$!

We can't understand why, if these three operating modes have advantages and drawbacks (there are less thermal losses in the 70° solar pond, but desalinisation is more efficient at 90°), we can't choose the most obvious solution, according to principles ① or ② : that the solar pond temperature be 90° in summer and 70° in winter.

Of course, this implies not to stick to the pure idea of nominal operating, but to reverse the problem : under defined boundary conditions, whatever, within reasonable limits, the pond hot brine flow we let in, something will necessarily happen in the plant, we'll probably reach a steady-state regime, reject a cooler brine and produce some distilled water ; to best use a fluctuant input, there are no reasons that only a year-long quite nominal operating point could yield a satisfying result. The following study of an electrical analogue may help change one's mind in such a way.

c) The system's electrical analogue

The system, as well as a simple electrical circuit, can be described by :

① a quantity which characterizes the introduced active fluid, but complementary to the flow variant (in electricity, it would be the voltage U , which is complementary to the intensity ; here, complementary to the heat calorific power, P_Q , which is carried by the warm water coming out from the solar pond / plant heat exchanger, it will be, for this pond, $T_{\text{source}} - T_{\text{sink}}$;

② a quantity with the same unit, corresponding to what the system demands to operate as we ask it to do : in electricity, the counter-electromotive force E' which characterizes a battery we want to recharge or an engine we want to rotate ; here, the ebullition temperature difference ΔT_{salt} between the salted water and the fresh water we want to produce, multiplied by the number n of desalinisation stages, as they're "connected in series".

For $\frac{1}{2}$ mol/l, i.e. around 30 g/l salted sea water, at 100°C , the saturating vapour pressure drop is 12.3 mmHg, i.e. less than 2 % of the fresh water vapour pressure (760 mm Hg). The corresponding temperature variation is 2 % of the quantity δT we introduced while presenting the energy towers, and whose value was 17° . Therefore, $\Delta T_{\text{salt}} \approx 0.3^\circ$;

③ still with the same unit, an irreversibility term (entropy creation), proportional to the fluid flow : in electricity, the resistance (possibly the sum of the receptor's and the generator's resistances, $R + r$) multiplied by the intensity ; here, a thermal resistance, characterizing the thermal exchanges in the boiler (and possibly in the solar pond / plant heat exchanger), multiplied by the heat flow, the result being a temperature gap, complementary of $n \cdot \Delta T_{\text{salt}}$ in $T_{\text{source}} - T_{\text{sink}}$.

Indeed, in electricity, for a circuit constituted by a generator, a resistor and a receptor, we know the relation $U = E' + (r+R) \cdot I$. Here, it will become : $T_{\text{source}} - T_{\text{sink}} = n \cdot \Delta T_{\text{salt}} + (r_{\text{th}} + R_{\text{th}}) \cdot P_Q$.

$T_{\text{source}} - T_{\text{sink}}$ (voltage analogue) widely commands the heat flow given by the solar pond and used for desalination, P_Q (intensity analogue), and thus the desalinated water output (analogue of the mechanical work output or battery recharging).

For $T_{\text{source}} - T_{\text{sink}} \approx 40^\circ$, if $n \cdot \Delta T_{\text{salt}}$, the analogue of E' , had been 30° , this dependence could have been very sensitive (a 10 % decrease in $T_{\text{source}} - T_{\text{sink}}$ could have caused a 40 % decrease in the desalinated water flow). But with $\Delta T_{\text{salt}} \approx 0.3^\circ$, and 20 (which is much) desalinisation stages, it'll be 6° , i.e. 5 times lower, so the relation will be much closer to proportionality.

However, such a relation exists. So, it could have been a good idea to limit the T_{source} variations, in order not to generate too big a flow of desalinated water in summer. But we can see in fig. 28 that the "ambient temperature", which widely determines T_{sink} , has a maximum in August. So, if we force T_{source} into a narrow variation interval, as the authors propose to do, $T_{\text{source}} - T_{\text{sink}}$ will have a minimum in August, and so could the desalinated output !

At first glance, we could have thought that the need to waste part of the summer energy, was included in a reasoning such as : "the inflow is very variable, it's better to stick to nominal values, that's why, independently, T_{source} should vary in a narrow interval, and we should let 180 peak clipping days per year".

But our study shows that it seems to be worse : "If $T_{\text{source}} - T_{\text{sink}}$ were highest in August, we could desalinate more water in summer, but the choice to vary T_{source} in a narrow interval, results in a lowest $T_{\text{source}} - T_{\text{sink}}$ in August, hence a lowest desalinated water flow, and a lowest use of the solar pond heat, when the input is, on the contrary, highest."

So, the T_{source} quasi-stabilization objective appears as the main cause of the solar pond summer wasting, and not as a parallel consequence of a simply shy sticking-to-nominal strategy.

This demonstration must be softened by the fact that when T_{source} and T_{sink} rise, the vaporisation kinetics improve, so that we can't have a perfect analogy with a constant electrical resistance R . But our will to improve the plant efficiency should still lead us to consider letting the solar pond temperature rise in summer, which would have the advantages :

- to help to produce more desalinated water in summer (just provide for large enough pumps), so that, naturally, part of the additional received solar flow will be absorbed in such a way, and the solar pond bottom temperature won't bear a very great risk to become too hot ;

- symmetrically, in winter, a possible fall of $T_{\text{source}} - T_{\text{sink}}$ could result in a slight relief about the efficiency⁷¹ : thanks to the fall of the desalination flow, and thus of the irreversible phenomena, it remains a constant, instead of falling as we're used to when $T_{\text{source}} - T_{\text{sink}}$ falls. So, the worry about a poor use of the facility in winter when T_{source} is low, which could have been a reason to reduce the difference between the used winter and summer inputs (and thus to clip the summer peak), is less serious than first thought.

Besides, the fresh water needs are probably lower in winter than in summer. Therefore, unless if we have very cheap leakless fresh water storage means, we've got an additional reason, in the economical field, to question the absolute (as it isn't discussed in the article) necessity to waste part of the solar pond produced heat at the moment where it could be the most useful.

So, we haven't found anything very logical to explain why the authors absolutely want to keep very stable solar pond temperature all over the year, nor why they feel obliged to waste part of the summer heat.

As a conclusion, solar ponds are not this thesis's heart, but here, about an ambitious article, as professional from a technical point of view than from an economical one, and with a very appropriate attempt to make a synthesis between these two approaches, we've got a typical example of what is still missing from something perfect. It is in particular a lack of flexibility about the solar pond warm water temperature annual variations, seen as an enemy, and not as the normal behaviour of a variant which we're allowed to vary.

The role of variants and parameters, the freedom we have to vary them, must lead us to theoretically define what an optimization process should be.

⁷¹ Electrical analogy : from the relation $U = E' + (r+R).I$, we get a power balance : $UI = E'I + rI^2 + RI^2$, and therefore an efficiency : $\text{output} / \text{input} = E'I / UI = E'/U = (U - (R+r)I)/U = 1 - (R+r)I/U$: if the generator's voltage source E falls while receptor's E' doesn't, the intensity will be lower than its nominal value, which reduces the output but increases the efficiency (lower entropy creation).

II.F.4 General economical optimization principles

a) Classification of the relevant variants and parameters

For any weather and solar flow linked energy production project, the various quantities we have to work with, belong to six categories :

- the facilities physical characteristics ;
- the corresponding construction costs ;
- control variants (the water flow we pump into a pipe, a turbo-alternator's magnetic excitation which will enable us to use one or another of its characteristics⁷², etc.) ;
- purely physical variants inside the system (the air velocity, its temperature, its hygrometry, the water quantity evaporating at a particular point, a heat storage⁷³ element temperature, ...) ;
- "temps" quantities - temps is the French word for both weather (as in "*temperature*") and time (as in "*tempo*") : the probability that at a given date, a given hour, the weather is fine or not, warm or cool, dry or steam saturated, that the outside temperature gradient $\partial T/\partial z$ is low or high ; the electricity demand⁷⁴ linked to the date and the hour but not to the climate ; the electricity demand linked to the climate (heating, air-conditioning, global demand from which we subtract the supply from other weather related energies, such as wind energy) ;
- and economical optimization variants (if there is no heat storage, we just have to calculate the incomes we get at different time, convert them to their current value, and add them up ; if there is a storage, then we must introduce an economical value function of, at each time, the various heat quantities we can imagine to have stored).

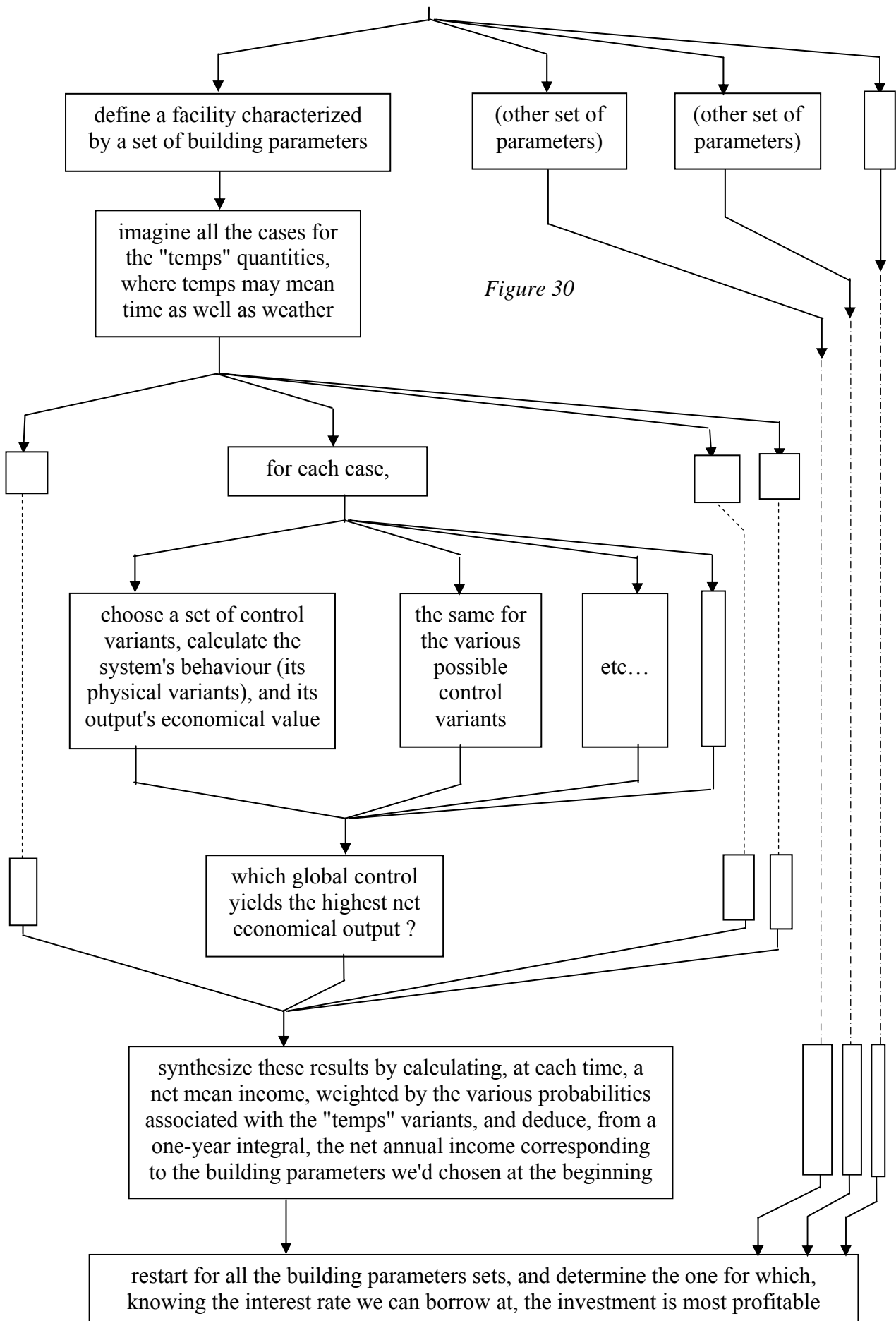
b) Optimization of a system without heat storage

If there is no energy storage (Australian tower without water-filled black bags, energy towers without altitude water storage) and once we've correctly classified these categories of quantities, we theoretically should (for further developments, Cf. appendix 4) :

⁷² Velocity and yielded torque linking curves.

⁷³ In the here less frequent cases where an energy storage would be an altitude dam, we'd have an equivalent variant and a similar optimization process.

⁷⁴ At what price (in €/s) can we sell 1 GW ? ; which price variation would we get if we were proposing only 900 MW ? or 1100 MW ?



c) Optimization of a system with a heat storage

Consider, for example, the Australian tower with black bags on the ground, or the solar pond we've just studied. At any time, the economical calculations must theoretically be completed by the following elements :

- we don't only know the same economical data as previously, but we assume that we know, at any period end ($H+1$ hour, for example), the economical value of any possible residual heat stock

- the goal is both to determine the value of the "converted energy" (electricity, fresh water) we can produce during the period (from H to $H+1$), and to reconstitute the hour H stock value function, so that to justify the previous hypothesis that such a function could be known ;

- to do this, we make a choice, for each possible heat H stock, between ① using up a lot of it (and produce a lot of converted energy) and having only a low stock at the end of the period, or ② the opposite, or ③ any intermediate solution. This choice (which of these various solutions gives the highest total "value of the stock in $H+1$ + value of the converted energy from H to $H+1$ " ?) determines the control values we'd implement, and enables to compute the stock value we had at H ;

- this yet doesn't fully determines the choice between all the possible "stock trajectories" : begin the day or the year with a low stock, then increase it during the period's 1st part, let it unchanged during the 2nd, increase it again, and finally use it up very quickly, or thousands of other solutions. What we must do is looking for the highest value of the total converted energy over a period for which we can assume that for a steady state it is logical to have the same stock at its beginning and at its end (24 h for a solar chimney, the year for a solar pond) ;

- and, as always, we must end with the final optimization of the facility's investment parameters, including the calculation, for any such set of parameters, the total income we've optimally determined at the previous point, the building cost, and the interest rate.

One of the storage advantages is that it provides a guarantee against the risk of production stoppage (lack of sun over an exceptionally long period). Is this correctly taken into account by the principles we've just described, or could too economical an optimization underestimate this prudence principle which is the basis of the storage rationale (an often made criticism about just-in-time management) ?

It mainly depends on the price structure we apply. If an operator must pay very high penalties to his clients in case of delivery stoppage, the model may include very high market prices for shortage situations (Cf. the very high power prices on the European market during the 2003 dog-days), and the optimal solution this model will generate will probably show a high stock level.

But we also know that a rational operator can offer preferential annual tariffs to some clients, if they accept to be cut off the grid a certain number of days at the operator's discretion : this reduces the shortage risk, and consequently the prices that the demand / supply law will result in. Therefore, the optimization process could yield a rather low safety storage strategy.

In conclusion, the only case in which this process could underestimate the useful stock level, is if tariffs were too simplistic ; then, it could be useful to modify the model, even if it should lose some of its economical purity, to introduce a minimum stock level. In fact, even if the real price structure isn't sophisticated enough, nothing forbids us to virtually imagine a more complete price system, to make the optimization model run with it, and to display its results : on one hand, the optimal parameters values, and, on the other, minimum storage rules to be set up and implemented.

Of course, it would be a good thing to discover a lot of such approximations able to simplify our work (see also appendix 4b, pages 159-163), but it is important to bear in mind that the best optimization implies not to restrict the wide freedom the economical theory gives us when we must lie the problem down. The various examples we've seen clearly show the drawbacks which appear when we dare not let some useful parameters freely vary.

The two following points, both about the solar chimneys and reminding the II-F-2 (pages 79 to 82), will also introduce the main improvement ideas, developed afterwards in the III.

II.F.5 The question of the solar chimney's 1 km height

Come back to the recent evolution, such as presented in page 79, of this tower's sizes : the collector diameter is quasi twofold (from 3600 to 7000 m), whilst the tower height is only slightly increased (1000 m instead of 950).

This evolution happened in two stages : we first passed from the 100 MW tower example in "The solar Chimney" ⁱⁱ (3600 m diameter, 950 m height), to a first 5000 and 1000 m Australian project, and finally to the current project (7000 and 1000 m).

Comparing the collector area rapid growth with the tower height dullness, we can think that it was a deliberate choice not to exceed, for this height, the 1 km psychological threshold, while feeling free to horizontally extend the collector. But first verify that it isn't a physical constraint, as it is for the sound barrier (1000 km/h) which a plane can approach and break only with the help of a very strong push from its jet engines.

First of all, we notice that in "The solar Chimney", beside the 5, 30 and 100 MW examples which will be studied hereunder, a 200 MW tower was mentioned, with few other details than a collector size hardly larger than the 100 MW one's, but a 1500 m height instead of the 950 m. Therefore, even if its architectural and economical characteristics are missing, it doesn't seem physically impossible to exceed 1000 m. A 1500 m tower is also mentioned in the 1999 article ⁱⁱⁱ.

Always in order to discuss a possible physical impossibility, we can report to this article, which, as we examined at point II-A-3, gives the tower thickness profile with respect to the distance from the top. After being constant (25 cm) between the 1000 m high top and a 600 m altitude, this thickness regularly increases as we come closer to the ground (table 4, page 29) :

distance from the top (m)	400	500	600	700	800	900	950
thickness (cm)	25	32	41	53	68	87	99

We saw that it corresponds to formula (13) yielding the thickness : $l_1 = 25 * \exp(z_1 / 400)$ where z_1 is the number of metres under the 400 m slice where the thickness is constant. This growth is exponential, but this doesn't imply that, after one or two additional intervals, we could reach quasi-infinite values, i.e. a physical impossibility.

Indeed, for $z_1 = 1000$ m, we find a little more than a 3 m thickness, which is much, but there is no fundamental change in the nature of the phenomenon, from the current project's 1 m thickness ; and, without any particular problem, we've added 450 m up, for a 1450 m total height (the constant 400 m from the top + z_1 + the 50 m pillars we've got in every case).

No change of nature, but an important increase of the concrete quantities we must use : the main obstacle seems to be economical. Is this the reason of the 1 km cap we can notice in this project's last presentations ?

"The solar Chimney", whose one of the greatest qualities is to include a thorough economic evaluation, enables us to compare the collector's and the tower's respective costs, for various power outputs : from 5 to 30 MW, the collector area's increase rate is four times higher than the tower height's one, and the collector's cost excess with respect to the tower moves from 30 % to 41 % ; these evolutions are even greater when we go from 30 to 100 MW, the sizes increase rates being now in a 1 to 6 ratio, and the collector's cost excess reaching 97%.

But, when two variants have comparable influences on a system's output, the economical optimum (maximum output for a given cost, or minimum cost for a given output) lies where the costs respectively corresponding to each of both variants are approximately equal.

As we spend much more for the collector than for the tower, we could be beside the optimum. For the 3rd case we've just discussed (100MW, 950 m high), the present appendix 3 modelling shows that it would probably have been better (around + 6 % power increase for the same cost) to imagine a slightly smaller collector and a higher tower, close to 1200 m.

The exact contrary has been done since the book was published, and for the Australian project presentation : a gigantic collector probably costing the much largest part of the available resources, a 1 km capped tower without economical justification.

The project's authors probably minded the symbol of a 1000 m tower : if they had targeted a greater figure, as the economical reasoning recommends it, they would have taken a risk to be considered as lunatics, like plenty have been before in the field of renewable energies. The same prudence lies in the calculation of the project's power : several times, an uncertainty about the possible power losses is concluded by the choice of the least favourable hypothesis. Then, when the tower is built, there will be only pleasant surprises.

Such a prudence is perfectly reasonable for the tower presently projected in Australia : after all, leaping directly from a unique prototype to a facility 17,000 times more powerful, isn't nothing.

But, beyond this first "big tower" whose financial break-even should come not only from the sale of electric power and of CO₂ emission quotas (non-pollution certificates), but also from tourist income, the important thing is to prepare mass production, for which there won't be new tourists.

The toughest economical laws will then apply. Having reached a price per kWh, 50 or 100% above the fossil energies will be, compared with a lot of other renewable energies, a remarkable performing, but yet unable to trigger an overwhelming development of this technology. Thus, it would be a pity to keep, on the long term, a "prudence" dogma, forbidding to target above 1 km heights, and to benefit from new scale economies.

And we saw previously that in order to limit the general atmospheric circulation perturbations, as well as to prudently manage some deserts whose area is in fact limited, a taller tower would also be useful.

II.F.6 The solar chimney output regulation during the first half of the morning

We saw (p. 12) that heat storage is possible for a 24-hour regulation of the tower output, but also (p. 63) that the most difficult time is the morning, when the electricity demand is already high, whilst the black bags have been cooled down all night, and the lighting conditions are most unfavourable.

But what we saw about the mpp (II-F-1), or the criticism we made about the sea water desalinisation study (II-F-3), remind us that we should check we don't forget to use a possible lever able to offset this unfavourable situation about "temps variants".

No efficient solar heating is possible as the sun is still very low over the horizon, the incoming air is quite tepid, the black bags are hardly warm, each air m³ won't receive much heat from them, and the tower, whose height can't be modified as a function of time, won't be able to produce a very powerful turbines aspiration.

However, there is, in this sentence, a word which isn't hopeless : "each" (before "m³"). Each m³ can't produce much, but many a little makes a mickle, and so far, we've met nothing obliging us to strictly limit the air flow to its nominal value.

Indeed, the power is proportional both to the inner air flow and to the temperature gap between the inner and the outer airs. Therefore, we can really fight against the black bags temperature weakness, by increasing the air flow (without going as far as trebling it, which would considerably increase the air kinetic energy linked losses (either turbulent or no), and would be globally worse), thus enhancing the bags / air thermal exchanges and helping to totally use this "last heat".

However, unless we'd forecast to use all the turbines only to manage this early morning's maximum flow, it is necessary that each turbo-alternator's air flow can rise. It's not really difficult to let them weakly resist this air flow, and accelerate : we just have to lower their magnetic excitation, a "control variant" which can classically be adjusted in order to shift the electrical machine's characteristic (the curve linking its angular velocity and its torque). But, for an optimal operating, we shouldn't let their angular velocity, the air velocity, and the blades inclination, vary independently.

Therefore, there are two possibilities to adapt the turbines to a higher air velocity : either we keep their angular velocity, and we modify the blades inclination ; or we adjust this angular velocity to the air velocity.

In the latter case, we can't directly produce the power at the grid's frequency (50 or 60 Hz). But it isn't forbidden to produce direct current (the words "turbo-alternator" I frequently use, may as well correspond to a "turbo-direct-current-generator"), partly for electrolysis use (aluminium, hydrogen), and partly to convert it to alternating current, either at the facility exit, or after a high voltage transport which, for a very long distance, is more interesting with direct current. There also exist frequency converters able to switch directly from any frequency to the grid's one.

So, the technical possibilities to produce a non negligible electricity output by night and early in the morning, exist. Then, the choice whether to implement them or not, needs an economical analysis : if we want to produce solar energy to prevent air-conditioning from power failures when the weather is very sunny, it isn't worth the trouble, and we can even forget the water black bags.

But if this is not the main solar chimneys use, then the question is worth being debated : variants, which are too often forgotten, are at our disposal if we need them for a wide range economical optimization. These variants are from various types : physical (air velocity, etc.), storage (how much heat should we keep in the black bags ?), control (turboalternators' magnetic excitation), and building (various options, Cf. following point).

If such a solution is implemented, the black bags, already used all night, and then completely wrung out from their heat by this higher than nominal air flow, won't be able of anything during the morning 2nd part. But the sun rays, slightly less low over the horizon, won't be blazing enough to let the tower operate at full load and, at the same time, heat these bags, which won't be immediately hot enough to efficiently pass their heat back to the air. This problem is studied next point.

III IMPROVEMENT PROPOSALS

The previous comments about some publications reveal that there isn't a large enough "critical mass" of debates and cross-examination among worldwide academics. Hence, the most advanced projects' engineers and specialists may suffer from a lack of outside looks and of confrontations with people coming from different horizons. That's why I venture to make some proposals.

One of them, possibly useful for both solar chimneys and energy towers, is presented in appendix 6b, p. 167-169. The others belong to only one main category, and are described hereunder.

III.A *Australian solar tower*

III.A.1 **About its efficiency with respect to the time**

While noticing the surprising fact that water is a good thermal insulator, and that it was a mistake to think that heating entirely black bags from above could allow to transmit 600 W/m^2 to the inner water, I gave the solution : that these bags upper face should be transparent. Therefore, I don't come back to it, but some other technical proposal are made of similar ideas.

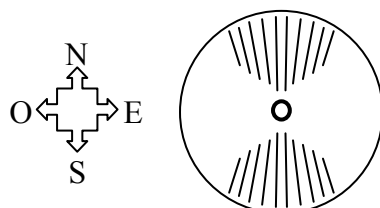
a) Black "curtain-hedges"

As we saw at the previous point, to solve the first morning hours, we can let in a large air flow which will finish to cool the heat storage bags down. But they might, in the morning's 2nd half, keep the main part of the solar heat received by the collector, and let too little heat for the air and for immediate electricity production.

One solution is to set in the collector some black "curtain-hedges", roughly aligned north-south. In the morning (and also in the evening), they will be perpendicular to the sun rays, and catch most of its light energy. On the contrary, around midday (or preferably slightly after), they'll have a much thinner shadow, and let the ground storage bags do their job, at a time when this job is the most useful.

Will these "curtain-hedges" oppose to the air flow which goes from the collector's circumference to its centre, where the tower stands ? If this air flow is parallel to them, not much. If the collector is circular and has no particular internal structure, it will only be possible to set curtains at the north and south of the tower, but neither at the east or west.

Figure 31

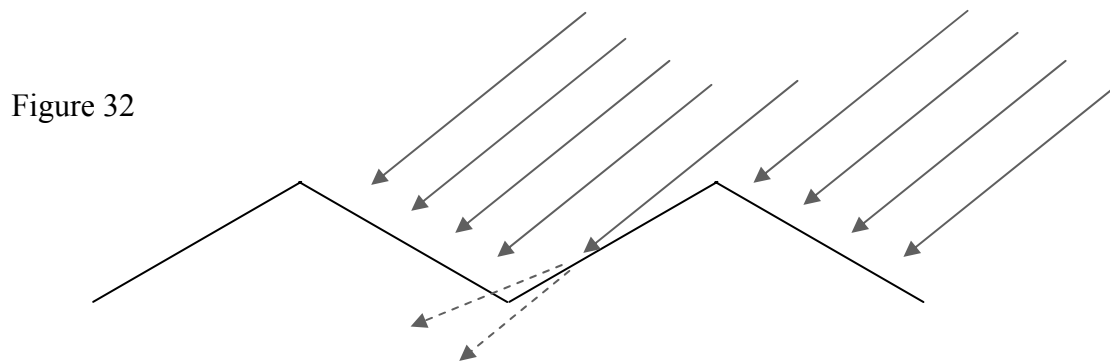


But we'll see later that not so simple collectors can be imagined, and then a larger part of their area can be fitted with north-south "curtain-hedges".

b) W profile for the collector glass roof

Another possibility to improve the efficiency in the morning and the evening, could be to reduce the sun rays reflections on the roof, especially if it's made of glass, with a rather high refractive index (plastics such as polycarbonate, which could be partially substituted, have a lower index).

The idea would be to build the roof with a W profile and north-south edges. So, at an hour when the sun rays inclination over the horizon would be between 30 and 40° (the incidence angle i is between 50 and 60° , hence $\cos(i)$ is no longer too low and the potential flow is already high, but the reflection coefficient is also non negligible), a roof inclination with the same order of magnitude would give the following situation :



We can see that :

- most of the rays come onto the face which has been turned towards them, hence with a much more favourable incidence (closer to the perpendicular), allowing to significantly reduce the reflection factor ;

- part of them arrive on the other face, with a less good reflection coefficient, but this is offset by two important facts : ① this part is much lower than what arrives on the correctly oriented glasses ; ② when the reflection is so grazing that the reflection factor is really high, then the reflected rays don't go back up to the sky, but hit the other glass, with a rather high likelihood not to be reflected a 2nd time (in spite of their unfavourable polarization).

From a strictly physical point of view, the drawback is that the glass-atmosphere thermal contacts are slightly increased, which could generate higher conduction and infrared losses, and limits the roof optimal inclination. There will also be a financial limit : more glass will be needed, and it may be more difficult to set up the grid of supports and steel bars which bears the glass panes. On the other hand, this geometry could ease the dust cleaning up and the glasses upper face transparency maintenance.

But the main drawback could be to give the wind a hold, as for dunes or sea waves, which are self-maintained and even amplified by an horizontal wind. Therefore, this solution seems adequate only :

- if, for other reasons, for example a location by a high latitude (deserts, north of the Tibet) and important energy needs in winter, we've already decided of a similar profile, to best face the south. In this case, it isn't much more a problem to combine it with a W profile, facing the east and west, as suggested here ;

- or if we make a double glazing, whose lower pane is made of glass : this one can easily benefit from such a W profile.

And we notice that this proposal is consistent with the previous one, as north-south curtain-hedges were implying that the air was flowing in the same direction, exactly as here.

c) Substitution of the curtain-hedges by simple suspended strings

I haven't precisely studied whether the solar heat absorbing black bodies must themselves, before giving it to the passing air, reach so high temperatures that their infrared reemission could be an important loss factor.

It's not sure, as what is often considered as a drawback, the fact that the solar energy comes to us as a low concentrated heat flow, is here an advantage : we haven't got a huge number of W/m^2 to transmit to the moving air, thus even relatively low thermal contact parameters (air thermal conductivity, air layer thickness, Nusselt's number) may enable this transmission without the need of a large temperature difference between the ground and the air.

If, however, it were the case, we should try to reduce this temperature by favouring even more the thermal exchanges with the air. From this point of view, black threads or strings⁷⁵, suspended to the collector ceiling⁷⁶, correspond to a maximum thermal contact. Like the curtain-hedges, they'll have a much thinner shadow at midday, enabling the heat storage in the black bags. Their geometry (Cf. the "deaf rooms" in acoustics) can also contribute to reduce the system's global radiation reemission.

In fact, the main problem is the air circulation resistance in the collector : a better thermal contact, widely characterized by a high Nusselt's number, inevitably corresponds to an increased turbulence (high Reynolds's number). Therefore, this proposal should be linked to another, discussed further (ribs, p. 106), which could contribute to seriously lower the turbulent frictions everywhere we collect the sun's light energy.

⁷⁵ Realised in a similar material as the strings farmers use to bind hay or straw bundles : cheap, perfectly black, sun and wind resisting, and able, if necessary, to be teased out into very thin threads.

⁷⁶ And whose fastenings would be spread, at both ends, along ropes, grouped within bundles which would be made in factories and set up at the same time as the glass panes.

III.A.2 How to keep on yielding scale economies

a) Problem presentation

We showed at II-F-5 (p. 91-93), that the 1 km tower height was very probably resulting from the will not to exceed an arbitrary psychological threshold, so that not to be accused of utopia. However, as no technical reason forbids to overtop this threshold, as the principle of scale economies (multiplication, in one shot, of the prototype power by 17,000 ; fact that each tower additional metre enhances the collector's financial yield, and each collector additional m² enhances the tower's yield) seems to be able to go on, and as the environment lowest perturbation requires to look for the best thermodynamic efficiency, i.e. the tallest tower, it may be useful to see which elements could help to increase its height.

From a general theoretical point of view, what does the materials resistance say about building a taller than 1000 m tower ? An interesting order of magnitude is the length of a material with a constant width, which resists to its own weight, either in tension (we imagine that we hang it to a balloon X km up) or in compression (which height of the same material can we put on its own head before it is seriously damaged under such a weight ?). This limit seems around 10 km⁷⁷ for steel and 4 km for concrete (Cf. p. 31). Therefore, there is no principle obstacle to imagine widely taller than 1 km towers.

b) Swapping the solar chimney's and energy tower's building principles

The simplest solution is to view as inconsistent that the solar chimneys promoters, which thermodynamically could grow up to 3 or 4 km, have chosen the concrete, which its own weight obliges to exponentially thicken with a pace of perhaps only 400 m, whilst the energy towers, which high altitude efficiency is low because already cool air is difficult to cool down even more, use the lightest technology (steel lattice), which is best adequate for very tall buildings.

<i>Table 7</i>	Solar tower	Energy tower
Functions of outside / inside isolation, and of structural stiffness	blended	separated
Corresponding material	reinforced concrete (thickness from 25 cm and above)	steel (structure + coating)
Consequences for the weight	very heavy	much less
Can the tower be even higher ?	to reach 2500 m, the concrete should be 42 m thick !!!	less unfavourable
Thermodynamic optimal height	2000 to 3000 m	1300 to 1400 m

⁷⁷ We can reach even higher lengths, by taking a low cross-section near the free end, where the cumulated weight is limited, and by widening it as we have to resist a greater weight.

Therefore, a common sense proposal is to swap these two preferences, which can hardly both be logical.

Other ideas, more thoroughly examined, are proposed hereunder. They're classified by their growing gap from the current Australian project and "The solar Chimney" model.

c) Simple expenditure rebalancing, from the collector to the tower

To overtop the current Australian project sizes, particularly its tower height, and thus satisfy the economical rationality and disturb the general atmospheric circulation as less as possible, the first idea is to look for a better balance among the two components of the "collector + tower" system. The model (Appendix 3, p. 144 to 149) I developed from "The solar Chimney" ⁱⁱ data gives the following results :

① for the same price than a 1 km tower and a 7 km wide collector (current project), the output can grow by quite 70 % (more than 40 % drop in the kWh cost), if the tower height rises up to 1700-2000 m, while the collector's diameter is reduced to about 5700 m.

Three remarks :

- the tower's cost is quite multiplied by 3, whilst the collector's one is reduced by only one third. Is this consistent with the idea that the total cost would remain unchanged ? Yes, for the collector's cost was initially about 6 times higher than the tower's. Just check the calculation, this 6 to 1 ratio becomes 4 to 3, with an unchanged sum. This recalls the idea that, with so different initial costs, we were far from the optimum, and that coming closer enhances the whole lot's efficiency ;

- these results are based on "The solar Chimney" official figures, corresponding to "southern European cost levels". But this book also notices that an "Indian contractor with experience in building large cooling towers" offers, for the tower, to divide the price by quite 4 ! This is interesting in order to assess the whole system's profitability, but also to choose between high towers and large collectors. Indeed, if the tower's price falls that much (compared to only -23 % for the collector), it is logical to benefit from it and build even taller ones⁷⁸.

- the optimum is reached for a rather high tower slender ratio (height / diameter, 12 or 13). According to the authors, this ratio should remain lower than 10. However, we discuss, in appendix 3 end, p. 150, the idea of targeting a higher than 10 ratio for very high towers, i.e. with very thick bottom walls. If this wasn't possible, complying to this limit isn't a serious impediment, especially if a change in the collector's structure, proposed a little further, enables to go on with scales economies thanks to a new growth of the collector area, and, hence, of the tower diameter.

⁷⁸ And come back to the optimum, characterized by a roughly equal expenditure for these two main elements. Besides, while drawing inferences from such a costs distortion, the project's promoters commit a Freudian slip which confirms that they hesitate only for symbolic, rather than objective, reasons, to go beyond a 1 km height. They write : "In a developing country with high material and low wage costs, other dimensions could prove more favourable, for example lower chimneys and larger glass roofs". Oppositely but truly, they write elsewhere that the tower should be lowered and the collector widened if glass (material) were *cheaper* than concrete (wages) !

② If we compute, not the best solution for the same price, but for the same collector's diameter (7000 m), the results are qualitatively the same, but a little stronger : optimum tower's height over 2000 m, kWh cost reduction about 45 %.

③ At last, a general optimum, independent from all the current Australian project's parameters, is theoretically possible, but the result depends very strongly from the method used to model the phenomena which make such optimum exist, i.e. which prevent the cost per kWh from becoming infinitely low if the tower and the collector were given gigantic sizes.

There are three such phenomena :

- the temperature gap between outside and inside the tower remains seldom unchanged when the air rises up⁷⁹, and, generally, it diminishes and reaches zero when we're 5000 or 8000 m up ;

- the tower's cost with respect to its height grows rapidly, and even quite exponentially (see formulas (13), p. 30, and (67), (68), p. 148 ;

- in very large collectors, in order to let enough room for the air progression towards the tower, the collector glass windows should be set at some dozens of metres over the ground. This certainly represents an additional cost, but I have few elements to estimate it (p. 148).

As previously said, either this additional cost doesn't prevent us from following on towards new scale economies by increasing the collector area, and everything is fine, or there is really a problem, and this justifies to examine an alternative solution, described further (point e).

d) The bicycle wheels and the question of their spokes' longitudinal stiffness

In the current Australian project, six bicycle wheels should be set at the altitudes of 280, 460, 600, 730, 860 and 990 m, to stiffen the tower and protect the concrete against wind-caused deformations and early aging. With an acoustical analogy, the concrete deformation will there be null, as at "vibration knots" in a flute. But, in most cases, an acoustical pipe may present at its end, not a knot, but a vibration maximum. Why not here ?

The 990 m high wheel seems indeed to be underused : while all the others contribute to stiffen both the concrete over and under them, this one is useful only for which is under it. Why couldn't it be possible⁸⁰ to build some dozens metres of additional concrete above it (and thus produce some more % of power, which is low but non negligible) and better profit from its stiffening effect which is not used up, or to slightly move down the 990 m wheel and some others, in order to make savings from their technical requirements⁸¹ ?

⁷⁹ The relationship between the outer air altitude and temperature is generally less sharp than what the "dry adiabatic gradient" law says ($\lambda = 10^\circ/\text{km}$), whilst the inner air must obey this law.

⁸⁰ Unless there would be a possible outgoing air vibration effect, or if we want people to go on the top.

⁸¹ In fact, considering that the tower can be ended by a vibration maximum instead of a knot, we save half a wheel (or slightly less, by prudence), which can lead either to reduce their number by 1 but pay a little more for each of them, or keep it but lower their cost.

More substantially, a bicycle wheels related question is the effect of their cable-spokes' catenary curve shape. From a given length, perhaps around 200 m (formula 34, p. 60), their stiffness falls because of this geometry. But we're thinking about building even taller towers, to increase the economical efficiency of even larger collectors. Therefore, both to prevent these towers from becoming too slender, and to let a greater air flow pass in, we must think about widening the towers diameter, thus increasing the difficulty to maintain these spokes' stiffness.

A solution could be to separate the functions of resisting the gravity, and stiffening the rim ; said differently, to help these spokes to bear their own weight, so that they can be more rectilinear, and that their apparent elasticity could diminish. Two options :

- a central pole could be built around the tower axis, be a support for the centre of each bicycle wheel, and reduce the catenary curve effect from the diameter to the radius size ;

- or each spoke could be suspended to a cable, whose catenary shape would generate no prejudice, as it wouldn't be its job to have a low elasticity. The one whose job it would be, i.e. the suspended spoke (as a suspended bridge) would be perfectly rectilinear and its stiffness coefficient would suffer from no geometrical term in addition to the steel intrinsic elasticity.

This would also be adequate for the following reason. The concrete tower deformation under the effect of the wind must be very low. To have a high intrinsic stiffness constant, we need cables with a wide cross-section. Therefore, they are heavy. If, in addition, they must be quite rectilinear to have a strong geometrical stiffness, their tension is very high. As we must also avoid to oval the concrete during the delicate operation which is to raise this tension, a very progressive procedure will be necessary : acting at the same time on all the spokes, or maybe acting successively on each but by small tension increases, i.e. a great number of operations. With the catenaries, this problem disappears if only we put the spokes under tension during a windless period (an idea could also be to heat them a little, tighten them, and let them recover their initial temperature).

e) Application of the same principle to the whole tower

In "The solar Chimney", there are three tower diagrams on the same page. Two of them are guyed tubes : guy rods link various parts of their cylindrical envelope, to fixing points, in the ground, aside from the tower bottom. Only the 3rd diagram is "free-standing", but this one has been chosen. One of the main reasons which lead not to choose one of the first two, may be the fact that too long cables necessarily take the shape of a catenary curve (II-D-1, p. 59-61), which sharply reduces their capacity to maintain a rather constant distance between their two ends, and therefore to fulfil this tower guying function.

If the main reason were this one, then the solution we just proposed for the bicycle wheels could be transposed to such guy rods : a suspending cable taking the shape of the catenary curve, and a stiffening cable whose distance variations between its ends would only be caused by its intrinsic elasticity.

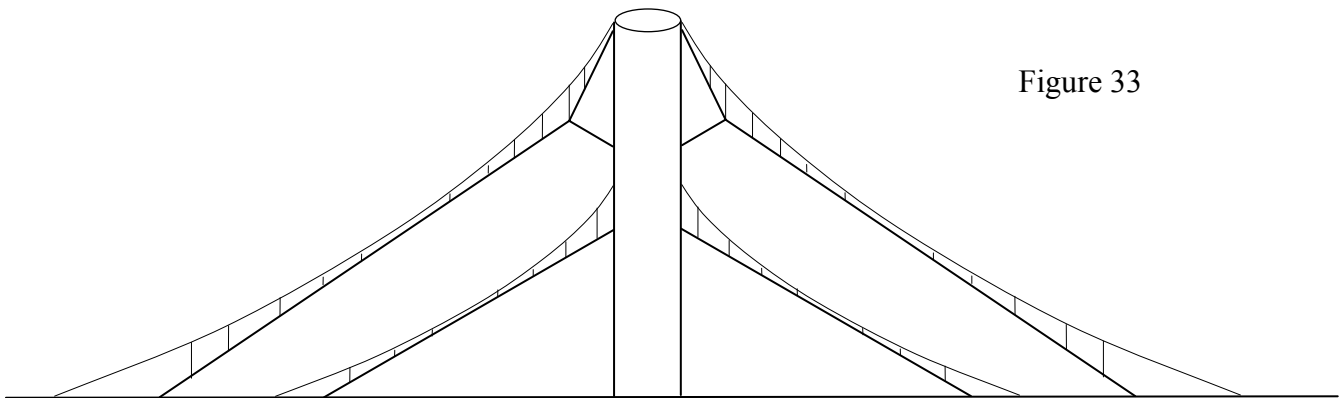


Figure 33

Such a system's feasibility can be assessed from a comparison with recent projects, which probably include a good safety factor, as their object is people transport : a telepheric (Vanoise-express) has just started to operate in France, with a 1800 m span, and a total cable curvature which doesn't seem to exceed 30° ; and the Messine Strait suspended bridge project has an even greater span, longer than 3 km. Therefore, it seems reasonable to think about such a principle and imagine towers quite 2 km tall, or even more.

What geometry for the guy rods ?

Their goal is to generate, if necessary, a wind resisting horizontal tension T_0 . As they can't be perfectly horizontal, this tension has also, inevitably, a vertical component.

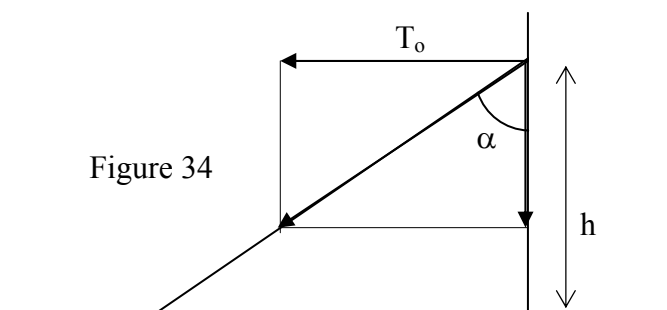


Figure 34

If, first, we neglect the necessity for the guy rods to bear their own weight, we can identify two cost factors for a given horizontal tension T_0 :

- the guy rod tension is $T_0 / \sin(\alpha)$, and the necessary guy rod length is $h / \cos(\alpha)$, thus the cost will be inversely proportional to the product $\sin(\alpha) \cdot \cos(\alpha)$, and minimum for $\alpha = 45^\circ$,
- and the vertical compression force undergone by the tower will be equal to $T_0 / \tan(\alpha)$, thus becomes very high if α is low.

Therefore, it is globally preferable that α is rather high, and anyway higher than 45° , as, up to this value the two cost components are decreasing functions of α , and as beyond it one of them is still varying in the same direction.

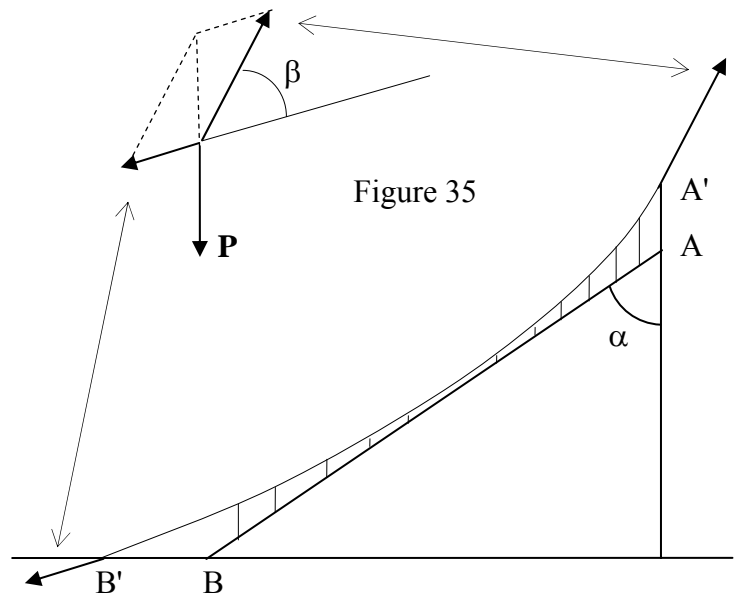
Equally, from the wind's action (reaction T_0 to create) and the cables elasticity, the tower top horizontal shift is \propto (proportional) to $1/(90^\circ-\alpha)$ when α is close to 90° , and even $\propto 1/\alpha^2$ when α tends to 0. Therefore, it keeps acceptable values only as far as possible from these two values, i.e. for α close to 45° , and rather higher.

But if we reintroduce the necessity to bear the cable's weight, things are less clear, even with the suspended guy rod system. Indeed, a rather high α angle is antagonistic to most of the other constraints we get in such a case :

- the suspended guy rod's tower fixation point (A) can't be as high as the suspending cable's (A'), so it doesn't perfectly fulfil its wind fighting mission ;

- at the ground, the suspending cable fixation (B') lies even farther than the suspended guy rod's (B), which is a very long span ;

- to limit these drawbacks, the suspending cable curvature must be low. But the lower this β angle, the higher this suspending cable's tension, compared to the sum P of its weight and of the suspended guy rod's.



So, the suspending cable's span could be limited, as well as the tower height which could be guyed, whilst we still want to build the highest possible tower.

In fact, the three constraints we've just listed are less severe if we relieve the above diagram from one of its implicit conditions, which obliges the guy rod to *hang under* the suspending cable. As we can see next page⁸², this enables to bring A nearer to A', B' nearer to B, and, if necessary, to increase the suspending cable curvature and reduce its tension.

⁸² Where, as here and to be simpler, I suppressed the guy rod splitting (near the tower top) that I had introduced, without any comment, in the first general diagram (figure 33, previous page). This idea remains possible, as well as a splitting into more than two strands, each one having to maintain a slice of the tower whose height we want to increase. No calculation specifically relating to this option, brings new elements of discussion.

For a system which could be based on the rather different idea of one or some taller than 1 km compression-resisting vertical poles, constituting a high and fix structure around which a tension-resisting envelope would hang (there is such a diagram in "The Solar Chimney" ⁱⁱ), it could make little sense that guy rods join this structure at intermediate heights, as they could as much weaken these poles, than reinforce them. But intermediate guy rods having to stabilize this envelope, and therefore linked to it and not to the central pole, would make sense.

Such an idea could, with a lot of prudence, be combined with Sorensen's idea, so that this pole could be replaced by a "captive balloon", filled with a buoyant gas, and laterally maintained by suspended guy rods. More modestly, such a captive balloon could also be used as a "crane" for the tower building.

There is naturally a counterpart, which is the necessity to link the suspending cable and the guy rod by an element no longer working in tension, but in compression.

This simple change of nature (buckling risk of a compression-working element having to keep a reasonable weight) is probably acceptable up to at least 100 m (quite 200 m long steel lattice elements have been used as temporary poles for the recently finished Millau viaduct, in France).

Another problem is such a device's stability. It can be solved rather easily, by splitting the suspending cable, in the part where it must be under the guy rod, and setting a little bar (having to work either in compression, or in tension, but anyway not much) to keep the right distance between these two cable halves.

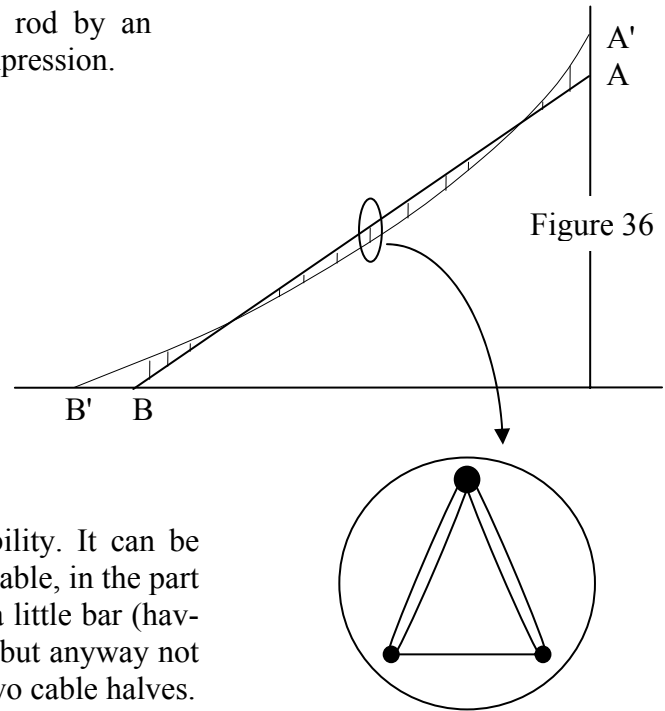


Figure 36

Everything else unchanged, this idea could help, without indirectly increasing the suspending cable cost, to raise the guy rod's middle altitude by at least 100 m, thus the tower height by 200 m, while continuing to benefit from the suspended guy rod principle and of the resulting stiffness enhancement.

Knowing the interest, in order to make the whole facility profitable, of a 200 m expansion, and how a non guyed tower's cost grows with respect to its height, this option may be worth the suspending cable splitting and the introduction of 100 m long compression-resisting linear elements.

Will such a tower benefit from scale economies ?

Assume that the tower air flow kinetic energy represents a fixed part of its negative buoyancy's work, thus its velocity varies proportionally to its height root. We also suppose that the tower's height / radius ratio is constant. The power output being proportional to the product of the height by the flow, i.e. of the height by the velocity and the radius squared, it will be $\propto h^{3.5}$.

In regard, how much guy rods are necessary ? The wind drag is, in Newtons (forces), \propto to the tower's height and radius, thus $\propto h^2$. Therefore, the cables cross-section is $\propto h^2$ (contrarily to a non guyed tower, no lever arm intervenes) ; their length being $\propto h$, their cost will rise as h^3 .

The comparison of the power output $\propto h^{3.5}$, and of the cost $\propto h^3$, gives a small scale economy, mainly due to the tower radius increase, rather than to its height's (which, on the other hand, is the only one which can enhance the collector's efficiency).

For very tall sizes, the constraints we described in page 103, and which will appear when we approach our 2 or 3 km target, will reduce, or even reverse, this scale economy. But this doesn't mean that we should stop looking for very large heights : this is still justified by the win-win strategy for the collector and the tower, as this effect was already operating when the concrete "free-standing" tower cost function was looking like an exponential. A h^3 cost function seems more favourable than an exponential, so it shouldn't prevent us from targeting largely taller than 1 km sizes.

Finally notice that if, contrarily to the conclusion I've drawn in page 30, the walls thickness profile wasn't justified by the concrete's compression resistance, but, at least partially, by the wind's effects, particularly its drag, long guy rods could help to resist it, and thus lighten these concrete walls. Therefore, the exponential pace could be raised, which would allow a "scale increase" for the whole system, instead of the little scale economies ($h^{3.5}$ vs h^3) we found for the isolated guy rods.

Conclusion

If we managed to get rid of the problem of the tower bottom wall thickness quasi-exponential increase with respect to its height, which was quite creating an economical difference of nature between ordinary sized and higher than 1 km projects, the tower height "theoretical reasonable limit" could move from a value around 1.5 km to one depending on steel cables theoretical spans, and, from the previously quoted examples, it could be about 2 or 3 km high.

This could then justify other qualitative changes in the tower building principles. We would be drawn back to guyed buildings practice, a field which enough people know well, so that it would be inadequate that I'd discuss further the various related questions and options⁸³.

f) Separation of the collector's air transport and heat collection functions

After having studied a first functions separation topic (table 7, page 98), and then separated, for a cable, the functions of resisting gravity and of stiffening the bicycle wheel rim or the whole tower, we now have to separate two collector functions, from a comparison with a hand, a maple leaf or an elementary photovoltaic generator. These three objects have indeed in common an arborescence structure which efficiently distributes a fluid on their whole area.

⁸³ Concrete or steel, or which combination of them ? How can we manage the guy rods' and tower's dilatation ? If the idea I developed in the previous footnote 2nd § was interesting, which characteristics for the central pole(s) : one of several elements, made of a lattice or from materials with the dimension of an area (or even of a volume), like the "Stade de France" steel "needles" ? etc..

Veins (or arteries) are visible on the hand's back, and we know that they divide in veinlets, and then in capillary blood-vessels. On a tree leaf, the ribs distribute the sap and collect it, once it has been enriched with photosynthesis generated carbohydrates. And, on some photovoltaic generators, a tree-like soft-solder design collects the power in the same optimized manner, by letting as much light as possible reach the electronic junction where the photoelectric effect takes place.

The Australian project isn't structured in such a way. The collector air transport and heating functions are blended, so that the air velocity considerably rises when it converges towards the centre, unless we'd highly raise the collector roof near its centre. Even far away from the centre, setting glass panes, on its whole area, 20 m above the ground, may generate a cost increase, and finally limit the collector size.

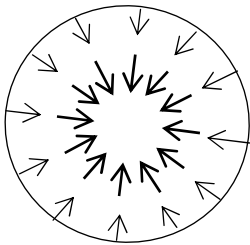
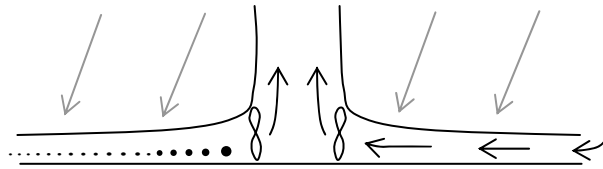


Figure 37



Therefore, the opposite hypothesis seems worth studying.

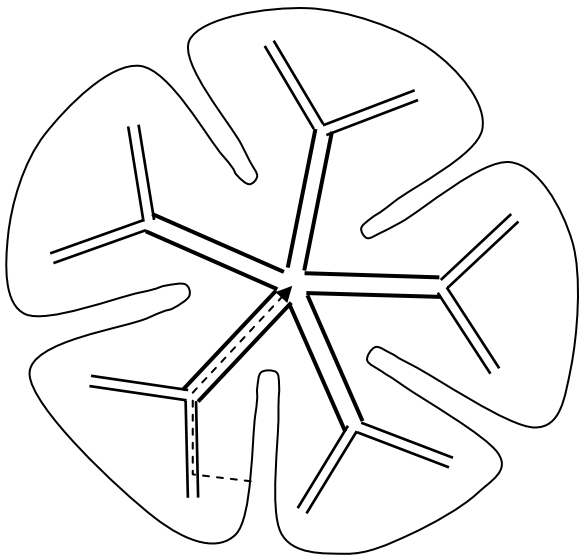
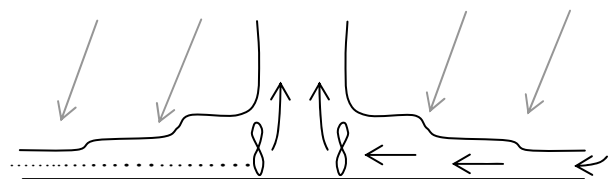


Figure 38



In fig. 38, the air is under the collector's commonplace (1st part of the dotted line way) only for a rather short journey. Besides, the collector outline indentations widen the entrance cross-section, which reduces the air velocity, thus the turbulent friction, even with a lower roof or a very large collector.

Afterwards, the air comes into the ribs, where the higher ceiling enables again to reduce its velocity and its friction, even near the centre, without having to modify the glass panes structure, as they only correspond to the light energy collecting function.

What sort of ribs would be necessary to realize separately the air transport in the collector ? The flow should be the same as in the tower itself. If the collector has a 12 km diameter, the adequate tower diameter is about 300 m. With 8 convergent ribs and a semi-circular profile, the required span is, at least, 150 m, and the height is 75 m, which, for classical constructive works, is not negligible. And these are only the smallest sizes : some of these ribs will have to keep a constant profile over several kilometres.

The solution may come from Sorensen's idea : these ribs could be inflatable structures. Their envelope could be made of a buoyant gas layer, between two layers of gas-tight fabric. To offset the weight of 2 mm thick textiles, we need a 2-meter layer of a very light gas (inflammable hydrogen, or costly helium), or 5 m of a gas approximately 40 % lighter than air (neon or ammonia⁸⁴, probably the best technical-economical compromises), or even 20 m of a gas 10 % lighter than the outer air ... like the inside air.

So, a 150 m wide and 75 m high rib could have a rather even and well stretched shape, from the double effect of the buoyant gases its structure could be filled with, and of the collector's own warm air. Of course, such a structure wouldn't probably be as lasting as a solid rib, but if its cost were much lower, it would remain economically sensible to set a new one several times during the dozens of years of the whole solar chimney's lifetime⁸⁵.

Three remarks for the design of these ribs and their branching :

- As we saw in the previous diagrams, the goal is to have the same flow, at a lower speed, under a lower roof, thanks to a much wider passage. Therefore, we increase the perimeter where the air goes out of the collector⁸⁶, but also the perimeter where the air comes into it. In the current project, the collector has the perfect shape of a circle, which, for a given area (linked to the light

⁸⁴ Ammonia gas, NH₃, is a compound of hydrogen, itself a possible derivative of solar electricity.

⁸⁵ Of course, this very long life is a solar chimneys advantage, but it is underestimated by the classical economic analysis. A facility's efficiency must be assessed with the help of a "discounting rate", which practically is close to the interest rate of the loans we use to finance it. With a 5% rate, i.e. 0.05, the relevant duration for the profitability analysis, is $1 \div 0.05 = 20$ years, which is called the temporal horizon : everything beyond it will poorly be taken into account. It is a pity, especially because environment and sustainable development would suppose to think with a longer term, but this is finance's law. But if there is a choice between a concrete structure built for 60 years, and inflatable ribs to be replaced every 5th year but 8 or 10 times cheaper, this discounting principle recommends to choose the inflatable ribs, because $20 < 5 \times 8$, the fact than $60 > 5 \times 8$ being irrelevant.

⁸⁶ In "The solar Chimney" : before going into the chimney ; here : into the ribs.

energy to be collected), has the *smallest* perimeter. But we want to *increase* its length, so any other shape will fit, and the less it will look like a circle, the better !⁸⁷

- in "The solar Chimney", a 10 km² collector with a 11 km outer perimeter and a 0.5 km inner perimeter needs 6.5 m high supports at the inlet and 20.5 m high at the centre. This could limit new scale economies from increasing the collector's area and height. Here, the typical figures will be 100 km² for the area, 200 km for the outer perimeter (costless), and about as much for the inner perimeter (100 km of ribs, which have a real cost, but possibly manageable). This could help keep the collector's height at 5 or 6 m everywhere, without increasing (on the contrary) the power losses from air friction.

- practically, the collector will be indented with long stripes of fresh air entrances, parallel to the first ribs, the air flow being perpendicular to all these structures. But, to increase the tower's power output in the morning's 2nd part, we needed black "curtain-hedges", and possibly glasses with a W profile, all this being oriented north-south without being an obstacle for the air flow (p. 95-96). This seems perfectly consistent with a ribs structure, if their orientation is east-west.

There doesn't seem to be any other general requirements commanding the design of the ribs and of the collector's shape. Thus, there are probably several designs approaching the optimum, and it's only to help to figure the concept, that the following drawing is proposed :

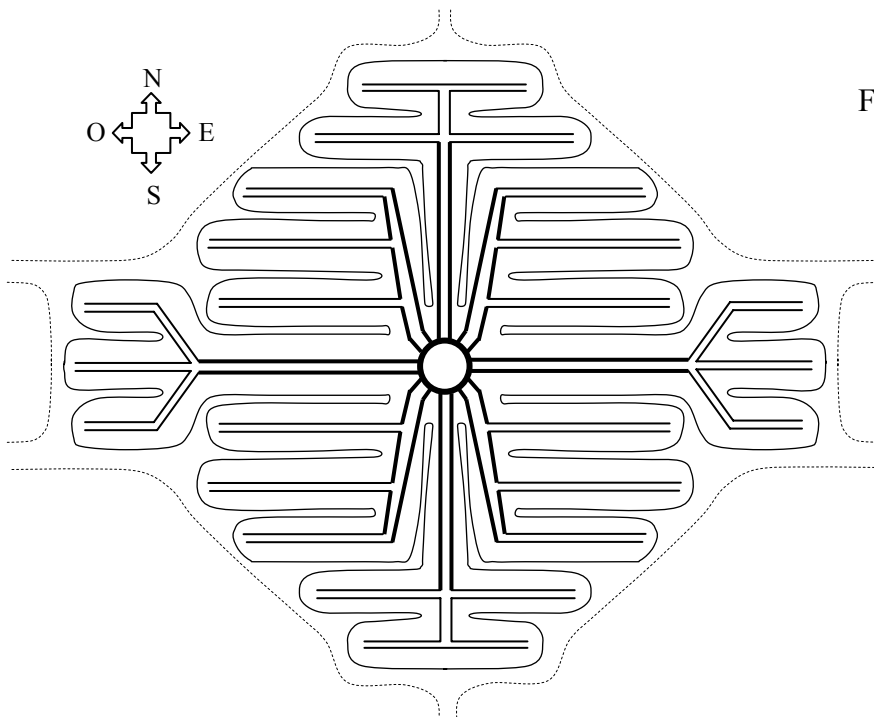


Figure 39

⁸⁷ But the desired shape must also *minimize*, for a given area, the mean distance between the tower and all the collector's points. A disk with the tower at its centre is, here, the optimum solution. That's why the present diagram has a rather round shape, which overall is centred by the tower. In fact, both conditions aren't incompatible, provided that we search a globally round, but deeply indented, shape. From this basis, it is even mathematically possible to find solutions as near as we want from both optima, the one which is a circle and the one which must be as different from a circle as possible !

g) Tower extension, working in tension

The very large quantities of concrete required for the Australian tower are computed with respect to three possible destruction factors : wind, tower crushing under its own weight, and earthquakes. The concrete is impressively thick at the bottom, but, hopefully, becomes thinner as we get higher.

However, the egg theory can't operate with an infinitely thin shell : beyond half or two-thirds of the tower height, the concrete thickness stops diminishing, and stays with a value of about 20 cm, which, over many squared hectometres, is very heavy.

This is a pity, for it would really be interesting to use the diminution of the stresses (above weight to support ; outer pressure > inner pressure, Cf. hereunder) with respect to altitude, to add, at a low cost, some additional tower height, whose economical interest doesn't decrease at all in the same proportions : if 200 m could be added up for the price of 100 m, and in a manner that wouldn't contribute too much to the lower stages stresses, this would yield, for a 1 km tower, about 15 % free additional power (20 %, minus the total cost's 5 % which the tower's 10 % should equal).

Adding up, at the tower's top, a layer made of a much thinner material than concrete, means that it must work in tension and not in compression. But we aren't, here, in the case of Sorensen's patent, with the turbines at the tower top, because this should modify too much things. So, it won't be possible to avoid that the outer air has the higher pressure, and that the tower's envelope will have to resist inwards stresses.

However, it is not impossible, as such a thin membrane may be fastened on a rigid structure. The solution is to put, on the last bicycle wheel⁸⁸, at the tower top, long poles able to resist compression. On these supports, a new bicycle wheel (various systems of stiffening cables can ensure that it stays precisely just above the tower).

Between these two horizontal wheels, a thin membrane would either be tensed outwards with the help of the guy rods we've seen at point d), or be arched so that to resist the outer air's pressure.

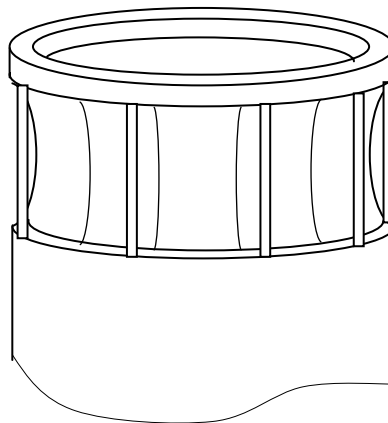


Figure 40

⁸⁸ So, we don't push directly over punctual zones of the concrete egg shell, which limits the risk of damaging it.

This inwards pressure difference is large only if we stand far from the tower's top. Therefore, a small additional height will be cheap and easy to build. So, if we want to be prudent, it will be possible to experiment this idea on the first towers, and to generalize it on a greater scale if these first tries prove technically feasible and economically profitable.

In an option, the two bicycle wheels holding the arched membrane (especially the upper one) could have a larger radius than the tower's one. So, the air passage at the tower top wouldn't be narrowed as it is on fig. 40, but, first, maintained at its normal size, and then widened upwards.

The outgoing air velocity would be reduced, which may be interesting because, in the energy balance which is ordinary made for such a tower, the outgoing air's kinetic energy is assumed to be lost. We saw, through the criticism of some publications in this field (II-B-1 and -3) that this idea is questionable. But, even if it would be possible to recycle part of this energy (and even with a purely cylindrical tower), it may be useful to prepare, from the tower's inside, the widening of the air flow which will afterwards be spread into all the free atmosphere over the tower top.

How much would all this reduce the stresses endured by the tower lower stages, by comparison with a concrete last stage ? The membranes lightness is an obvious advantage against the risk of the tower's crushing under its own weight. As well for earthquakes, in addition to a greater elasticity. But what about the wind, and in particular its horizontal drag ?

Two possibilities : either, in the computation of the tower sizes, the first two risks had a large part, and, by reducing them, we already save money by comparison with a whole concrete tower. Even with taking into account the wind effects on the whole height, much of the economical advantage will be kept, and we can build this new stage as just defined.

Or the wind is the main risk. By following suit to the calculation begun at appendix 3's end, we realize that exceptionally violent winds, over 200 km/h, are being considered. Such winds will probably never occur, and these figures include a large enough safety factor to be sure that the tower won't ever topple down. An additional stage will oppose widely to the wind (through the added up area, and through the maximum arm lever with which it will create a torque). So, it would be better to design it so that it could retract or vanish if extreme conditions occurred.

If we suppose that these conditions would be very rare, then an adequate solution would be to accept the risk of sacrificing the membrane to be stretched between the two horizontal wheels (the remaining structure would much less oppose the wind). We only have to adjust the membrane's upper bindings so that they break off for a given tension. This membrane's fall, probably inside the tower, can be considered as a safety-valve, a complementary and ultimate guarantee against a wind intensity which, very probably, will never occur.

Another solution is to have a reversible retracting device : ① either rectangular surface elements with a supple fixation at their upper side, and a reversible opening (e.g. magnetic) at the three others ; ② or a hoisting mechanism (with adequate counterweights) for the elements with the largest area opposing the wind : surely the thin membrane ; maybe the lot {membrane + upper bicycle wheel} ; perhaps this lot plus the supporting poles, which would then act like jacks. The supple membrane would be guided so that to fold up close to the inner side of the concrete tower wall.

The 1999 article ⁱⁱⁱ explains that steel structures and thin materials have been honestly studied, but that concrete was preferable because of its longer life-span. It must be remembered that in many deserts, wind carries much sand, which is one of the main causes of natural erosion. So, the base must surely be built with concrete. But, several hundreds of metres above, the problem may be different.

Would such a limited number of anchoring points, which concentrate the stresses, be structurally inconsistent with the idea of building part of the tower from the egg principle ? The answer would be yes if we had a pure egg, i.e. a thin concrete wall and nothing else. But the bicycle wheels which provide the tower's stiffness, can also become the supports for the upper part of the structure, and efficiently spread the punctual loads transmitted by the upper vertical poles.

This possibility to switch from a massive material to a lighter structure might also be combined with the suspended guy rods theory which has been developed in d). The concrete lower part of the tower could probably be very strictly stiffened by these perfectly rectilinear guy-rods, whilst the tower extension would be useful to hold the suspending cables. The points A and A' in figures 35 and 36, pages 103-104, correspond to these two parts of the tower. These suspending cables' greater elasticity (intrinsic elasticity + catenary curve elasticity) wouldn't be a problem, because of : the steel extension structure greater flexibility ; and this extension's lower wind drag if the corresponding membrane were retractable.

h) From ribs to leaf-stalk

The Solar Chimney's concept is often described as the "desert hydroelectric energy" ^{ii, 89}. Such an analogy must be pushed further : as altitude differences are essential, as well as for the hydroelectric power, is it possible to use mountains to provide this altitude, and save money from the tower ?

Building a very tall tower is tempting because it helps increasing the collector efficiency (and produce as much power while less perturbing the high atmosphere), but is also very expensive. Assume we try to reach a 2000 m altitude difference by combining a 1000 m penstock (one more time the hydroelectric analogy, and the botanical one : these penstocks are like the leaf-stalk natu-

⁸⁹ To emphasize it's perfectly renewable and cheap, to stress the differences between its turbines and open field wind turbines, and to evaluate the staff required to operate it.

rally continuing the ribs we've described previously) fixed aside of a mountain, and a tower with an equivalent height. The financial advantage will result from the comparison of the penstock price, and the cost difference between a 2000 m tower and a 1000 m one, i.e. 2 or 3 times the cost of the 1000 m one : it doesn't seem out of reach.

Besides, why should a 1000 m penstock be more expensive than an equivalent tower, with 1 m thick concrete at the ground to prevent its crushing under its 1 km height ? Because a penstock with a 1 km altitude difference, it's not a 1 km long duct, but rather 5 or 10 km. Remember, in the sunny countries, there hasn't be any ice age as in the Alps, where we can see quasi-vertical cliffs up to 1000 m high.

One of the only geological phenomena which have created, in tropical countries, real cliffs with, at their top, a plateau where a tall tower can easily be built, and, downside, vast, quite even and sunny areas, is the opening of the East-African rift, which brings rather favourable conditions in Eritrea, Ethiopia and Yemen. But these sites and some rare others are, compared to the whole necessary tropical desert areas, very insufficient.

Therefore, it will be necessary to use, either (the deserts north of Tibet) very high altitudes but weaker light flows, especially in winter, or much older and worn mountains. In the latter case, how can we build, for reasonable costs, large ducts, both longitudinally (to yield a good altitude) and laterally (to offer a high efficiency to collectors representing a large part of the neighbouring desert area) ?

One more time, Sorensen's principle helps not to be too afraid of the necessary works' size. In particular, if we keep on setting the turbines at the tower's base, this leaf-stalk is situated between them and the collector, and Sorensen's conclusion applies : the leaf-stalk will be overpressured⁹⁰.

As well as for the ribs, even if we think it'd be useful to realize the leaf-stalk with thin materials filled with buoyant gases, the main part of its resistance to the wind⁹¹ will come from this overpressure, with a good stabilizing effect as soon as we're some hundreds metres above the collector's inlet.

⁹⁰ The same for a penstock which would bring the air from an "energy tower like" dam, as in the Assaf & Bronicki patent^{vii}. Opposing a previous patent, they exclude the idea of such a penstock, and only imagine turbines at the very outgoing of which, in their description, is a whole water spraying and evaporation volume. However, the present idea seems adequate, provided that the dam would have a great volume and the penstock a very wide cross-section.

Ideally, it would be useful that, in a space which would in fact be the last part of the dam and would replace the penstock, water evaporation could go on when the cooled air adiabatically goes down and receives pressure work which can raise its temperature. But the idea to locate a dam on a plateau with the turbines down sort of a cliff, is clearly not mentioned in this patent, though it would have the advantage of a greater altitude difference.

⁹¹ I.e. its capacity to undergo some violent winds without being torn. This risk threatens more a structure softly floating in the wind from a gust to another, than a well inflated and thus well tensed structure. The leaf-stalk will resist wind-carried sand if, as previously seen, its sides are build in concrete up to about 100 m, only the covering being made of thinner materials. And, to lead hot air from a plain upwards, these big pipes can probably be build in talwegs naturally sheltered from lateral winds.

i) Towers with a modifiable geometry

We saw, when examining Sorensen's principle, that the main reason why it didn't seem very realistic to fully implement it, was the problem of the wind.

Its various actions, at various scales, allow, if any, only one strategy : the ostrich's, don't fight the wind, shelter. We've previously examined such a solution, in the case of the stretched structure added up at a concrete tower's top, to yield some additional power : in the case of a very strong wind, it, or at least its greatest areal elements, would be sheltered inside the tower. The same principle could, perhaps, be implemented for the tower main part, with different options.

We could first imagine to build a telescopic tower, constituted from a dozen supple⁹² elements with slightly increasing sizes, able :

- when the wind is strong or middle-sized, to be brought down together, each one embodying the smaller one. A 200 m tall concrete structure could shelter the whole lot.

- in case of a weak wind, to be drawn up, by a counterweights and bearings device, while sliding around a fixed structure, which would oppose a much reduced area to the wind, and would probably be tightened by point d) suspended guy rods. With a set of turbines permanently situated at the top, Sorensen's effect would be ensured each time the tower is fully drawn up.

The turbines total cross-section area must be close to the tower's one, so that the whole nominal air flow can exit from it. It could be necessary to have a (retractable or not) top, containing horizontal turbines (vertical axis, upside flow), and also vertical turbines (horizontal axis, radial flow), being part of the highest retractable element.

Another option could be to reduce, when the wind blows, the tower width. It could, for instance, be made of vertical articulated panels, able either to be displayed so that their total area gives a cylinder with the required sizes, or to fold up round a central pole, with a much reduced diameter, and thus a lower wind drag.

The same effect could also be imagined with an envelope made of much more supple material, fixed to cables with a slight excess length so that they can take an arched shape, either outwards, or inwards.

⁹² Again, this word only means that it can't resist a high outer pressure by itself, as an egg shell. It seems highly preferable to realize it with metal sheets, rather than with textile materials.

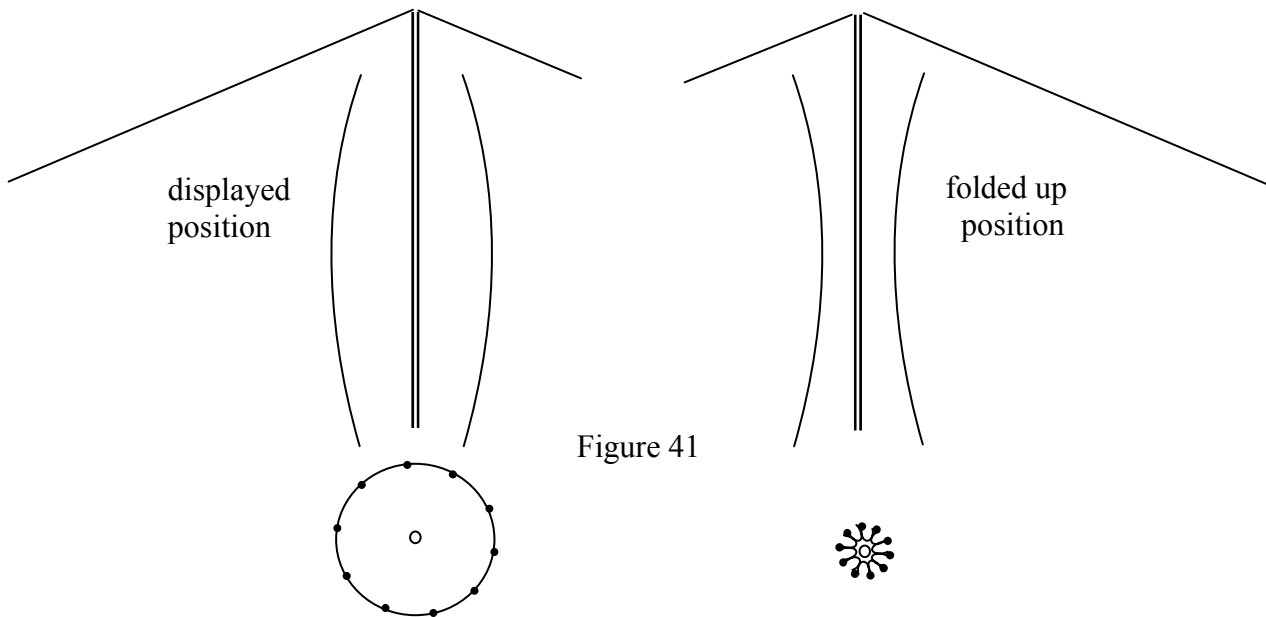


Figure 41

This option needs two Sorensen's effects : a positive one, outwards, and a negative one, inwards. To allow both Sorensen's effects to take place, an auxiliary mechanism should enable us to switch either the thermodynamic operating modes, or the operating turbines positions (Cf. fig. 7, p. 22).

So, the tower could, in its displayed position, be an upwards solar tower, but with the main turbines at its top, and, for the negative Sorensen's effect generation, offer the possibility to lock these main turbines open, and let a small quantity of warm air pass through auxiliary turbines at the tower bottom. This would indeed help the tower to fold up in case of a very strong wind.

It also could mainly be an classical energy tower (with water sprayers at its top and turbines at its bottom), and, in its folded up position, a solar chimney, also with bottom turbines, and a small collector which would only be useful for this negative Sorensen's effect auxiliary function.

Such solutions, even if they are complex⁹³, would be useful if we'd want to use lighter materials than concrete, while not excluding very violent winds even if they are very unlikely. Another advantage is that there seems to be no logical reason that the mobile elements cost should rise much faster than the tower height (regardless to the dependence on its diameter), whilst for a "free-standing" concrete structure, the proportionality is, if not exponential, at least to the height squared. Here, this will perhaps be the case for the inner rigid pole, but only for part of the global cost.

Therefore, such an advantage could appear for very large heights, which was indeed the goal of all the solar chimneys improvements proposed from page 98 so far.

⁹³ Jörg Schlaich said one of his solar tower's advantages was that, apart from the turbines, there wasn't any mobile element ; here, we've got some. However, modern architecture accepts the idea of very large mobile sets boldly using the opposition between compression and tension, as for a price recently awarded to a rotating (round an horizontal axis) footbridge spanning a Britannic harbour entrance. Very large airship sheds have also around 1 hm² "doors".

III.B Energy towers : using big enough drops so that they can be recovered before the air goes into the tower

We saw that the principle of letting the droplets be dragged along by the moving air, and create a fog, could have two drawbacks, which the Israeli-Indian presentation and the Technion Institute work seem to address (but we don't have all the necessary details) : if we use salted water, the outgoing air, at the tower bottom, could be environment-unfriendly ; and, unless we choose Assaf and Bronicki's patented dam solution ^{vii} (preferably with a more specialized overpressure penstock than in this patent), there is a dilemma, notably resulting in rather high pumping up losses, between too big drops which evaporate too slowly, and too little droplets, requiring sprayers with high investment and maintenance costs.

An alternative solution could be to propel, into the incoming air flow, water jets with a sufficient diameter so that they will break up in rather large drops able to be collected by adequately placed trays, without being carried along by the air into the tower.

Of course, heat exchanges⁹⁴ will be less efficient than with smaller droplets well mixed with the air. But, to create the water jets, much less energy will be consumed, compared to what is necessary to pump water from the tower bottom up to its top. So, it will be possible to propel water in very large excess, again and again, and restore a correct thermal efficiency.

So, we have an alternative solution, compared to the so far rather mysterious "enhanced coalescence", in order to use sea water without rejecting big amounts of salt into the environment (if this mystery got cleared, the present point would only be useful to introduce the use of the same idea for the following proposal, notably page 117 top).

During its evaporation, the sea water salt concentration will rise, which lessens its ability to evaporate⁹⁵. It's therefore necessary, once its volume has been significantly reduced, to let it go down and recycle its gravitational energy as for a classical hydroelectric dam. As previously, neither the hydraulic turbines, nor the pumps who initially brought the water up, have a 100 % efficiency. But, as soon as at least half of the water evaporates, we're far from consuming more power than what is produced (Cf. the 12 % ratio, (9), p. 15).

As for solar chimneys, a vertical tower can be substituted by an "air penstock". The air and water mixing facilities would be easier to build on a mountain than at a tower top⁹⁶. This penstock can again be realized, for a large part, in thin materials : to overpressure it, we only need to place the turbines at the bottom, which isn't difficult ; and, to flow down a mountain, it's often possible to find dales quite well sheltered from lateral wind.

⁹⁴ Widely meant : heat diffusion between the droplets surface and the air ; and steam diffusion, very analogous.

⁹⁵ The most salted water can be used for the 1st evaporation, which will occur anyway, as the air is still very dry ; the less salted water is kept for the final evaporation, for which the best thermodynamic conditions are required.

⁹⁶ Reinforced concrete has a longer life-span under dry conditions, as explained in "The Solar Chimney".

If the topography is favourable, salted water resulting from evaporation can be stored in altitude, and its energy's recycling can be postponed. For instance, it can work during the morning, when the operating air's negative buoyancy is too low. And in the afternoon the maximum power output will help pumping water up with no simultaneous opposite movement⁹⁷.

III.C Other change of state and latent heat systems

In the case of energy towers, the water vaporisation brings the raw energy, and enables us to avoid building a collector ; besides, this energy ("latent heat") is generally viewed as being more "concentrated" than the incident solar flow. Therefore, a thorough examination of all the possibilities resulting from such principles must make us wonder whether other changes of state could also yield interesting results.

III.C.1 Polar air and water freezing towers

a) The principle

Energy towers are based on the fact that, in contact with a dry air, liquid water can generate a cooling down. But the heat pumps⁹⁸ show that, especially in a polar region, liquid water also contains heat, which can be extracted in large quantities if a process can turn this water into ice.

This process is more or less the same as for the "snow guns". Water is sprayed into a very cold air⁹⁹, and the water's icing warms the air up. This air becomes buoyant, and electricity can be produced as in a solar chimney, but, again, without a collector.

⁹⁷ Such a game with dam water gravitational energy to get the best from the different values of electric energy at various day and night hours, is already implemented by electricity companies. It's also mentioned in the energy towers presentation^{vi}, which considers it as a possible reason to build them in concrete instead of a steel lattice, in order to realize, in altitude, as for a water-tower, a gigantic water tank.

⁹⁸ Systems enabling to heat a house by letting a fridge operate the wrong way up : the cold it produces is transferred outside, e.g. to a lake, and, at worse, will turn water to ice ; and the warm convector which, in a normal fridge, stands behind it, is used to warm the house. The energy balance shows that the house receives the fridge's electrical power + the thermal power corresponding to the outside rejected cold quantity : compared with an ordinary electrical heating, the efficiency is higher (possibly much higher) than 100 %.

⁹⁹ Snow guns are often said to need very cold and dry weather. But no evaporation process is at work, so the air doesn't need to be dry in the same sense as for the dry air towers (= energy towers). It must just be dry to prevent the water vapour, which is opaque to infrared radiation, from stopping the ground's night freezing (greenhouse effect). In fact, the weather mustn't be cold and dry, but dry, hence cold. Of course, from the laws of the vapour / condensed state changes, it is also cold, hence dry.

We notice that the best snow guns can make snow even during insufficiently cold nights, as they compress the air, then let it cool down and finally expand, which artificially colds it down. Here, the analogy is only with ordinary guns, without such a device.

However, the heat produced by the icing of 1 g of water is 7.3 times lower than the coolness its vaporization produces¹⁰⁰. And the high value of this vaporization latent heat was necessary to get a 20 % only upwards / downwards ratio. Here, will it be 100 % or more, and this idea hopeless ?

No, because here, there is no need to pump the water up, for it is used to warm the air up at the tower bottom so that its buoyancy leads it to the top. However :

- contrarily to what happens with a snow gun, water mustn't be transformed into light snow flakes which could be dragged along with the air, because this air would then be weighed down by these flakes and lose quite all its buoyancy. The solution, as just proposed for energy towers, is that the water drops are large enough to be recollected, and aren't carried up by the air flow ;

- with the exception we'll see next page in b), there are few opportunities to use mountains altitude differences, because bringing large water quantities just to the bottom of rather high mountain ranges, generally needs to pump it up (and evacuating large ice quantities isn't simple either).

What sort of needs can this principle satisfy ? The system can operate only if the air's temperature is negative (in ° C), and preferably very negative. So, the towers must be built as far northwards as possible, and operate by night. This may seem contra-economical, but we must remember that, in winter, beyond the polar circle, night lasts all day ! And it makes sense to have a maximum production in winter.

Of course, we are again at least 2000 km far from the biggest consumption centres. It is a fact that many renewable energies, among the most economically promising ones, are well adapted to non temperate climates. Thus, the question of electricity transport must be addressed, and its effect on the economical efficiency be assessed.

The "water" resource can be fresh water taken from non entirely frozen lakes or rivers coming from south. All this might be found in Siberia as well as in Canada. We can also use sea water, whose ice point isn't much colder than the fresh water's. The "air" resource also bears few limits, as the air we've just used rises up to a high altitude, gets cooled down through infrared radiation, and can be viewed as recycled.

However, in the global atmospheric circulation, the polar regions mainly receive their air from the sky, as in subtropical deserts. So, it could be prudent to study the possible environmental impact of the relatively warm air flows sent from the tower up to the high atmosphere.

¹⁰⁰ The profitability criterion, in a competition with solar chimneys, is now (by comparison with the equivalence set in footnote n° 19, p. 19), of 1 m² of a collector, and a device able to evaporate 6 litres of water each day) whether a facility allowing 45 litres of water a day to freeze by being in contact with an icy air, is cheaper than 1 collector m². A more precise calculation, taking into account the fact that for water evaporation lowering factors equal to -12 and -8 % had been used, and that they seem pointless here, yields a 35 l/day result. If we assume that we have only six favourable months per year, this figure is to be doubled, so the freezing capacity to be available for the same price as one collector m², should be of 70 litres per winter day, i.e. 3 l/h.

Anyway, because of their geographical localization and their best production periods during the year, polar air towers are more complementary, rather than in competition, with solar energy. The main competitor is wind energy.

b) A region of particular interest : the northern Atlantic Ocean

The fact that the outgoing water is mixed with ice, is interesting not only because we oppose the current anthropic (greenhouse gases effect) warming of the polar zones, especially in winter, but also because it theoretically enables us to do something about the threats linked to the thermohaline circulation, i.e. the Gulf Stream.

At the junction between the Atlantic and Arctic oceans, in winter, unsalted sea ice appears and, in the remaining water, the salt concentration rises. As it becomes heavier, this cool and highly salted water dives down to the Atlantic Ocean bottom, and will get up very slowly anywhere in the world. So it lets its room, at the surface, for water coming from elsewhere, i.e. mainly the Gulf Stream.

In spite of recent studies which moderate the most appalling prospects^{xxv}, there could be a double-double threat upon this mechanism :

- the global warming reduces the pace of sea ice creation, this warming coming both from the greenhouse effect which, notably by night and in winter, opposes to the sea surface cooling down, and from the reduction of the snow cover of the polar regions, which thus become less white (albedo variation).

- incoming fresh water (floating at the surface or mixing with the salted water), reduces the possibility of creating enough salted water able to dive properly, and thus to pull the Gulf Stream ; this fresh water could come from the inlandis melting (Greenland), and from Siberia, where the climate could become moister, which could increase Ob, Yenissei and Lena water flows.

With a weaker Gulf Stream, the western Europe's climate could become much colder in winter. To avoid such a change, a 1st idea is to catch icebergs during the spring, and pull them so that during their drift, less of them melt just in the middle of the Gulf Stream. We can hear about it from time to time, when it comes to fresh water supply in dry and hot regions. Here, we're just adding a public interest rationale to the sending of this ice's fresh water and cold in Tenerife, Lisbon, Seville or Casablanca, where the climate change will anyway boost the demand.

If, for any reason, such a solution would prove difficult, costly or insufficient, we could consider the idea of artificially increasing the sea ice and salted water production, with the help of the towers we've just described. A favourable location could be in the northern Scandinavian Alps, near Tromsø, 400 km north from the polar circle. There is, distant by only a dozen km from various fjords, a mountain quite 2000 m high, on which such towers could be built. Then, with an air column height¹⁰¹ around 2500 m, the air warming systems could benefit from a correct profitability.

¹⁰¹ One of the advantages of using a natural mountain is that, if the tower's building is very expensive (for instance by comparison with the water freezing systems), it can be better used in the following way : such systems are set up not only at the sea level, but also at middle-height of the mountain, or at its top. Downwards ice and water flows behave like counterweights (in the same way as in a lift) for the upwards water flow (with a possibility to delay this counterweight equivalence, i.e. to store gravitational energy in a dam, and deliver it in an optimal way at different parts of the day). The interest is that the air which has come from the bottom, has been adiabatically cooled down (10°/km). Its temperature being now well under 0 ° C, it's easy to warm it up again, and it yields an additional power corresponding to the air column height which it hasn't gone up yet, until the tower's top. This can also enable the system to operate during other moments than at the boreal winter heart, even if the air temperature at the sea level is too close to 0 ° so that at this level water freezing wouldn't be efficient.

The electricity consumption centres are, 1400 km away, Oslo, Stockholm, Finland and Saint-Petersburg, and, at a distance around 2000 km, Copenhagen, Hamburg and Berlin.

What would be the size of a system able to compensate a 0.5 albedo variation (half the gap between the extreme values 0 and 1), for a 1000 km x 1000 km square ? Due to the clouds and the very low position of the sun above the horizon, assume an annual energy flow 10 times lower than in the sunniest regions, i.e. 240 kWh/m².y, thus a $1.2 \cdot 10^{14}$ kWh/y heat to be processed, or $4 \cdot 10^{20}$ J/y. To simplify, we suppose that the facility can operate at full power during all the night periods, and never during daytime, i.e. $1.6 \cdot 10^7$ s/y, which gives a peak power around $2.5 \cdot 10^{13}$ W. With a theoretical efficiency about 8 % (the air column being 2500 m high), and a total losses ratio chosen to be 50 %, the electrical power would reach about 1000 GW, a non negligible input into the European grid.

If we warm the arctic nightly air by 20 °, whose specific heat is $3.5 \cdot R \approx 30$ J/°/mol, each air mole, i.e. about 20 litres ($\frac{1}{50}$ m³), takes 600 J away, thus, for each m³, $3 \cdot 10^4$ J/m³. Therefore, the $2.5 \cdot 10^{13}$ W thermal power corresponds to a $8 \cdot 10^8$ m³/s air flow. So, with a 40 m/s air velocity¹⁰², we need to build, for instance, 40 towers, each of them having a $\frac{1}{2}$ km² cross-section, which is much at the top of a mountain, but is perhaps possible.

When it comes to ice, the same $4 \cdot 10^{20}$ J/y are to be compared to the water's fusion latent heat, i.e. 6 kJ/mol, with 1 mole weighing 18 g, hence a latent heat per ton of $(1/3) \cdot 10^9$ J/t. Thus, the ice quantity being produced in one year is $4 \cdot 10^{20} / \{ (1/3) \cdot 10^9 \} = 1.2 \cdot 10^{12}$ t/y. The number of m³ is slightly higher, i.e., in km³, about 1300 km³/y¹⁰³.

¹⁰² 144 km/h : much higher than in a classical solar chimney ; but, as we work from a change of state and not from a solar collector, the power output - and sea ice - maximization introduces the mpp theory, thus very high flows, and air mechanical losses about one third of the initial power are easily acceptable.

¹⁰³ The water flows can be easily deduced : if, for instance, we want to rise the water's salt concentration by 10 %, the water flow will have to be ten times higher than the ice flow. With a 10 hm² cross-section, the water velocity should be 500 m/mn (Cf. calculation for the ice, next page), i.e. 8 m/s. Such a cross-section gives an idea of the size of the droplets spreading systems (inside a very quick air flow, and with the need to recover these undercooled droplets) which will be required.

But, to make sense, they must be compared with the quite 1 million km² large glass collectors Jörg Schlaich imagines to feed Europe with renewable electricity. Here (1000 GW during 6 months per year), we fulfil only part of the needs, so that the comparison must be done with around 170 000 km². We come back to the idea (footnote n° 100) that the problem is whether, in order to heat 1 m³ of air with the same number of degrees during the same time, a 1 m² collector is more or less expensive than a system able, each day, to freeze 70 litres of water, i.e. to use 700.

By dividing the previously given figures { a 10 hm² cross-section, a 8 m/s velocity } by $1.7 \cdot 10^{11}$ (quotient of 0.17 million km² and 1 m²), we get an incoming water flow of 5 m/s by 1 mm², during 100 000 s per day, which yields the same kind of result : 500 l of water to be filled in the freezing system each day, to be compared with a 1 m² collector (the difference between these 500 and 700 l comes from the fact that it isn't enough to wonder whether we heat 1 m³ of air with the same number of degrees during the same time, because it depends also on the way this heated m³ is used, i.e. the forecast efficiency : here, the tower's height is enhanced by the possibility to build it at the top of a mountain ; but is partially offset by a mechanical efficiency supposed to be as low as 50 %, in spite of 80 %, precisely because of the large water and ice flows to be handled).

N.B. : if the collector 170 000 km² we consider here for a 500 GW yearly mean output, are checked to the mean 85 MW the Australian tower will produce (750 GWh/y), we find that its collector theoretical area should be 28,5 km², i.e. a rather low figure, compared to the 7 km diameter the media announced. We come again to the idea that this collector very large sizes go with a facility efficiency under-evaluation (maybe from a prudence excess) or decrease (notably by comparison to "The solar Chimney" 100 MW towers), Cf. the interpretation given in point II-F-2-a, p. 80.

This is a considerable volume, which is normal, as it is the first goal (in addition to the production of a lot of electricity) : compensate the undesirable and predictable weakening of a natural mechanism which produces a lot of ice each winter as well. But this rises two main questions : how remove it from the production site so that it could keep on operating ? And what is to be done with this ice, once we've put it aside ?

As the production is to be organized in a fjord rich region, it seems logical to begin by floating this ice away. Each hour, during the whole boreal winter (4400 h), about 270 million tons would have to be evacuated ; i.e., thousand oil tankers, each of them of 1 million tons (1 hm³), organized in a sort of automatic bucket-conveyor, having a 4 h cycle between the production site and the open sea (some dozens km). As usually, these figures are impressive, but not out of reach, with regard to the electric power to generate, and the usefulness of controlling Europe's climate.

Having reached the seaside (during the production season, the sea is probably frozen, and therefore it might be difficult for boats to work), there is a choice to do among various ways to cope with such an amount of ice. It could be possible to :

- ① bring this ice to a prominent point in front of the sea, up to 100 m high¹⁰⁴, and dump it. As long as it remains rather homogeneously mixed with water, the whole lot will remain fluid and will spread easily ; if it proves impossible to prevent it from behaving like a whole piece of solid ice, it will create a glacier which, typically 1 km² in cross-section (10 km wide and 100 m high), will have to move at the rate of 0.3 km/h (1300 km for a six months' production, i.e. 4400 h), or 5m/mn.

Once in the sea, we can imagine a development similar to the soil brought by abrupt mountain streams when they reach the valley : an ice spit develops ; when it becomes too long and gets restrained by the ice-bank, another spit starts aside, etc. So, there's not much point in worrying about the possibility for the ice to spread : from a starting altitude up to 100 m, it wouldn't be theoretically difficult to set up a little floating glacier with a 10 000 km² area and a 130 m mean thickness (13 above the water line, all the remaining under).

The question is rather whether, for instance due to a good fluid behaviour, and then a larger spreading, we could contribute to cool down an important part of the northern Atlantic ocean, and to bring its mean albedo back to its usual value. Or whether, on the contrary, a risk of creating a lot of icebergs would be a big drawback of this way of coping with the ice. Precise studies on these topics would be necessary.

- ② try to export it towards hotter zones, in order to extract its fresh water and its cold, and to sell them,

¹⁰⁴ We had found a first feasibility ratio equal to 100 %, which meant that as long as we haven't to carry the ice up to an altitude equivalent to the tower's top, we don't use more energy than what we could theoretically produce.

- ③ the same, but in order to let it spread and melt among warm seas, and limit their upper layers' dilatation¹⁰⁵. The $4 \cdot 10^{20}$ J which could be extracted each year from the warm seas correspond, for a total oceanic area around $4 \cdot 10^{14}$ m², to a cooling of about $\frac{1}{4}$ of a degree for a 1 m thick layer (or 0.01° on a 25 m layer), and a lesser than 0.1 mm dilatation reduction, which is few. This could become non negligible if we could consider that this phenomenon accumulates each year.

So, it would be necessary to know the thermal time τ with which the ocean reacts to outer influences. In particular, the current worries about a possible rise of the sea line by several dozens cm, can be explained by dilatation, only if a layer much thicker than 1 m is considered, thus with a big thermal inertia. Besides, spreading a cool water layer on the ocean's surface could limit the whole atmosphere steam quantity, and could restrain a possible positive retroaction¹⁰⁶ of the water cycle, from the anthropic greenhouse effect.

- ④ try to store this ice over the land, if flat and large areas could be found not far from the production site, which is the case only in the most northern parts of Russia and western Siberia¹⁰⁷. For a 100 m thickness, the area of a square with 115 km sides would be needed each year. It could yield a 3 mm/y reduction of the mean seas level, which is much more than the 0.1 mm we saw previously, and with a reasonably certain accumulation of this effect, as a glacier put on a flat land in a polar country could stay a very long time without moving.

A completely new science of public works made out of ice should be developed (dikes made out of ice, canals filled with very salted water, even tinted in black, allowing canal-boats to move between such dikes, techniques aimed at maintaining the fluidity of ice-water mix so that it can flow efficiently into dumps enclosed by these dikes, etc.) !¹⁰⁸

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There is a plurality of solutions, each of them having its own difficulties, but all of them liable to contribute positively to solve problems like sea level elevation, Gulf Stream slowing down, etc. (in addition to the fact that the electricity output is renewable). Therefore, these questions could be worth further investigation.

¹⁰⁵ Anyway, and with any of these solutions, we get an effect in the same direction, as we accelerate the northwards transit of the Gulf Stream's warm water, which is replaced by cool water coming up from the oceans bottom everywhere. But this effect is probably weak (no latent heat exchanges).

¹⁰⁶ With all the uncertainties which are well known about this positive retroaction, and notably the difficulty in evaluating the corrections to be made because of the variation of clouds sizes and characteristics, which is linked to ocean evaporation.

¹⁰⁷ Thus, it would finally be necessary to transport this ice, by sea, with the difficulties we can imagine, to these regions' coasts. Should we also transport the needed power for their elevation ? Not sure, as it could be more efficient to build there, even if there aren't high mountains, similar towers, producing their own ice, and whose electrical power output would be adjusted to the need to carry this ice up, in addition to what would be imported from Norway.

¹⁰⁸ Executives with an interest in the same region could at once have the idea to divert fresh water from the Ob drainage basin, and, with the cost of a comparable altitude difference, reject it into the Aral sea, but the water volumes they could get rid of in such a way, are lower.

III.C.2 Steam saturated air towers

a) Autonomous use

This last example of a latent heat tower is rather curious :

- starting with the same phenomenon than the energy towers, it reaches an opposite result (a warmer air than the ambient one, and a positive buoyancy) ;
- under some conditions, it becomes possible to think about systems freely floating in the wind, contrarily to the scepticism I have previously expressed against such systems ;
- the origin of its economical interest is very different and hypothetical, but is worth being examined.

The idea is to introduce into the towers some air, already quite steam saturated, taken near a summer sun-heated ocean surface. By reinforcing the thermal contact between this air and the warm water of the ocean's surface layer, we might really saturate it with steam, and even rise its temperature while keeping this saturation.

Then, this air will be around the same temperature than the ambient air. Will it be enough for it to move upwards ? Yes, because at a higher altitude, instead of cooling down rather quickly as the outer air, it may benefit from steam condensation which, as we've noticed previously (in the opposite direction) is a brake against temperature variations. The inner air will become relatively warmer than the outer air, and will draw¹⁰⁹ the one which, at the bottom, hadn't yet such an advantage.

The air and warm water mixing device, designed to ensure a very good thermodynamic contact between both fluids, will be floating at the water's surface, and, if equipped with sails, it will be drawn by the wind. The chimney itself could be a thin supply duct floating in the wind, and kept with inner overpressure by the turbines put at its top. But why accept here this poorly rigid configuration we had previously refused for other applications of Sorensen's effect ?

First because, if the surface device is drawn by the wind and if the high altitude one is as well, these wind velocities might be, under a given altitude limit, not very different in directions and magnitudes. And the stress the materials have to resist varies with respect to the difference between these vectorial velocities, in fact this difference squared. If the surface device's speed is half the altitude wind's mean speed, such a stress will be divided by 4 !

¹⁰⁹ This term sounds like a depression, although wind floating systems require the benefit of Sorensen's effect. In fact, it will operate in altitude, if the turbines are placed at the system's top. But, at the bottom, for some hundreds of metres, it might be necessary to afford a bicycle wheel reinforced duct, to fight efficiently against inwards pressure forces.

But also because, the more extreme the meteorological conditions will be, the more profitable the system will prove. This is because it can be analyzed, not only as a renewable energy conversion system, but also as a hurricane prevention tool.

Hurricanes come from the existence of very warm water at the oceans surface, from the ability of this water to saturate the neighbouring air with steam, from the power of the thermal machine which is fed, at a higher altitude, by this steam's condensation, and from Coriolis's force which changes the upwards air flow into a gigantic swirl.

Here, we're creating a competing system which uses the first three phenomena for itself, and controls the fourth one by confining the uprising air in a conduit which limits its ability to rotate, and taking its power into the turbines.

So, insurance companies facing the "hurricane risk" could be interested by such a principle, and agree with the need of periodically buying new textile envelopes used for the supple "towers" of this configuration.

Such an additional income would indeed be necessary to compensate the wide technological uncertainties introduced by this idea :

- a system floating in the wind and filled with heavily raining air ;
- buoyant balloons and turbines located at this system's top ;
- sailing surface equipment having to be so wide that a reasonable number of them could skim a large part of the excess heat off the ocean and reduce the hurricane risk ;
- thermal contact to be created between the warm water and the air we want to saturate with steam without forgetting to have condensation germs ;
- transformation or transport of the electrical power output ;
- etc.

Environmentally speaking, it can be added that cooling down the oceans' upper layers (especially if evaporation is adjusted so that the cooled water can be re-injected at an optimal depth) helps again to fight against one of the global warming effects, the sea level rise.

This may seem ridiculous, but this rise only comes from the degradation (because of the greenhouse effect) of a heat evacuation mechanism (infrared radiation) from the atmosphere lower layers and from the sea's surface, to the high atmosphere. Here, we help another heat transfer mechanism (convection) from the same origin to the same destination. If, looking both to the oceans energetic potential and to the usefulness to regulate them, there was a serious will to compete with the millions of km² considered for solar chimneys, all the warmest oceans area could be periodically scoured.

b) Use in synergy with energy towers

We saw at II-E-2 (p. 71) that the energy towers outgoing air had some common features with the one just over the tropical oceans surface, in summer, especially when it has been heated by the sun (e.g. through a contact with the ground) all day long, and that there was a risk of triggering "continental hurricanes" if this was generating enough humid and warm air.

To deal with an analogous problem, look for an analogous solution. If this risk were real, we could imagine to build large towers able to tame the energy towers outgoing humid air condensation, thus generating an upwards flow going back to the high atmosphere, and defusing, by an earlier trigger, this condensation's aspiration. These towers could start to operate, each morning, by using during some minutes their turboalternators as engines, to blow the air into the tower, upwards, until the condensation creates enough depression, first so that the flow could be self-maintained, and then to generate power, under control.

Globally, we'd have quite a real cycle, which in the afternoon would be the following :

- ① the desert sky dry air comes into the energy towers, where, between 1 and 0 km up, it produces its 1st power from water evaporation ;

- ② then it is heated by the sun ;

- (it is even possible to evaporate fresh water, so that this air becomes both warmer and more steam saturated) ;

- ③ then, in these new steam towers, it goes up mainly from its condensation above 1 km, which again helps to produce power ;

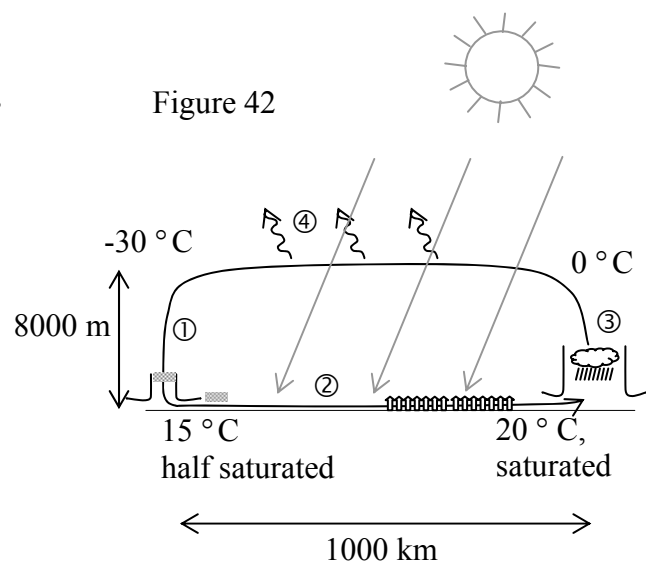
- ④ eventually, it stays in the high atmosphere as long as needed to cool down (infrared radiation) to its cycle start temperature.

The advantages are the following :

- this device produces, in two stages, a power which, theoretically, can be approximately calculated as a function of the received solar power (without needing to have a collector) and of the tallest tower height (with no need of water sprayers at *its* top), hence with a theoretical efficiency around 10 % if we could reach a 3 km height ;

- it distillates sea water and provides a favourable moist air to possibly irrigated regions ;

- and the environment perturbing effects are reduced as we operate quasi-cyclically, which, for the global atmospheric circulation, is as close to neutrality as possible.



All this probably deserves that we'd consider building a rather low number of these very large complementary steam towers (their cross-section can be wider than for energy towers, as, thanks to their taller size, there is no great drawback to let the air come in as a several hundred metres thick layer), which could probably benefit from new scale economies.

New questions will appear. How recover the gravitational energy of the 2 km up condensed water, and prevent these rain drops from falling down to the tower bottom and "eating" the growing uprising droplets (could a spiral internal structure be the solution, Cf. appendix 6-b, p. 169) ?

The idea of spraying new fresh water droplets into the energy tower outgoing air is interesting, as it helps to increase the solar energy density (latent heat) this air can contain, without being buoyant (this is the condition to remove the collector whose function is mainly to prevent warm air from rising up without passing through the solar chimney) before it goes into the steam tower.

But if these droplets' radius is too low, this air layer could look like a cloud, and shadow the ground, which won't receive the solar light it needs (both for agricultural purpose, and to transmit some solar heat to this air layer). Would simply watering the ground be enough ? Will this air layer be stratified, and how will the steam and heat exchanges among its sub-layers be enhanced by its turbulent horizontal drift from the energy towers to the steam towers ?

III.D Solar ponds

We mentioned the solar ponds only because remarks about them were helping to understand other subjects. But their stakes are lower, in particular because only some thousand km² are available for solar ponds. Besides, in the long run, its probably most adequate energy conversion mode, sea water desalinisation, could be challenged by fresh water imports from temperate zones. That's why possible technical improvements will be limited to only one point.

In solar ponds economical balances, a non negligible cost element is the salt gradient maintenance : salt diffuses, slowly but surely, from the pond bottom where the brine is most concentrated, to the upper layer, where it is least. Therefore, people periodically dump solid salt down to the pond bottom, in order to strengthen this gradient.

One of the advantages of Assaf & Fisher's patent ^{ix} technology is that this work becomes totally useless. Indeed, the system automatically takes warm and highly concentrated bottom brine, to evaporate it in a boiler. For the authors, the only interest is that it will become cooler and even more concentrated, which will ease its way out downwards, and thus all its movement generation. The appearing steam is used to produce electrical power, then condensed by contact with the solar pond upper layer cool water, which will necessarily even lower this salt layer's concentration.

Therefore, we've automatically got what we thought we had to do voluntarily : a concentration rise of the most concentrated layer, a dilution of the most diluted. This is clearly an opposite (and thus corrective) action to the natural diffusion evolution. Such an effect is finally so simple, quite natural (I use this word on purpose, for it is related to solar ponds natural ability to appear and maintain spontaneously), that we can imagine to generalize it for all the solar ponds, even those for which the lower layer's heat is extracted with an exchanger, thus without any possible evaporation, as, for example, the sea water desalinisation plant that Agha and alii ^{xi} studied.

IV GENERAL PROSPECTS

IV.A *Can we have an equivalent system, without using altitude ?*

This question is worth being raised, for at least two reasons. First, it wouldn't be reasonable to run headlong into an adventure which remains uncertain, without having seriously searched alternative solutions. Second, we can easily feel that one of the solar chimneys main advantages, the fact that we need no heat sink, is what we swap for the very high altitude at which we release the air. Are we sure that this deal is the best option ?

Releasing the air at a high altitude, is necessary to avoid having to recompress it after it has delivered its work during its pressure drop (expansion). If we want the equivalent by the ground, we have no choice, it will be necessary to have, after the air expansion exploiting system, another one to recompress the air before releasing it in the ambient atmosphere.

With which thermodynamic transformations ? Put the question otherwise, and assume that the wind problem doesn't exist, so that Sorensen's principle is very tempting. But we hesitate to hang turbines 2000 or 3000 m above us. We keep the collector, and the inflatable conduit upwards, filled with warm, light and thus overpressured air. But we'd like to exploit at the ground level this higher pressure than outside. If the air gets back downwards without anything happening at the tower top, its overpressure difference will vanish. Conversely, it can be kept if the inner air gets back downwards at the same temperature as the outer air.

The air leaving the collector is 70 °C hot, at P_1 pressure ; its temperature, which falls by 10°/km, becomes 45° at 2500 m, with a pressure $P_{3/4} \approx 3/4$ atm ; we want to cool it down to 20°, like the outer air at the same altitude ; its temperature will reach again 45° by the ground ; there, it will drive the turbines and be released. How can we efficiently refresh air from 45 to 20° ? As for energy towers, by interacting with water drops, whose evaporation brings the required coolness.

We release the air under atmospheric pressure, so it must be possible to find an equivalent solution, without using altitude. First, we must lessen the air pressure from P_1 to $P_{3/4}$. It isn't difficult, we just need to let the air join this low pressure and drive a turbine. After that, the heat exchange with the evaporating water : not more difficult. And, last but not least, compress the air back from $P_{3/4}$ to P_1 : a turbine will have to take the same quantity of air, to let it endure a pressure modification exactly symmetrical with the first one, and finally all this must yield a positive energetic balance !

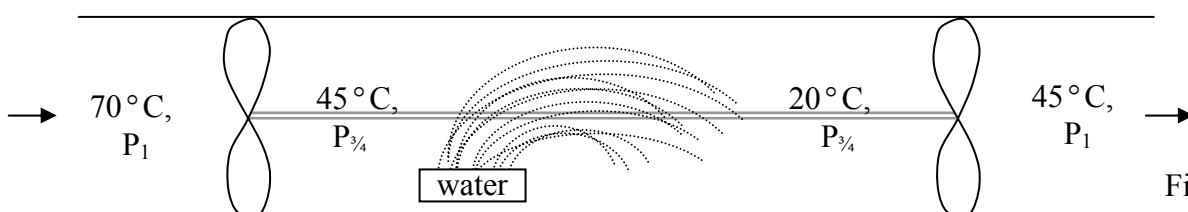


Figure 43

This paradox is only apparent : "take the same quantity of air" means taking the same mass, but of a cooler air, slightly contracted, and whose volume will be down by 8 or 9 % (these figures must themselves be lessened by, again, about 20 %, to take into account the volume of created steam, so that the volume diminution will eventually be only around 7 %).

A gas and turbine exchanged energy calculates by multiplying the pressure difference between upstream and downstream, and the relevant volume, which is 7 % higher for the 1st turbine than for the 2nd one. Therefore, the 1st turbine can theoretically drive both the 2nd one, and, with the power residue, an alternator. But each of these turbines must have lower than 3.5 % losses, if we don't want the balance to be negative.

And, if we want to justify the fact of searching the equivalent of a 2500 m altitude instead of being happy with the Australian tower's 1000 m, we need that each turbine efficiency is higher than, not only 96.5 %, but 98 % ! This is a really new constraint, which is what we get in exchange for doing without altitude, and which doesn't seem easy to satisfy.

However, to be sure not to miss an interesting solution, a last option must be examined : we can wonder whether it could be possible to by-pass the 93 % minimum efficiency obstacle, by substituting the two turbines by a very large piston. This piston, moved by the incoming air pressure (diminishing from P_1), would accelerate while compressing the outgoing air, from $P_{3/4}$; then, the speed resulting from this acceleration would help it to compress the outgoing air until its pressure reaches P_1 , while the incoming air's one falls down to $P_{3/4}$.

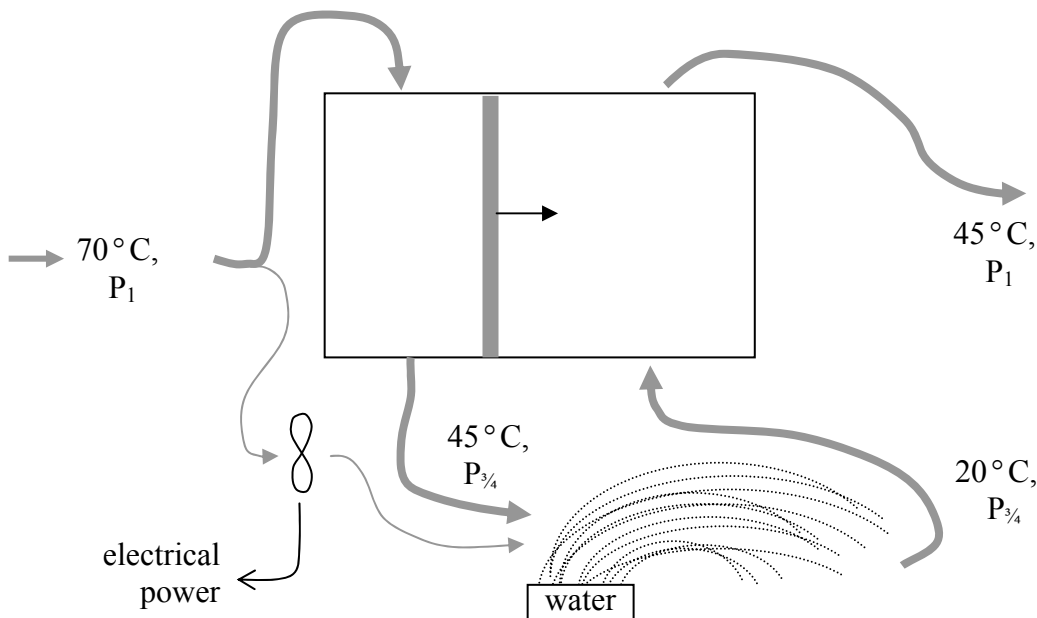


Figure 44

If this operation has a correct efficiency, it can be realized with approximately equal flows, in volume (m^3/s), for the incoming and outgoing airs. But, as the latter is cooler and therefore heavier, i.e. more concentrated, some additional incoming air is available (again, about 7 %). It can pass from P_1 to $P_{3/4}$ through a little turbine and produce electricity. And this turbine is not submitted to a 98 % minimum efficiency constraint (the piston is, but this might perhaps be easier to comply to).

We can see on this figure 45 (whose diagrams can easily be completed by two others, before the cycle will be ended by a fifth one which will be identical to the first one) :

- that, provided that we have two "piston-blocks", there is a permanent warm and dry air incoming flow, a permanent tepid and humid air outgoing flow, a small permanent incoming air flow which is diverted through the central turbine and expands from P_1 to $P_{3/4}$, a permanent dry $P_{3/4}$ and 45° air flow which goes into the central compartment and is cooled down by water jets ;

- that, in these piston-blocks, the air undergoes four phases : induction, expansion, recompression, exhaust, which must last equal times, and, in the water jets room, an intermediate cooling down phase, between the previous 2nd and 3rd, whose duration can be chosen independently ;

- that the induction and exhaust phases, as well as the flows from and to the water jets central room, result from the movement of 4 small auxiliary pistons, weaker than the 2 big pistons as they bear the same pressure from both sides, but which must be thoroughly studied, because their width must vary from one phase to the after-following one.

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This question of a "solar air plant at the ground's level" is one of those I examined most thoroughly, including a lot of false trails. Only the two above variants have a relative simplicity, allowing not to exclude that they could be interesting.

Compared to solar chimneys, they have two slight advantages :

① if each one of the previous four phases were lasting 10 s, and the water spraying cooling down, 20 s, each air volume would produce its work in 1 mn ; in a 2500 m solar chimney with a 15 m/s velocity, quite 3 times more time would be required. Therefore, we can produce the same power with a three times smaller (in volume) facility.

② to make the collector profitable, we yield the same theoretical efficiency than with a 1000 or 2000 m tower, regardless to the system's sizes. So, classically, we can begin with a little prototype, then go on with less small ones, etc. ... But the solar chimneys great interest is the already made decision to go directly from the prototype to the realization of a 17,000 times more productive and quite economically profitable facility. So, this ground plant's gradualness advantage seems irrelevant.

The final question is the following : can we build two "piston-blocks" and a water jet room, each of them being 1 hm³ big, for 1/8th of the price of a 2500 m high tower with a 200 m diameter (25 times lower volume but, as previously described, with a favourable 3 factor) ? Two remarks. A slightly favourable one : here, the turbine will operate with a reduced flow but under 25 000 Pa, whilst the solar chimney's had to swallow a much bigger flow but with a lower pressure difference. A very unfavourable : in this price, we must include, during all the facility's life and until the temporal horizon's limit (from the applicable interests rates), maintenance costs for the huge moving parts, whose movements don't seem easy to pilot.

As for competing projects, this system's environmental impact must be assessed. We release some air which, for an optimal efficiency, is as warm or slightly warmer than the ambient air, but much moister. Hence, it should reach the high atmosphere without losing its warm temperature, because of condensation. Clouds would appear, and, maybe, some rain (not very salted, even if sea water is used).

This latter consequence might be a good thing, if the clouds don't shade the collector or damage it through hail-stones (we had the same problems for the Australian tower, whose warm outgoing air could, at a very high altitude, undergo possibly stormy water condensation). So, the relative positions of the collector, of the ground plant, of the sun, of the main winds, etc., must be thoroughly calculated. Anyway, it seems difficult to have a great number of such facilities in a large desert area.

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We can finally wonder whether, to be able to do without gravity, it is absolutely necessary to combine two transformations, a collector heating, and the water droplets vaporisation cooling down.

Theoretically, no. For instance, we could take the air at 30 °C, compress it until its temperature reaches 50 °C, then send it under a collector where the sun would heat it up to 70 °C, and eventually recover the initial compression work, plus a small profit, while letting it expand back to the atmospheric pressure. Besides, the largest part of the collector received heat would still be available to go up into a tower and produce more electrical power.

This wouldn't break any thermodynamics law ... but what about economical laws ? Indeed, in a collector, one metre water overpressured air would exert considerable stresses on the glass or the polycarbonate, as well as on the supporting structure. A cost doubling would make such a idea totally unprofitable.

We could as well take very dry 35 °C air, let it work by expanding until its temperature decreases down to 25 °C, then spray the water droplets to cold it down to 15 °C, and eventually give it back 98 % of its pressure work, through compressing it back up to the atmospheric pressure.

However, by comparison with a 1000 m high tower with a 400 m diameter, we'd have to process an equivalent volume, for example in a 400 m wide and high, and 1000 m long parallelepipedic "plant". The advantage of "no longer use the altitude" would then look very pale, compared to the drawbacks of figure 45's mechanism which should replace the energy towers much more simple principle.

Therefore, it was, one more time, a false trail.

IV.B After the semi-finals, the final

In this thesis as well as in the available papers, the warm uprising air collector solar tower, and the symmetrical droplets vaporisation "energy tower", are the most detailed studied options, which is right as they seem the most interesting ones.

For each of them, we had a "semi-final".

The solar towers have mainly been studied, on the one hand by M. Lohdi^{xiv}, with all the mistakes we noticed at point II-C-1-a (p. 44 to 46), and on the other hand by the team which, from Manzanares experiment preparationⁱ to the Australian project and to the last discussed article^{iv}, was always structured round of Stuttgart University and Schlaich Bergemann & partners cabinet.

The energy towers have been studied on the one hand by the Tel Aviv University team^{xvi}, with the many remarks I developed in points II-B-5 and II-C-2, and on the other hand, much more seriously^{vi} by a Haifa Technion Institute team, with D. Zaslavsky and R. Guetta.

Among the two teams which, each one in its field, proved much less criticisable than the first papers which enabled me to be aware of such researches, there remain :

- possibilities to find syntheses, as in III-A-2-b, pages 98-99 (realizing a much higher solar chimney with the steel lattice structure proposed for the energy tower, or symmetrically a cheaper or stronger concrete energy tower, as indicated in The solar Chimneyⁱⁱ for less than 1500 m high towers) and in III-C-2-b, pages 124-125 (quasi cyclical operating with a combination of energy towers and of collectorless, very tall, upwards, sun-driven, condensation solar-like towers),

- and a competition, which isn't only virtual : Schiel and Weinrebe's article project^{xv} has the explicit will to compare these two types of towers, and gave rise to particularly scathing remarks from D. Zaslavsky.

They were partly justified. Schiel and Weinrebe reach the conclusion that the solar towers (their project) are about five times better than their rivals, from a fundamental logical mistake. They assert that they validated their own model, as they find the same power as the Technion team, for atmospheric conditions whose extremely favourable character they stress besides : 45 °C and 16 % humidity¹¹⁰.

In fact, they reason as follows : "we find the same results as Zaslavsky for 45 ° and 16 % humidity, this proves that our model is right *and* that the energy towers are supposed to operate by 45 ° and 16 % humidity". Such a reasoning is improper. If they found the same results than Zaslavsky and if it were sure that energy towers operate under such favourable conditions, then, it would prove that their model is right (which, formally, they try to establish at this point of their paper) ; or, if they found the same results and if, besides, it had been established that their model were right, then it would prove that the energy towers are supposed to operate by 45 ° and 16 % humidity (data they always use afterwards). But this can't *prove both* from none of them.

¹¹⁰ "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"

In fact, the only thing we can say is that their comparison between their 386 MW and Zaslavsky's 388 MW, makes it *possible* that their model is right *and* that the energy towers must operate under such favourable conditions as 45 ° and 16 % humidity. But another hypothesis is, too, possible, and probably more likely : that their model gives a much underestimated power and that Zaslavsky's meteorological hypotheses are more reasonable, around 25 or 30 ° and 40 % humidity.

D. Zaslavsky's counterattack, against the solar towers, also uses questionable figures. First, he quotes the number of kWh the Manzanares prototype annually produced. But we saw that it was strangely low, compared to the various elements efficiencies, and to the summer peak power. The explanation that, except in this season, a large part of the sun heat could have been wasted in evaporating the ground's water, would enable us to hope that real desert towers could have a higher efficiency, especially if we'd collect the rain water (with a lot of possible uses outside the collector) to prevent it from uselessly and noxiously permeating the ground.

We also saw that Zaslavsky was widely applying the mpp theory to solar towers, twice multiplying their theoretical output by the 2/3 coefficient : first, by taking air mechanical losses into account as 1/3 (although, with a collector, people generally beware that they don't exceed some %), and, second, by an analogy with its own pumping up losses coefficient, which has obviously nothing to do in a solar tower. On his behalf, we notice that the German team own appraisal of the mpp theory has long been mistaken, and that they only recently, and not crystal-clearly, corrected it.

In the (interesting) controversy which arose about this article project and the defending response, we can notice that each part is rather wrong when it criticizes the other's project and rather right when it defends its own one. This isn't surprising : we're supposed to be more competent for what we've thought about during many years, than for what we view as a competing and potentially hostile option.

What would be my own opinion ? About this controversy, as Schiel and Weinrebe's mistake is about logic, hence is more fundamental, I weight it slightly more than Zaslavsky's ones. But the main thing is that no one makes serious mistakes about its own project. The water droplets vaporisation seems more artful and thus more promising than the collector's ground and air heating. The steel lattice structure is also fascinating (but bold) ; in fact, we saw it wouldn't be very logical that energy towers would be built in such a way, while solar towers wouldn't. It seems that, maybe by chance, Zaslavsky prefers this more economical option he's trusting, whilst Schlaich sticks to the concrete, but the contrary could have happened as well.

The final verdict could come from the atmospheric sciences : would the injection of large quantities of warm air into limited portions of the deserts sky, create a global circulation destabilization risk ? Are we sure that an energy tower outer air will really be as warm and dry as if this tower didn't exist and if the ground wasn't permanently covered by the cool air it produces in large quantities ? What computational difficulties would we face while studying the behaviour of a combination of energy towers and upwards very tall condensation towers, which in my opinion is most interesting in the long run ? These three questions, which are not addressed in the various available papers, could be among the most useful to study in the future.

IV.C Can the power output be exported ?

In "The solar Chimney" ⁱⁱ, such chimneys massive development prospects need two stages : first of all, they can bring to desert neighbouring third world cities, the electricity they need for their economical growth, without emitting greenhouse gases. And, only second and mentioned in rather imprecise words, they could be connected to the developed countries grid. The typical distance from a good desert to the more intense consumption centres being over 2000 km, we can understand that such a transport remains difficult. The choice of the Australian tower location has largely been driven by the near passage of a high voltage line able to absorb its 200 MW.

The fashionable issue of a hydrogen economy offers an alternative : electrolysis (production from renewable electricity being the best way for the "non polluting" adjective which is sometimes associated with this fashion, to be fully reality-based). Besides, it mostly allows to get free from the producing - consuming places distance constraint. A possible option is aluminium electrolysis.

From an economical point of view, high voltage electricity transport remains a serious competitor. From analogy with the solar chimneys, we must notably wonder whether the distance could be offset by scale economies linked to the magnitude of the power we must transport, around 10 000 GW¹¹¹ if the goal were to feed western Europe from the Sahara.

Power is the product of the voltage by the intensity. The latter being unavoidably limited by Joule's effect (power losses, which cause both a lower global efficiency, and a heat evacuation problem as the cables could even melt)¹¹², only the voltage is useful for scale economies. That's why the current high electrical power transport grid uses the 440 kV standard.

These 440 kV lines need very high pylons, because it is necessary to keep a voltage proportional distance between the cables. This generates technical, economical, and environmental problems (controversies about the landscapes impact, or the low frequency magnetic and electric fields). So, we'd rather not bet on even higher voltage lines. Besides, such lines can't cross the sea.

In the latter case, a possible alternative is submarine cables. The insulation can't result from a thick enough air layer, but needs to switch in a non gaseous insulator. The problem is that, the higher the voltage, the thicker the insulator, the higher its thermal resistance, the more difficult Joule's effect heat evacuation, the lower the current's intensity limit, which reduces the interest of having risen the voltage in order to increase the power.

¹¹¹ "The solar Chimney" mentions a 950 km diameter circle ; a 200 MW Australian tower roughly corresponds to a 5 km diameter (1st version, not much mistaken in my opinion), i.e. 190 times less. Thus a total output : $0.2 \times 190^2 = 7200$ GW, plus the demand growth from 1994 to 2030.

¹¹² Joule's effect could disappear from the use of supra-conductivity. Hopes came back during the last two decades, with the discovery of new families of supra-conducting materials even at the liquid nitrogen temperature ; however, supra-conductivity disappears near intense magnetic fields, which are precisely produced when we try to let very high currents flow. In fact, we come back to the same sort of problems as for classical metallic conductors.

More precisely, to multiply the voltage by k , we must do the same for the insulator thickness. Hence the same ratio for the thermal resistance, so we must divide the disposable heat by k . For the same conducting metal cross-section, we now have to divide the intensity by $k^{1/2}$. The operation isn't totally useless, as we multiply the transported power by $k^{1/2}$ without increasing the metal cost, and by multiplying the insulator's one by k . Therefore, we've got a margin for progression, as long as we spend less for the insulator than for the metal (and besides, we reduce the Joule's effect voltage drop all along the line, which increases the physical efficiency).

However, once we're at this relative optimum where we spend quite as much for both materials, the only hope of new scales economies is from increasing the various quantities together. Consider a metallic cable with a resistivity ρ , a radius r and a voluminal cost c , coated by an insulating layer with an electrical field limit E , a thermal resistivity ξ , a voluminal cost b and a thickness e , which we suppose is much lower than r . The maximum difference temperature between the metal and outside is ΔT .

$$\text{As the lineal costs must be equal, } \pi r^2 c = 2\pi r e b, \text{ i.e. : } \quad e/r = c/2b \quad (39) \quad ;$$

the cable temperature constraint implies that the lineal Joule's effect, $\rho I^2/\pi r^2$, equals to ΔT divided by the lineal thermal resistance, $\xi e/2\pi r$. This yields a 2nd equation with e and r : $\rho I^2/\pi r^2 = 2\pi r \Delta T/\xi e$,

$$\text{i.e. : } \quad \xi \rho I^2/2\pi^2 \Delta T = r^3/e \quad (40).$$

As we know two different quotients of powers of e and r , we deduce these two sizes :

$$r = [r^3/e \times (e/r)]^{1/2} = [(\xi \rho I^2/2\pi^2 \Delta T) \times (c/2b)]^{1/2} = (c \xi \rho/b \Delta T)^{1/2} \cdot I/2\pi \quad (41)$$

$$e = r \times e/r = (c \xi \rho/b \Delta T)^{1/2} \cdot I/2\pi \cdot (c/2b) = (c^3 \xi \rho/b^3 \Delta T)^{1/2} \cdot I/4\pi \quad (42)$$

$$\text{The limit voltage the system can bear is simply : } \quad U = e \cdot E = (c^3 \xi \rho/b^3 \Delta T)^{1/2} \cdot EI/4\pi \quad (43) \quad ,$$

$$\text{hence the power : } \quad P = UI = (c^3 \xi \rho/b^3 \Delta T)^{1/2} \cdot EI^2/4\pi \quad (44)$$

The cable lineal cost is proportional to r^2 , thus to I^2 , as is P . For the insulator, it is \propto to $e \cdot r$, thus again to I^2 . No more scale economy is possible.

The only solution would be that the insulator thermal resistance wouldn't be proportional to its thickness. This is possible, if it's made of insulating oil, able to carry the required heat flow away by convection. In this case, the same flow can be transmitted, from approximately the same temperature difference, even if the insulator thickness is increased ¹¹³.

Of course, security devices would be needed to keep the right distance between the cable(s) and their outer metallic envelope in spite of the electrostatic attractive forces they will undergo, and to prevent any oil leak (double, or even treble hull) which could generate a short-circuit. However, as oil is already used as an insulator and a heat-carrying fluid in the transformers which stand at both ends of a 440 kV line, we can hope that it could be technically feasible ; and the possible scale economies, as well as the possible Joule's effect losses reductions, enable us not to be too pessimistic about economics.

¹¹³ It would be even more efficient to evacuate Joule's effect as a latent heat : at the cable contact, the oil would boil, and condensate only at the contact of the outer envelope. But this is probably impossible, as electric discharges occur much more easily in a gas than in an insulating liquid, and are against the goal we target.

IV.D The investments financing

Thanks, in particular, to the wind and photovoltaic energies, the "new" renewable electricity production rises very quickly. But its level is still low ¹¹⁴ (as well as the targets it helps to reach, which result from the Kyoto protocol).

Does it mean that we are thousand miles away from our only possible goal in the long run, such a massive renewable energies development, that it would marginalize the fossil energies ?

If the renewable production costs remain widely higher to the fossil costs, the financial effort we ask the society will be so high that, for long, it will stay in Utopia. But, when the costs begin to converge, this effort will quickly alleviate. And, if we'd reach equality, any constraint would disappear : the renewable energies growth could, by itself, become irresistible.

For a lot of renewable energies, the highest cost is capital financing, thus the interest rate, whose rather high level reflects a middle term temporal horizon, while environmental problems belong to the long term¹¹⁵. For fossil energies, the fuel cost is an operating expense, which doesn't undergo this interest rates tyranny.

However, from the producing countries point of view, this fuel should be considered as a capital, what, besides, both the economical theory and the oil markets do. If these countries sell it to finance their current consumption, they grow poorer. A mean to edge such an impoverishment is, oppositely, to draw the highest part of the oil income towards long term investments.

During the 1980's, the oil producing countries invested this income, at best, in purely financial assets, which fed a worldwide inflation. A better "petrodollars recycling" would be to convert them to renewable energy production facilities, in particular for the many oil-exporting countries which, meanwhile, own large and sunny deserts. Therefore, a solar chimneys or energy towers investment, without forgetting means for power exportation, seems a reasonable way to prepare the post-oil times, and, now, to create jobs in the local public works.

From a strictly economical point of view, if it were possible to justify an alignment of the solar chimneys or energy towers temporal profitability horizon, on the oil reserves pumping out prospects, around fifty years, then we'd find a 1/50 discounting rate, i.e. 2%/y, for which these towers would be very competitive.

¹¹⁴ This isn't contradictory : we can have a high growth rate and a low level if we start from quite zero, which is the case for all the renewable electricity sources, except hydroelectricity.

¹¹⁵ If we don't worry about the future generations' fate, but only about our retirement pensions and perhaps about our descendants that we personally know, then we can say like Keynes that "in the long run, we'll all be dead". This explains that the mean economical temporal horizon is 25 years, thus the lowest long term interest rates are 4 %/y.

IV.E Conclusion

Jörg Schlaich concludes "The solar Chimney" by the spell-like words : "They can be economically viable if we want them to be", financial version of the German proverb "Wer will, der kann"¹¹⁶. A rational examination of this question should stay apart from such professions of faith, but, when it comes to close this study, we can't help noticing how important the questions of pre-conceptions and of points of view relativity, are.

A well known physics paradox is the following : a wall hanging mirror is isotropic in its plane, nothing, e.g. in its fabrication, enables to distinguish its lateral dimension from its vertical one. However, we say that it transforms the right hand into a left hand, not the scalp into a beard. Why? Because we compare our image in the mirror with what we'd be if we were behind it without undergoing a reflection.

To imagine ourselves, behind it, with the scalp at the beard's place and reciprocally, we must assume that we'd bypass it by climbing over it, then plunge head first : it is physically possible, but the competing hypothesis, which is simply to bypass the mirror by walking aside, occurs more naturally to us. That's why the idea that a mirror exchanges the right and the left, although it isn't objectively truer, is psychologically preferred to the top-bottom exchange idea.

When I talk about the Australian tower project, the first question is : isn't it extravagant to imagine it that tall ? However, various aspects of the issue (economics, environment) should make us wonder : isn't it extravagant to imagine it that small ? So, there may be, as for the mirror, a pre-conceived point of view, which we'd try to turn topsy-turvy.

Why is our first reflex to estimate it's too high ? Of course, it's because nobody ever built anything so tall. But why ? Because, so far, all we needed to build, were flats, offices, plants (and churches, but we must beware that they didn't become Babel's towers). And there are two objective reasons not to raise such high buildings : because, if we want to put people inside, we must drastically reduce the top's oscillations ; and because the cost could be more than proportional to the height, i.e. that the m² price could be higher than the real estate market.

Here, both arguments are perfectly reversible : there are no more non-oscillation constraint at the solar chimney's top, than which results from the materials resistance ; and even a rapidly growing cost with respect to the height, is not totally unfavourable, as a large solar chimney helps to make the collector more profitable (and then to increase its area).

So, the solar chimneys and the energy towers deserve a much more thorough attention than what could be imagined first. From the examination of the available publications, the situation isn't satisfying, whatever the reasons. Either I managed, by chance, to completely record the worldwide main papers about these topics, and it seems that they don't reach a sufficient critical mass to ensure that, for example, an article such as in point II-C-1-a (p. 44-46), wouldn't be published.

¹¹⁶ "Who wants, he can"

Or there are still other teams which produce high quality work, but so secretly that it doesn't reach the water's surface¹¹⁷. When scientists don't publish, it means that they're taking patents, which is the case both for Schlaich's and Zaslavsky's teams. Such an attitude might be inadequate : the main risk could be that, for still many years, the only alternative about the number of possible economical partners (States having a post-oil era to prepare, large public works or electricity production companies, banks), is among 0 and 1. And as long as they're not at least 2, a patent has not much value, as, in this field, the scientists, and not their possible partners, are in the situation of begging that somebody should take an interest in what they do (and if it eventually results in something concrete and convincing, they'll have won glory). Hiding our work in order not to let our ideas be stolen, makes little sense here.

A feature of these projects is their particularly high unit-cost, which make the passage to full-size realization difficult. It looks like the chemistry well known opposition of thermodynamics and kinetics. Once the prototypes have been tested and the optimal size agreed, the very interesting profitability prospects are like an exothermic chemical reaction result. But the sharp way (unfavourable kinetics) which leads to it if we want to begin with intermediates sizes, corresponds to unprofitable prototypes, and this opposes to a progressive¹¹⁸ way towards this ultimate advantage.

We're only left with the tunnel effect equivalent, i.e. a direct leap from very small prototypes or simples studies, up to a quite optimum size. The thermodynamics / kinetics duality then gives way, in the financial field, to the one among profitability and risk (which it's the scientists responsibility to most reduce by, first a frank debate, then consensus building).

There aren't such constraints for photovoltaic cells or wind turbines, as we can see, year after year, the studies being checked against experimental results, the materials progress, the installed powers increase, the industrial partnerships develop. Here, the order of magnitude of the waiting time before building a really significant prototype, seems closer to twenty years than ten.

¹¹⁷ For example, I knew for several years that a well named "electricity from dry air" thesis had been written in 1995, in Israel (hence, probably in Hebrew), about the energy towers. The author, Rami Guetta, had published nothing else, until very recently^{xviii}. Therefore, I thought he didn't follow suit to his interest in this subject. In fact, as I heard of this year, he had become D. Zaslavsky's deputy director in the Technion Institute team who had kept on working hard about this topic !

¹¹⁸ However, it's not impossible that this threshold could be lowered, as we can do in chemistry with catalysers. For the solar towers, this is the goal of the project aimed at bringing tourists to the 1st tower. As long as it remains the only one, the tourist income will be high and reduce this last prototype's cost. If solar towers become common, and even more if higher ones are built, it'll mean that at last we proved that they're profitable and that it is a realistic energy production mode, which is what we want (the 1st one will lose money, as the tourist income will fall, but it isn't a problem as it will be offset by other towers' income).

For energy towers, some specialists' opinion is that their main interest, in the long run, is to produce electricity in a desert's heart, with a sea water canal, pumps and very cheap land, enabling to convert this electricity into fresh water (inverse osmosis process), then into agricultural crops. But, irrigate a really dry desert is very costly, because of the climate related very strong evapotranspiration. However, these towers precisely modify this local climate, as they create a cool and humid air layer all around themselves. Therefore, a 1st little (200 or 300 m tall) tower project, not far from a sea, would have two advantages :

- this humid and cool air production doesn't depend much on the tower height, thus, as a useful output, it's interesting to know that it wouldn't suffer from too little a height ;
- and the salt rejection into the environment, if the enhanced coalescence efficiency is less than 99.99 %, remains a concern. If one of a demonstration tower's main goals is to fertilize the surrounding desert, then this question will necessarily be very thoroughly examined, its results will widely be publicized, and, if they are positive, this will be a guarantee that there won't be, about this issue, much opposition against more and higher towers.

Compared to a scientist's active life, this is much, and engaging into such a project is, like the Desert of Tartars hero, taking the risk of being left aside before seeing what one gave its life to.

This could explain that few scientists, worldwide, work on these subjects which, objectively and with regard to the stakes that I didn't even mention as everybody knows them, seem to deserve a better fate. Isolation, the impossibility to rely on real experimental results (we saw that the numerical experiments, quite a standard in this field, must be thoroughly checked), the lack of a scientists' critical mass, allowing to reach a state either of consensus or of dissensus, become handicaps for all these technologies, and prevent the lancing of some acrimony abscesses which exist in this small circle, as they exist in any other small circle. All this seems to generate self-maintained pessimism, unlinked with the underlying physical reality.

Globally, the two leading projects, the German-Australian and the Israeli-Indian, have inherited a very large data, calculations and thoughts accumulation. Reaching, for one of them, a 1 km tall "2nd prototype", after Manzanares, and for the other, a 200 m 1st prototype, would be a very encouraging step. Again delaying it would be a strong decision that mustn't be made unthinkingly.

However, I raised some points which could possibly justify, not that people tergiversate one more time about the interest to make something more real, but that, in parallel, an academic reflection should be amplified. To be useful, it should mobilize more research teams, able to work both in an autonomous way in order to multiply the chances of not missing a relevant idea, and with gathering times to show that, about the main topics, a good consensus is building up.

The prospect we should keep in mind is to provide, as a minimum, all the electricity needs of towns close to sunny deserts, and, as a maximum, all the planet's driving power (electricity + fuel such as hydrogen) needs.

On such a scale, all the energy production processes perturb the ecosystem. I stressed the solar chimneys or energy towers winning cards, but also their uncertainties, particularly about their interaction with the atmospheric circulation. However, these drawbacks mustn't be overestimated. These towers will produce a renewable energy, thus help to reduce the greenhouse effect gases (CO₂) emissions, which *accumulate* in the atmosphere. Oppositely, the perturbation towers could generate won't worsen as they would be constantly operating. For example, if the risk of perturbing the monsoon triggering would be proven serious, we could, at worse, stop the solar chimneys during the critical period. And the possible synthesis of energy towers and solar-like very tall steam towers, seems to be an interesting idea to reduce these perturbations.

Power production by these various towers, possibly modified if some of the ideas I expressed here prove interesting, seems one of the best possible compromises between the following criteria : being not too destructive for the environment, not too destructive for the economy, not too sophisticated (which would make it difficult for the developing countries to receive properly such a technology transfer), technologically not too uncertain, not too irregular through the day and the year, and having a good potential for a massive development at a date not too far.

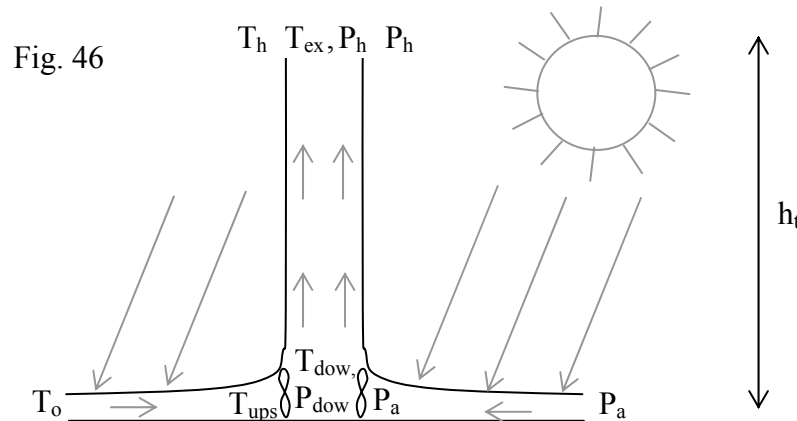
V APPENDICES

V.A Appendix 1 : Solar chimney theoretical efficiency

V.A.1 Basis calculations

A system based on the idea that "warm air rises, cool air falls" can be analyzed, either as an open system, which is enough to make an empirical study, or as an element of a closed cycle which includes the air way back, outside the tower and in the opposite direction. When we talk about Carnot's efficiency, this second theoretical frame must be used, and the heat source and sink must be looked for in opposite points of such a closed cycle.

Therefore, the good heat sink temperature must be the tower air's, when it goes out of it, at its top (T_{ex}), and not the ambient bottom air's. We come back to the fact that the solar chimney effect, based on the warm air buoyancy, is best exploited if this voluminal mass difference is used along a large altitude difference ; indeed, the air temperature difference between the ground and the top, $T_{ups} - T_{ex}$, is also, as a 1st approximation, proportional to this height : all this seems consistent with the fact that the efficiency depends on $T_{ups} - T_{ex}$.



This can be precisely demonstrated from the ideas, ① that two moving air transformations : $[(T_{ups}, P_a) \rightarrow (T_{dow}, P_{dow})]$ and $[(T_{dow}, P_{dow}) \rightarrow (T_{ex}, P_h)]$ undergo no change of state (water condensation of evaporation) and are adiabatic and reversible (thus isentropic), ② and overall that we could make the same hypotheses about the relations between the outer air in the states $[(T_o, P_a) / (T_h, P_h)]$.

For these three couples of states, we can apply the perfect gases isentropic transformation law, $PV^\gamma = cte$, and its equivalent $P^{\gamma-1}T^\gamma = cst$ ¹¹⁹. For the two of them which imply the gravity, we write, in addition, the dry adiabatic gradient law (temperature decrease with respect to the altitude, $T = cst - \lambda z$, where :²

$$\lambda = \frac{gM}{(7/2)R} = \frac{9.81 \text{ m/s}^2 * 0.029 \text{ kg/mol}}{8.32 \text{ J/mol.K} * (7/2)} \approx 10 \text{ }^\circ\text{/km} \quad (3) \text{ ,}$$

¹¹⁹ with $\gamma = 7/5$: air is considered as a diatomic gas, which also justifies the 7/2 in formula (3).

As the rising air and the ambient air both verify this $T = \text{cst} - \lambda z$ ¹²⁰ law, we can deduce in particular that :

$$(\lambda h_t =) T_o - T_h = T_{\text{dow}} - T_{\text{ex}} \quad (45)$$

An important adiabatic transformation feature, from its mere definition (no heat exchange) is that, if we want to get some work from the pressure forces, while being (e.g., a turbine) between two pressure stabilized sources, then we must consider that this work can come only from a gas's enthalpy H diminution. Here, for the transformation $(T_{\text{ups}}, P_a) \rightarrow (T_{\text{dow}}, P_{\text{dow}})$, the work will be :

$$W = H_{\text{ups}} - H_{\text{dow}} = (7/2) nRT_{\text{ups}} - (7/2) nRT_{\text{dow}} \quad (46)$$

For the same air quantity, the received heat between the collector inlet and the turbine is :

$$Q = (7/2) nRT_{\text{ups}} - (7/2) nRT_o \quad (47)$$

Therefore, the system's ideal efficiency is : $\eta = W/Q = (T_{\text{ups}} - T_{\text{dow}}) / (T_{\text{ups}} - T_o)$ (48)

where, by combining with equation (45), we can eliminate T_{dow} :

$$\eta = (T_{\text{ups}} - T_{\text{dow}}) / (T_{\text{ups}} - T_o) = \{T_{\text{ups}} - (T_{\text{ex}} + T_o - T_h)\} / (T_{\text{ups}} - T_o) = 1 - (T_{\text{ex}} - T_h) / (T_{\text{ups}} - T_o) \quad (49)$$

From the perfect gases isentropic transformation law, $P^{\gamma-1}T^{\gamma} = \text{cst}$, we write the relations : $P_a^{\gamma-1}T_{\text{ups}}^{\gamma} = P_{\text{dow}}^{\gamma-1}T_{\text{dow}}^{\gamma} = P_h^{\gamma-1}T_{\text{ex}}^{\gamma}$, and : $P_a^{\gamma-1}T_o^{\gamma} = P_h^{\gamma-1}T_h^{\gamma}$, which enable us, by dividing member for member and eliminating the inlet and outlet pressures P_a and P_h which are common to the outer and inner transformations, to show that :

$$T_{\text{ups}}/T_o = T_{\text{ex}}/T_h \quad (50), \quad \text{which can be written : } T_{\text{ex}}/T_{\text{ups}} = T_h/T_o = (T_{\text{ex}} - T_h) / (T_{\text{ups}} - T_o) \quad (51).$$

Equations (49) and (51) then yield, as announced : $\eta = 1 - (T_{\text{ex}}/T_{\text{ups}})$ (1)

Therefore, the system has indeed sort of a Carnot's efficiency, which equals to what we'd get with a thermal machine whose heat source would be at the air temperature once it has been heated in the collector, upstream the turbine, and whose heat sink would be at the air temperature when it goes out of the tower (and not at the ambient air's, by the ground).

Finally, (49) and (51) could as well have yielded $\eta = 1 - (T_h/T_o)$, which, with the help of (45) 1st part : $\lambda h_t = T_o - T_h$, allows to set up the proportionality relation of the efficiency to the tower height :

$$\eta = \lambda h_t / T_o \quad (4)$$

¹²⁰ The temperature fall is explained first by a pressure drop with regard to altitude, because higher we are, more air we have above us ; then, this pressure drop lets the air expand ; but, for its volume to increase, it must thrust its neighbours aside, i.e. produce some work ; it can take it only from its internal energy, which thus will diminish, and the result is that its temperature falls.

V.A.2 Tower diameter condition to keep $P_{elec} \propto H_t \cdot D_{coll}^2$

For P_{elec} to keep the announced proportionality relation, the losses must represent a constant fraction of the power. They are thermal and mechanical losses.

First, the thermal losses ratio doesn't vary if $\Delta T = cte$ (it $\approx 30^\circ$). This gives a condition on the air flow N (m^3/s) : $N \propto D_{coll}^2$; but $N \propto v_t \cdot D_t^2$, hence :

$$v_t \cdot D_t^2 \propto D_{coll}^2 \quad (52)$$

Second, the mechanical losses ratio is : $\Delta P_{fr} / \Delta P_{engine}$, and we want it to be constant. But, in a turbulent flow, $\Delta P_{fr} \approx \propto v^2 \cdot H_t / D_t$ (53). Besides, if $\Delta T = cte$, the pressure difference between upstream and downstream the turbines, ΔP_{engine} , is $\propto H_t$. Therefore, we must have $v_t^2 \cdot H_t / D_t \propto H_t$, which simplifies to :

$$v_t \propto D_t^{1/2} \quad (54)$$

By substituting v_t in (52) by its expression given by (54), we get : $D_t^{2.5} \propto D_{coll}^2$, which yields¹²¹, as announced :

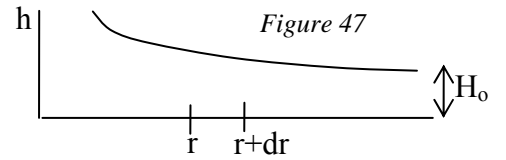
$$D_t \propto D_{coll}^{0.8} \quad (6)$$

V.A.3 Collector roof height condition

The difference is that here, there is not one "roof height", but that it is a variant, for it must increase as the air flow converges to the collector centre.

We can choose a power function : $h = H_o \cdot (r/R_{coll})^n$

Then the turbulent pressure drop is : $\Delta P_{fr} = \int dP_{fr} = \int C_p v^2 \cdot dr/h$.



v , which depends on r , is yielded, as previously, from the condition on the m^3/s flow, N : $N \propto D_{coll}^2$. We've got now $N \propto v \cdot r \cdot h$, hence : $v \propto D_{coll}^2 / rh$ (55), and :

$$\Delta P_{fr} \propto \int (D_{coll}^2 / rh)^2 \cdot dr/h \propto (D_{coll}^4 \cdot R_{coll}^{3n} / H_o^3) \int (r^{-2} / r^{3n}) \cdot dr \propto (D_{coll}^{4+3n} / H_o^3) [r^{-1-3n} / (-1-3n)] \quad (56)$$

the integration being from : R_t which can be neglected if $n < -1/3$, to : R_{coll} .

$$\text{It will give : } \Delta P_{fr} \propto (D_{coll}^{4+3n} / H_o^3) \cdot (R_{coll}^{-1-3n}) \propto (D_{coll}^3 / H_o^3) \quad (57).$$

Besides, as previously, the proportionality relation we want to keep implies that $\Delta P_{fr} \propto \Delta P_{engine} \propto H_t$, and we deduce that we must have : $D_{coll}^3 / H_o^3 \propto H_t$, i.e. the announced condition :

$$H_{coll} \propto D_{coll} \cdot H_t^{-1/3}, \quad \forall n < -1/3 \quad (7)$$

¹²¹ Some precisions : first, the air density decreases with respect to the altitude, so, unless the tower cross-section widens in the mean time, keeping a constant flow implies that the velocity increases ; second, the symbol $\approx \propto$ in (53) recalls us that when Reynolds's number rises, the proportionality coefficient slightly decreases. For a tower whose all sizes increase, these two effects are in opposite directions and could more or less offset each other.

V.B Appendix 2 : Air temperature decrease potential

We represent, hereunder :

- the exponential we get when integrating Clapeyron's equation, and which gives the saturating steam pressure as a function of the temperature.

- a line element (arrow) which describes how the air absorbs the vaporisation latent heat. Evaporating a little quantity of water is enough to sharply diminish the temperature, so this arrow has a low inclination.

Then, the temperature reduction potential is equal to the abscissa diminution we get when we follow this arrow, leftwards, until it intersects the exponential.

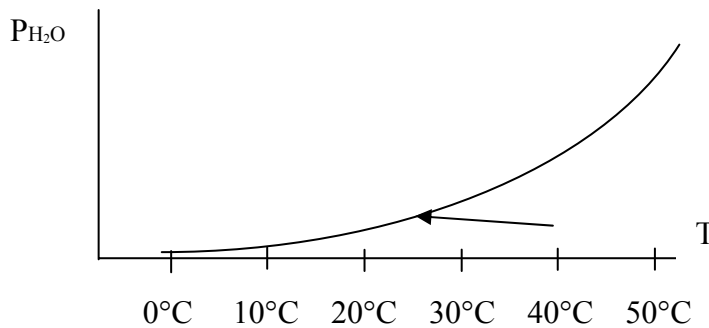


figure 48

Three cases are theoretically possible :

① What we want to cool down is warm and rather humid air.

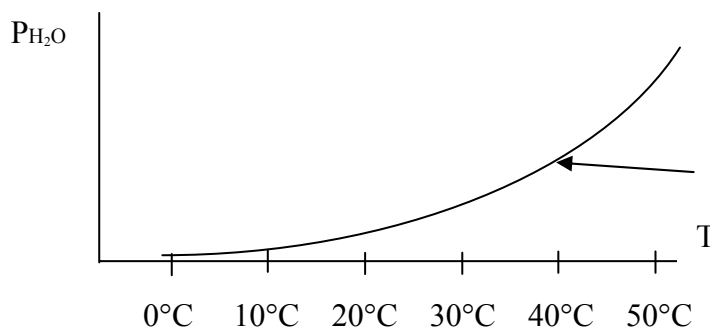


figure 49

From a point with a rather high ordinate, the exponential's tangent slope is higher than the arrow's, and the latter can be seen as a horizontal. The air temperature we get is the one for which the already present water vapour becomes saturating. But we need around 10 or 12° for modify the saturating pressure by a factor 2. Therefore, with a 50 % hygrometry, we diminish the temperature, at most, by 12° ; with 25 %, by 24° ; etc.

② We want to cold down an air already so cool that Clapeyron's curve has a lower slope than the line whose intercept we look for.

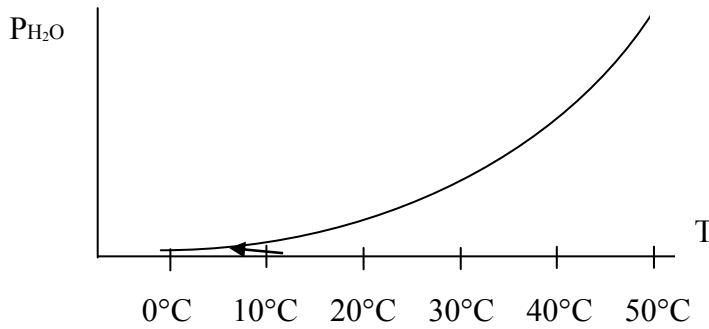


figure 50

In this case, the intercept must be found without neglecting the heat the air can absorb when we evaporate the low water quantity which is missing for its vapour to be saturating. This temperature reduction is lower than if we applied the previous reasoning. The cooling becomes twice more difficult each time we want to reach a 10° lower temperature.

③ We want to cool down a warm and dry air. In this case, we get a large temperature diminution which, in a 1st part, analyzes as in the 1st case above and, when the air is cold enough, gets closer to the 2nd one.

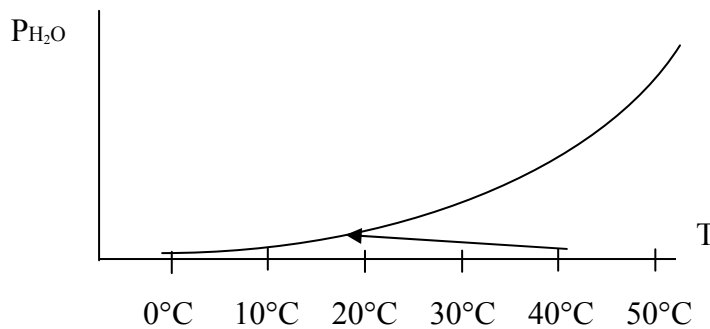


figure 51

Where is the two first cases border ? Where the decreasing line and the increasing exponential have equal slopes. We get the first one by writing that, for one air mole, whose enthalpy is added by $c_p dT$, we must evaporate dn water moles so that $L dn = c_p dT$, with $dn = dP_{\text{water}}/P_{\text{atm}}$, i.e. $c_p dT = L dP_{\text{water}}/P_{\text{atm}}$. The second one is Clapeyron's equation : $L dT/T = dP (u_v - u_l) \approx dP u_v$, where $dP = dP_{\text{water}}$.

By dividing, member for member, we get : $L/Tc_p = u_v/(L/P_{\text{atm}})$, or, if substituting c_p by $7R/2$ and u_v by $RT/P_{\text{sat.vap}}$:

$$P_{\text{air}}/P_{\text{sat.vap}} = 2L^2/7R^2T^2 \quad (58)$$

This equation's solution is $T \approx 284 \text{ °K}$, because $2L^2/7R^2284^2 \approx 86$, and a saturating vapour pressure $1/86 = 0.012 \text{ atm}$ precisely corresponds to a 11 °C temperature. So, as long as we don't try to reach a lower than 20 °C temperature, the law yielding a 10 to 12° decrease each time we multiply the hygrometry by 2 applies regardless of the temperature ; but for lower temperatures, the cooling down becomes more and more difficult (10° pace difficulty doubling law under 0 °C , more complex transient zone between 0 and 20 °C).

V.C Appendix 3 : Australian solar chimney size optimization

The following table 8 is based on figures from "The solar Chimney"ⁱⁱ, for the three power outputs this book discusses : 5, 30 and 100 MW. The used data are : the collector and tower sizes ; some physical parameters ; and the corresponding costs.

nominal power			5 MW	30 MW	100 MW
collector diameter	D_{coll}	m	1110	2200	3600
chimney height	H_t	m	445	750	950
chimney diameter	D_t	m	54	84	115
collector internal diameter	$D_{coll,i}$	m	162	252	346
glass roof height (external)	$H_{coll,e}$	m	2	4.5	6.5
glass roof height (internal)	$H_{coll,i}$	m	10	15.5	20.5
temperature rise in collector	ΔT	°K	25.6	31	35.7
solar air heating ¹²²	Q	W/m ²	562.4	547.2	526.2
total pressure difference	ΔP_{tot}	Pa	383.3	767.1	1100.5
pressure loss by friction (collector and tower)	ΔP_{fr}	Pa	28.6	62.9	80.6
pressure loss at chimney top	ΔP_{top}	Pa	40.4	75.1	117.5
chimney cost (million DM)	C_t	MDM	18	67.5	136.4
collector cost	C_c	MDM	23.5	95.6	269.6

From these data, the goal is to compute, with the lowest error, the power produced by a similar tower with different sizes, and its cost.

V.C.1 Physical modelling

The turbines and alternators efficiency is considered to be another problem, so we only deal with the air's mechanical power. First, we assume the hypothesis (as in "The solar Chimney") of a low heat storage in the collector's ground. Grossly, this power is, as shown all along the present thesis, proportional to the collector area and to the tower height.

It can be written, with a constant multiplier¹²³, $P_{power} = Q \cdot D_{coll}^2 \cdot (\Delta P_{tot} - \Delta P_{fr} - \Delta P_{top}) / \Delta T$ (59).

¹²² I got these figures by multiplying the maximal incident solar flow, i.e. 1000 W/m² according to "The Solar Chimney" appendix, by the values of the collector's efficiency which lie, as well as the other above mentioned data, in the main text tables of the same book.

¹²³ Which includes the air voluminal mass, its specific heat, gravity acceleration g , and a $\pi/4$ coefficient for the area calculation.

$Q.D_{\text{coll}}^2$ represents the collector's heat. The subtracting terms help to take into account the losses due to the creation of an air motion. They appear through the lines "pressure loss by friction (collector and tower)", ΔP_{fr} , and "pressure loss at tower top", ΔP_{top} , which, logically, are to subtract from the line "total pressure difference", ΔP_{tot} .

Finally, the division by ΔT (temperature difference with the outer atmosphere) comes from the fact that ΔP_{tot} calculates from the buoyancy, so is approximately proportional to ΔT . But, if we neglect the losses, we can pass from $Q.D_{\text{coll}}^2$ to the power output, by using the theoretical efficiency which includes, not ΔT , but the temperature difference between the bottom inner air and the same air, at the top (which is proportional to the tower height h , already taken into account in ΔP_{tot}). So, we must eliminate this useless dependence on ΔT , which the proposed division does.

We must now model the variations of ΔP_{tot} , ΔP_{fr} and ΔP_{top} with respect to the collector's and the tower's geometrical parameters.

ΔP_{tot} is proportional to the tower height, as long as the temperature gap between the inner and the outer air remains constant. This requires that the outside temperature decrease follows the "dry adiabatic gradient" law, which is not always the case. If not, we may consider that the temperature gap decreases linearly with respect to altitude, so we must substitute the tower height H_t by a polynomial expression : $H_t - a.H_t^2$.

And, as previously recalled, ΔP_{tot} is proportional to ΔT . Hence : $\Delta P_{\text{tot}} = b.\Delta T.(H_t - a.H_t^2)$, with two constants a and b we must adjust from the three values given in the table. This adjustment, with the lowest squares method, yields an excellent result, as the three modelled ΔP_{tot} have only a 1 % mean gap from the table values. We get :

$$\Delta P_{\text{tot}} = (0.034714 \text{ Pa/m.K}).\Delta T.(H_t - 6.785 \cdot 10^{-5} \text{ m}^{-1} .H_t^2) \quad (61)$$

We remember (Cf. point II-A-1, p. 28-29, "What we don't know, but we try to imagine" - "Distinction between turbulent friction losses in the collector and the tower") that, having no correct data for ΔP_{fr} and ΔP_{top} modelling, we decided to swap these two data lines in table 8 !

Two similar adaptations have been made for the choice of the variants describing the friction losses in the collector.

① First, the same feature about the gap between the value for 30 MW and the geometrical mean of those for 5 and 100 MW, appears for the external (inlet) glass roof height : in the 2 ; 4.5 ; 6.5 series, this indicator is 25 %, when it is only 8 % for the internal (outlet) glass roof height. The consequence is the same : we can't realistically adjust the modelling parameters. But, as we had data both for the collector's outlet and inlet, I used only those corresponding to the outlet to model the air friction for the whole collector's area.

This requires to use the collector's internal diameter. So, we use three parameters for the collector : external diameter, internal glass roof height, internal diameter. But this is one too much

for a good economical use of the modelling, and only the first two¹²⁴ could be kept : the external diameter to calculate the sun's energy, and the internal glass roof height, combined with the external diameter (= length of the air movement in the collector) to calculate the friction. But, for such a calculation, we need to know a speed, which depends from a cross-section area, thus from the collector's height, but also from a circle's perimeter : so we can't totally do without the collector's internal diameter.

So, I had to model it. We can see, in the table, that it is equal to three times the tower's diameter, an architect's choice which brings no problem. But we couldn't use this relation because, if a parameter (the collector internal diameter) which commands the collector losses, depended upon a quantity (the tower width) which only the tower cost depends on, the economical optimization would yield absurd results. So, I modelled the collector's internal diameter as a function of its external diameter and of the internal glass roof height, with rather good results (in all the simulations made afterwards, it remains near three times the tower diameter). The result is :

$$\text{- collector internal diameter : } D_{\text{coll},i} = 34.364 + 10.4418 \cdot H_{\text{coll},i} + 0.2322 \cdot H_{\text{coll},i}^2 \quad (62)$$

② We must also calculate a dully variant, representing the "velocity in the tower"¹²⁵ and enabling us to model the different types of losses. As we saw it for formula (59), we start from the heat flow caught by the collector (with a constant multiplier, as usual) : $Q \cdot D_{\text{coll}}^2$, which we must divide by the temperature rise, in order to deduce a convecting air flow, : $Q \cdot D_{\text{coll}}^2 / \Delta T$; and, finally, to get a velocity from this air flow, we divide by the cross-section area, i.e. by D_t^2 :

$$v_t = Q \cdot D_{\text{coll}}^2 / \Delta T \cdot D_t^2 \quad (63)$$

From this velocity, we model the tower's top losses (with, as explained previously, an adjustment to the three values : 28.6, 62.9 and 80.6 Pa). The relevant physical phenomenon is the loss of part of the air's kinetic energy at a v_t velocity. But, the higher the tower, the lighter the air, the quicker it must go for the same flow, and the higher the losses, which is expressed through the formula, obtained after an adjustment¹²⁶ :

$$\Delta P_{\text{top}} = (0.38024 + 1.76 \cdot 10^{-5} \cdot H_t) \cdot v_t^2 \quad (64)$$

The friction losses are the sum of the tower's and the collector's. A two-parameter adjustment, which enables us to verify its quality (we'll reach a reasonable 1.2 % mean gap) allows only one for each term : so, we'll only consider multipliers.

For the modelling itself, we must use the turbulent friction laws : with a C constant, the pressure drop for a length equal to the conduit width, corresponds to an energy loss equal to the air's kinetic energy (for a length N times greater than the width, we multiply by N). But C is often slightly decreasing with respect to the velocity, so we can take, instead of a v^2 - law (from the kinetic energy), a v^α - law, with α slightly lower than 2 : here, I took, rather arbitrarily, $\alpha = 1.85$.

¹²⁴ For the tower, we have of course only two parameters : height and diameter, used in the same way as those which are defined here.

¹²⁵ In reality, the velocity is varying continuously between the walls and the centre.

¹²⁶ Which, with the least squares method, yields errors up to 5 Pa, but we knew in advance that the 62,9 Pa value would be difficult to model.

The adjustment result (from the values of 40.4, 75.1 and 117.5 Pa, as explained previously), is the following formula, composed of two terms of quite equal magnitude :

$$\Delta P_{fr} = 0.0008166 v_c^{1.85} \cdot D_{coll} / H_{coll,i} + 0.04597 v_t^{1.85} \cdot D_t / H_t ,$$

where v_c is determined in the same way as v_t : $v_c = Q \cdot D_{coll}^2 / (\Delta T \cdot D_{coll,i} \cdot H_{coll,i})$.

These results enable us to determine, for various sizes H_t , D_t , $H_{coll,i}$, D_{coll} , the power of a similar tower to those described in "The solar Chimney"¹²⁷. But it's more interesting to analyse the ongoing Australian project, and to wonder whether the tower height limitation at the 1000 m threshold, comes from economical and rational, or symbolic, reasons.

For this, we take into account the fact that the sun energy flow is slightly lower (I divided Q by 1.15, which corresponds to a 2000 kWh/m²/y annual global radiation instead of 2300), and the fact that, during daytime, we accumulate some heat, and return it by night.

The important thing is to use a realistic velocity, for a correct calculation of the pressure losses I have thoroughly detailed. Therefore, we substitute the collector's efficiency by an "instant efficiency" : the heat quantity immediately given to the moving air¹²⁸, divided by the incident sun power.

So, the 526.2 W/m² value we had for a 100 MW tower is divided, first by 1.15, and then by the quotient of ① the term (750 GWh/y / 200 MW) which represents the intensity of the 24 h heat regulation for the Australian tower, and ② the corresponding term we had, in the book, with a lower regulation, for the 100 MW tower (305.2 GWh/y / 100 MW).

The heating term used to model the air convective motion and the speeds v_t and v_c , is then reduced to 372.2 W/m². Then, we can calculate a power whilst taking into account that the heat storage enables, with the same sizes, to have at each time a lower air flow, and therefore lower losses¹²⁹. But, of course, when it comes to determine the total annual electricity production, we multiply the power back by (750 GWh/y / 200 MW), so that not to be limited by the peak power.

¹²⁷ We ought to take into account that the taller the tower, the greater temperature difference ΔT we should have (notably to resist to the fact that outside, the temperature gradient is lower than the dry adiabatic gradient), even if, in exchange, the collector's thermal efficiency η_c decreases, as we can see it, in table 8 page 144, for the quantity Q which is proportional to it. However, having no precise modelling of the relevant parameters (infrared reemission, which varies very sharply with respect to the temperature, as we have a T⁴-law ; possibility to use double-glazing, etc.), I just kept, for ΔT and η_c , the values they had with the 950 m tower : the result will be slightly suboptimal, i.e. conservative.

¹²⁸ This is exactly true only during the day ; night electricity is produced with a lower speed, and therefore a higher efficiency ; but as, generally, electricity has a lower value by night than by day, we can suppose that both effects more or less offset each other, and it didn't seem useful to follow on.

¹²⁹ The ultimate consequence, once the optimization is done, being that narrower passages helps saving money from construction costs, but with not too high power losses.

V.C.2 Cost modelling

One more time, for the tower as well as for the collector, we'll adjust realistic cost functions to the three data series given by the book "The solar Chimney"ⁱⁱ.

For the tower, to be conservative, we should imagine an exponentially growing cost with respect to the height, as we had mentioned it about the $\exp(z_i/400m)$ thickness growth rate with regard to altitude (with the uncertainty that, from other data, the relevant parameter could be closer to 4000 m than to 400 m, Cf. page 31, 1st §). The diameter has mainly an influence through the perimeter, and possibly through the fact that it is easier for a wider tower to resist the wind. This is a reason to think about a cost dependence like : $C_t = a \cdot \exp(b.H_t) \cdot D_t^\alpha$.

But an adjustment of the three parameters : a, b and α , from the three values we have, yields absurd results, notably α being equal to -6.69 !

Conversely, two models are consistent with a D_t exponent which would be close to 1.

The first solution is to oblige it to be equal to 1, and to add a supplementary variant for the H_t dependence : we lay $C_t = a \cdot D_t \cdot \{\exp(b.H_t) + c\}$, which, after an adjustment, yields :

$$C_t = 1.0719 \cdot D_t \cdot \{\exp(0.0008586.H_t) - 1,1543\}. \quad (67)$$

This formula's problem is obviously the negative term, which, for lower towers than 167 m, would get over the positive one ! Of course, the tower cost can't be negative, and this formula probably gives a rather correct approximation only for greater heights than 300 m. But, as what we're interested in, is extrapolation towards higher sizes than 1000 m, this modelling isn't probably more wrong than another in this range of heights. We can also notice that the exponential pace, $1/0.0008586 = 1165$ m, ranges between 400 and 4000 m.

The 2nd solution is to build a formula without any exponential, and looking like those commonly used in economics, i.e. : $C_t = a \cdot H_t^\alpha \cdot D_t^\beta$. The adjustment to the three given examples yields

$$C_t = 10,64 \cdot H_t^{1.7534} \cdot D_t^{0.92} \quad (68). \quad \text{The fact that } \beta \text{ is slightly lower than 1 is rather likely.}$$

There are equivalent difficulties to find a cost function for the collector. With respect to its area, this cost function has only to be proportional. But, with respect to the glass roof height, there remains three parameters to adjust, which lets a great range of possibilities. We could for instance try a trinomial function : $C_c = D_{coll}^2 \cdot \{a.H_{coll,i}^2 + b.H_{coll,i} + c\}$. But, to be prudent, we mustn't exclude that the cost could grow very rapidly for greater heights, hence a formula where one of the adjustable parameters is an exponent : $C_c = D_{coll}^2 \cdot \{a.H_{coll,i}^\alpha + b\}$, becoming :

$$C_c = (D_{coll}/1000)^2 \cdot \{0.000905.H_{coll,i}^{2.559} + 18.7456\} \quad (69).$$

For a 40 m height, the $H_{coll,i}$ dependent term exceeds 60 % of the constant term, and 107 % for 50 m. In fact, quite no simulation reaches such heights. But for 20 m, it accounts only for 10 %, which means that we extrapolate important variations from data belonging to a small interval near zero. So, we've been prudent, but without really knowing whether it was necessary or not !

V.C.3 The results

All this can be done on a simple Excel sheet and, from this modelling, we can answer some questions, such as :

- which maximum power (with what sizes) can we get for the same cost than the 100 MW tower described in "The solar Chimney" and in the same solar heating conditions (same lack of heat storage, same 2300 kWh/y annual energy flow) ?

- which maximum power can we get for the same cost than the Australian 7000 m diameter system, in the same conditions of solar heating (same 2000 kWh/y annual energy flow, same heat storage¹³⁰) ?

- which minimum cost per kWh can we get by modifying the Australian system, but keeping its 7000 m diameter ?

- which minimum cost per kWh can we get by modifying the Australian system's four parameters (D_{coll} , $H_{coll,i}$, H_t , D_t) ?

The answers to these four questions, with the two possible cost functions for the tower (monomial : $C_t = a \cdot H_t^\alpha \cdot D_t^\beta$, and exponential : $C_t = a \cdot D_t \cdot \{ \exp(b \cdot H_t) + c \}$), lie in table 9 below :

	cost function	P/C increase ¹³¹	H_t	D_t	D_{coll}	$H_{coll,i}$
P_{max} for the same cost as the 100 MW tower in "The solar Chimney"	monomial	5.45 %	1171	107	3265	20.5
	exponential	6.55 %	1207	104	3250	20.5
P_{max} for the Australian project cost	monomial	72 %	1938	145	5631	25.4
	exponential	67 %	1764	151	5777	26.1
Minimum kWh cost for the Australian system, with $D_{coll} = 7000$ m	monomial	88 %	2531	176	7000	29.3
	exponential	75 %	2018	181	7000	29.6
Absolute kWh minimum cost for the Australian system	monomial	109 %	3716	304	12599	41.2
	exponential	80 %	2315	244	9606	35.7

V.C.4 Tower slenderness coefficient

In the table we've just drawn, the tower height to diameter ratio mostly lies between 10 and 15. But "The solar Chimney" tells us that this ratio should be lower than 10. Surely, a very thin and

¹³⁰ By chance, this simulation, as well as the one implemented in order to complete the reference figures of the Australian project, yield quite the same collector height.

¹³¹ Power divided by Cost, i.e. kW/€ increase, in percentage.

slender tower would seem fragile¹³². Therefore, this limit appears as a sound prudence (at least, if for a reason or another, it wouldn't be a good idea to implement the proposal from point III-A-2-e, p. 101-105, to use suspended guy rods in order to stiffen the tower from outside).

But we've seen that there are some reasons to wonder whether the design of an optimal facility may have been misled by excessive prudence. Therefore, and without pretending to do better than materials resistance specialists, it might be interesting to wonder whether this figure of 10 is based on absolute principles, or marginally modifiable rules.

The question of how much each block of concrete resists to the weight of everything standing over it, is to be solved column by column, independently from the distance to the opposite point. Therefore, for this problem the tower height is a crucial parameter, but its diameter isn't one.

A uniform wind's pressure is to be multiplied by its opposing area (i.e. the product of the tower's height and its diameter). The result is a force, whose effect is multiplied by the wind's lever arm (relatively to the tower's toppling down risk). The wind pushes, as a mean value, at the tower middle, so this lever arm is half its height. Assume that the tower resists with its weight, which is proportional to its height, to its perimeter (thus, to its diameter) and to the wall thickness. This weight, located on the tower axis, has a lever arm too, which is half the diameter. This results in :

$$\text{Wind's pressure} \times H \times D \times H/2 \propto (\text{proportional to}) Th \times H \times D \times D/2, (Th = \text{Thickness}) \quad (70)$$

$$\text{i.e., if the wind pressure is uniform :} \quad H/D \propto Th. \quad (71)$$

So, there truly exists, because of the risk that the wind topples the tower over, a limit that the H/D ratio mustn't exceed. But this limit is proportional to the mean thickness of the tower's wall, which isn't a constant. As a matter of fact, to help the concrete to support the weight above it, the higher the tower, the thicker the wall : 30 cm at the bottom of a 445 m high tower, but 1 m for a 1000 m one. Thus, the necessity that the tower must resist a uniform wind, is not contradictory, per se, with the possibility that its H/D ratio may increase a little when higher towers are thought about.

Of course, a dynamic analysis (effects of earthquakes or tower oscillations caused by wind irregularities) is more complex. A very high and thin tower will, one more time, seem fragile. But the wheel spokes principle will bring an appreciable additional stiffness, and, if the H/D ratio increases, it seems logical to begin by raising the number of such wheels to reinforce the tower.

As a conclusion, it can't be excluded that it would become very difficult to increase the tower's height beyond 10 times its diameter. But it seems equally prudent not to exclude, just because it causes vertigo, the opposite idea.

¹³² But the tower is, like a tumbler (toy clown which always automatically comes back to its standing position), heavier at its base than at its top. This helps to correct the first appraisal, from an outer glance, of its stability.

V.D Appendix 4 : Expansion in series optimizations

V.D.1 Appendix 4a : systems without heat storage

Diagram 30 page 89 may seem very complex for a concrete implementation. However, we can define, under some particular conditions, a methodology whose results are rather heartening.

These conditions are mainly a linearizability hypothesis, which gives the way to process the problem through finite dimension linear algebra, i.e. by matrical calculation, which computers can implement without great difficulties. That for, we need that the operating system can be represented by a finite set of parameters, and that around a mean operating point, we make not too big an error by using the technique of the expansion in series (ES ; polynomial series, of course).

To find an economical optimum, i.e. a technical-financial function maximum or minimum, this ES must at least be of the 2nd order, i.e. be made of :

- a constant,
- terms proportional to the variations between the reference point and the variable point,
- and terms corresponding to these variations squared, or to the products of the variation of some parameters multiplied by the variation of other parameters.¹³³

According to the diagram page 89, the parameters we must use belong to three categories :

① control variants. For a solar tower, they mainly describe how we control the air velocity, by acting on the turbines : their blades orientation, some electromagnetic parameters of the alternators to which they're connected, can make them rather strongly resistant (they limit the air velocity by opposing a high torque) or more supple (we can get the same power with a lower torque but a higher angular velocity).

For a solar chimney, this gives only one freedom degree, therefore only one control variant, which will simplify the matrical calculations (matrix A hereunder, whose inverse we need to calculate, will be a 1x1 matrix), but there is no reason to drop the matrical formalism, which is well adapted to the interaction with the other parameters, and in other cases we can have more control variants (for an energy tower, we have two levers : as here, the turbine strength, and besides, the water flow we pump up to let it evaporate).

② "temps" parameters (weather and time). For example : the hour, the day (which modify both the sun rays inclination and the economical activity, thus the power demand), the lighting, the ambient air temperature, its hygrometry, the kWh market price at such a time and with such meteorological conditions, the temperature lapse rate ($^{\circ}/\text{km}$) outside the tower, etc.. These parameters can vary very freely, but in principle we can know a distribution function of such conditions.

¹³³ If this leads to too imprecise results, we can imagine to work with 3rd order ES, thus replace the squared matrices by cubic ones ; or even higher orders. There is no theoretical objection to such a sophistication, and the principles to be implemented aren't of a different nature compared with what will be developed here, but the real calculations will clearly be heavier.

E.g., the probability to be in February, between 15 h and 16 h, that the lighting lies between 300 and 400 W/m², that the ambient temperature lies between 20 and 25°, and decreases between 6 and 8°/km, and that we can sell a kWh between 4 and 5 euro cents, can in theory be determined : it'll be, for instance, 0.002 ‰.

We may also choose continuous probability densities : February the 8th, between 16 h and 16 h 01, which probability in 10⁻¹⁵ that the lighting is 320 ± 1 W/m², etc. ?, with the idea that this probability ρ can be a continuous function of all these variants, and even be substituted by an analytical function, or in any case correctly designed for integral calculation.

③ construction parameters : tower height and width, collector diameter, inlet or outlet roof height, (possibly intermediate values), glass thickness, percentage of double glazing collector, ground albedo, etc. The important thing being that, for each of these parameters, we could model both its effect on the electricity output, and on the facility's cost.

The final result is f, as Function, or as cash Flow¹³⁴. The construction parameters are : c₁, ..., c_i, ..., c_n. As well, the "temps" parameters are t₁, ..., t_j, ..., t_m, the control variants are r₁, ..., r_k, ..., r_q. The total parameters number is : n + m + q = s.

The approximation we do is that the result function f is quite well described by its expansion in series at the 2nd order, around a mean point, as a function of all these parameters¹³⁵. If we gather all the parameters under the letter V¹³⁶, as a set of elements describing the variations from the reference point V_o and named from v₁ to v_s, such an ES around V_o can write :

$$f(\mathbf{V}) = f(\mathbf{V}_o) + (\partial f / \partial v_1)_o \cdot v_1 + (\partial f / \partial v_2)_o \cdot v_2 + \dots + (\partial f / \partial v_s)_o \cdot v_s + \frac{1}{2} (\partial^2 f / \partial v_1^2)_o \cdot v_1^2 + (\partial^2 f / \partial v_1 \partial v_2)_o \cdot v_1 v_2 + \dots + (\partial^2 f / \partial v_1 \partial v_s)_o \cdot v_1 v_s + \frac{1}{2} (\partial^2 f / \partial v_2^2)_o \cdot v_2^2 + \dots + (\partial^2 f / \partial v_2 \partial v_s)_o \cdot v_2 v_s + \dots + \frac{1}{2} (\partial^2 f / \partial v_s^2)_o \cdot v_s^2, \quad (72)$$

which can also be written, with the matricial formalism, as :

¹³⁴ This variant we must optimize could be the electricity output (GWh) with a constant cost constraint. This is a classical optimization problem (Cf. appendix 3), but here it would only increase the whole formal complexity, therefore we look for a unique number to maximize or minimize. We could look for the lowest possible kWh cost, but this would lose the idea to refine the evaluation by taking into account a market price variation as a function of the hour, of the temperature, etc.

A good result to optimize seems to be the facility's internal rate of return (IRR) : knowing on one hand the construction cost (punctual, or even spread over some years), and on the other hand the expected incomes over a whole lifetime, we compute the discounting rate which equals them. Then, the available interest rate isn't a helpful data to foresee the initial investment's annual cost, but a final comparison parameter : if the maximum IRR we find is 4.6 %, this means that if we manage to borrow at this rate with a long duration, the facility is profitable ; which is also possible, as a 1st approximation, if we borrow 75 % of the capital from commercial banks at 5.2 %, 15 % from the World Bank at 3 %, and we finance the last 10 % from environment-friendly private shareholders who'd accept a 2.5 % only profit (0.75 x 5.2 + 0.15 x 3 + 0.1 x 2.5 = 4.6).

¹³⁵ Therefore, f must be a rather regular function of all these parameters. But the poorly linearizable fact that we have two very different lighting regimes, whether clouds shade the sun or not, doesn't forbid to use this methodology. This will yield a probability function of the "temps" parameters which will have two well separated series of maxima : it would be stupid to try to force this probability function ρ into a quadratic model corresponding to a 2nd order ES, but precisely we don't need such an hypothesis : all the following calculations are correct, whatever the shape of this probability density ρ as a function of the temps parameters (this wouldn't be true for the result f as a function of these temps parameters, as it must be rather close to a 2nd order ES, but it is another problem, which will be discussed again in the post-calculation comments).

¹³⁶ As "variants", or , as we'll see further, "vector".

¹³⁷ the subscripts "o" mean that all these partial derivatives are taken at point V_o ; however, as this notation is rather ponderous, it'll be dropped as soon as there will no longer be any ambiguity and it won't be useful any more.

$$f(\mathbf{V}) = f(\mathbf{V}_0) + \left[\left(\frac{\partial f}{\partial v_1} \quad \frac{\partial f}{\partial v_2} \quad \dots \quad \frac{\partial f}{\partial v_s} \right) \right] \times \begin{pmatrix} v_1 \\ v_2 \\ \dots \\ v_s \end{pmatrix} \\ + \frac{1}{2} \begin{bmatrix} v_1 & v_2 & \dots & v_s \end{bmatrix} \times \begin{pmatrix} \left(\frac{\partial^2 f}{\partial v_1^2} \right) & \left(\frac{\partial^2 f}{\partial v_1 \partial v_2} \right) & \dots & \left(\frac{\partial^2 f}{\partial v_1 \partial v_s} \right) \\ \left(\frac{\partial^2 f}{\partial v_1 \partial v_2} \right) & \left(\frac{\partial^2 f}{\partial v_2^2} \right) & \dots & \left(\frac{\partial^2 f}{\partial v_2 \partial v_s} \right) \\ \dots & \dots & \dots & \dots \\ \left(\frac{\partial^2 f}{\partial v_1 \partial v_s} \right) & \dots & \dots & \left(\frac{\partial^2 f}{\partial v_s^2} \right) \end{pmatrix} \times \begin{pmatrix} v_1 \\ v_2 \\ \dots \\ v_s \end{pmatrix}$$

(the partial derivatives being, as previously, taken at the reference point \mathbf{V}_0).

$$\text{This result can be written :} \quad f(\mathbf{V}) = f_0 + {}^t\mathbf{G}_v \cdot \mathbf{V} + \frac{1}{2} {}^t\mathbf{V} \cdot \mathbf{M} \cdot \mathbf{V} \quad (73),$$

where \mathbf{V} corresponds to the column matrix, or "vector" going from \mathbf{V}_0 to the variable point ; \mathbf{G}_v (as "gradient") is also a column matrix, made from partial derivatives of f with respect to the various components of \mathbf{V} ; \mathbf{M} is the square symmetrical matrix made of the same derivatives, but of the second order ; and the t symbol, up left a matrix-letter, means that we transpose it : a column matrix is transformed into a row matrix, etc. The matricial product rules show that all the above terms are scalars, i.e. 1×1 matrices, in fact simple real numbers.

In order to remind the general optimization principles of quadratic functions, imagine, as a pure example, that we look for the absolute maximum of f , while feeling free to vary every \mathbf{V} component. The \mathbf{V} value corresponding to this maximum is the one for which all the partial derivatives of f with respect to its s components are null. From (72), the 1st partial derivative is :

$$\frac{\partial f}{\partial v_1} = \left(\frac{\partial f}{\partial v_1} \right)_0 + \left(\frac{\partial^2 f}{\partial v_1^2} \right)_0 \cdot v_1 + \left(\frac{\partial^2 f}{\partial v_1 \partial v_2} \right)_0 \cdot v_2 + \dots + \left(\frac{\partial^2 f}{\partial v_1 \partial v_s} \right)_0 \cdot v_s,$$

the 2nd is :

$$\frac{\partial f}{\partial v_2} = \left(\frac{\partial f}{\partial v_2} \right)_0 + \left(\frac{\partial^2 f}{\partial v_1 \partial v_2} \right)_0 \cdot v_1 + \left(\frac{\partial^2 f}{\partial v_2^2} \right)_0 \cdot v_2 + \dots + \left(\frac{\partial^2 f}{\partial v_2 \partial v_s} \right)_0 \cdot v_s,$$

and so on, until :

$$\frac{\partial f}{\partial v_s} = \left(\frac{\partial f}{\partial v_s} \right)_0 + \left(\frac{\partial^2 f}{\partial v_1 \partial v_s} \right)_0 \cdot v_1 + \left(\frac{\partial^2 f}{\partial v_2 \partial v_s} \right)_0 \cdot v_2 + \dots + \left(\frac{\partial^2 f}{\partial v_s^2} \right)_0 \cdot v_s$$

To be at the maximum, all the left hand members must be zero. This gives s simultaneous linear equations in s unknowns. The formally simplest way to solve it is to express it under a matricial form. The required matrices are those introduced in (73). We can write (equality among three column matrices) that : $0 = \mathbf{G}_v + {}^t\mathbf{V} \cdot \mathbf{M}$ (74).

This validates, from the result, a method which would be to look for an extremum by "deriving" (73) with respect to \mathbf{V} , and considering that the term $\frac{1}{2} {}^t\mathbf{V} \cdot \mathbf{M} \cdot \mathbf{V}$ identically depends on \mathbf{V} by

the tV left-hand multiplication and by the V right-hand multiplication, thus that its derivative is equal to what we'd get by considering tV as a constant but deriving twice the term $V : {}^tVM$.

Equation (74) is very simply solved : as we assume f has an optimum, there is one and only one solution, thus M is an invertible matrix. Therefore we just have to right-hand multiply (74) by $M^{-1} : 0 = G_v.M^{-1} + {}^tV.M.M^{-1}$, thus ${}^tV = -G_v.M^{-1}$, or : $V = -M^{-1}.{}^tG_v$ (as M and by consequence M^{-1} are symmetrical, it is useless to transpose them ; for the remaining, transposition inverses the order of the matrices multiplication).

Naturally, this "optimization" was just an example, as it doesn't obey diagram 30 page 89 ; however, the same principles will be very useful to apply the procedure this diagram prescribes.

As indicated in its centre, we must, once we've modelled the system behaviour as equation (73), research, for all the values of the construction and temps parameters, the optimum with respect to the control variants. We remind that vector V is made of these three types of parameters, successively ordered : $c_1, \dots, c_i, \dots, c_n, t_1, \dots, t_j, \dots, t_m, r_1, \dots, r_k, \dots, r_q$, which we can sum up in a matricial form :

$$V = \begin{bmatrix} C \\ T \\ R \end{bmatrix}, \text{ or also } V = \begin{bmatrix} P \\ R \end{bmatrix} \text{ if temporarily grouping C and T in a set of parameters P we don't yet need to optimize}$$

As well, the gradient vector (or column matrix) can be split down into 3 or 2 parts :

$$G_v = \begin{bmatrix} G_c \\ G_t \\ G_r \end{bmatrix} = \begin{bmatrix} G_p \\ G_r \end{bmatrix}$$

Finally, matrix M must also be split down into several matrices, among which some, situated on the diagonal, are still square and symmetrical, while the others are rectangular but make pairs, corresponding to each other by a symmetry about the diagonal, and a transposition :

$$M = \begin{pmatrix} (\partial^2 f / \partial v_1^2) & (\partial^2 f / \partial v_1 \partial v_2) & \dots & (\partial^2 f / \partial v_1 \partial v_s) \\ (\partial^2 f / \partial v_1 \partial v_2) & (\partial^2 f / \partial v_2^2) & \dots & (\partial^2 f / \partial v_2 \partial v_s) \\ \dots & & & \\ & & \dots & \\ (\partial^2 f / \partial v_1 \partial v_s) & \dots & & (\partial^2 f / \partial v_s^2) \end{pmatrix} = \begin{bmatrix} E & {}^tH & {}^tI \\ H & F & {}^tJ \\ I & J & A \end{bmatrix} = \begin{bmatrix} B & {}^tD \\ D & A \end{bmatrix}$$

E is the square matrix of the second partial derivatives of f with respect to all the construction parameters, F those of "temps", A the control variants ; the rectangular matrix H gathers the crossed second partial derivatives with respect to construction and temps parameters, etc. (I , to construction and control, J , to temps and control).

Expression (73), $f(V) = f_0 + {}^tG_v.V + \frac{1}{2} {}^tV.M.V$, thus becomes :

$$f(V) = f_0 + \left[\begin{array}{c|c} {}^tG_p & {}^tG_r \end{array} \right] \left[\begin{array}{c} P \\ \hline R \end{array} \right] + \frac{1}{2} \left[\begin{array}{c|c} {}^tP & {}^tR \end{array} \right] \left[\begin{array}{c|c} B & {}^tD \\ \hline D & A \end{array} \right] \left[\begin{array}{c} P \\ \hline R \end{array} \right]$$

$$f(V) = f_0 + {}^tG_p.P + {}^tG_r.R + \frac{1}{2} {}^tP.B.P + \frac{1}{2} {}^tR.A.R + {}^tP.{}^tD.R \quad (75)$$

We remind that we try to optimize this expression only with respect to the control variants, hence, by deriving "with respect to R" (according to the previously determined methodology). All the terms which don't include R will yield 0, the terms including a right-hand multiplication by R (${}^tG_r.R$ and ${}^tP.{}^tD.R$) will be derived "naturally", and finally $\frac{1}{2} {}^tR.A.R$ will give ${}^tR.A$.

So, we get : $0 = {}^tG_r + {}^tP.{}^tD + {}^tR.A$, i.e. ${}^tR = -({}^tG_r + {}^tP.{}^tD).A^{-1}$, or, by transposition :

$$R_{opt} = -A^{-1}.(G_r + DP) \quad (76)$$

To go on with the procedure described page 89, we now substitute R by this optimized value, in formula (75) :

$$\begin{aligned} f(P) &= f_0 + {}^tG_p.P + {}^tG_r.R_{opt} + \frac{1}{2} {}^tP.B.P + \frac{1}{2} {}^tR_{opt}.A.R_{opt} + {}^tP.{}^tD.R_{opt} \\ &= f_0 + {}^tG_p.P - {}^tG_r.A^{-1}.(G_r + DP) + \frac{1}{2} {}^tP.B.P + \frac{1}{2} ({}^tG_r + {}^tP.{}^tD).A^{-1}.A.A^{-1}.(G_r + DP) - {}^tP.{}^tD.A^{-1}.(G_r + DP) \end{aligned} \quad (77)$$

Some simplifications and gatherings yield :

$$f(P) = f_0 + {}^tG_p.P + \frac{1}{2} {}^tP.B.P - \frac{1}{2} ({}^tG_r + {}^tP.{}^tD).A^{-1}.(G_r + DP) \quad (78),$$

hence :

$$f(P) = f_0 + {}^tG_p.P + \frac{1}{2} {}^tP.B.P - \frac{1}{2} {}^tG_r.A^{-1}.G_r - \frac{1}{2} {}^tP.{}^tD.A^{-1}.DP - {}^tG_r.A^{-1}.DP \quad (79)$$

Then, before the final optimization using the construction parameters C, we must add up, in each C case, the values of f for all the "temps" situations, whose distribution $\rho(T)$ is supposed to be known. So, the time has come to split the matrices P, G_p , B and D, which contain construction C and temps T dependent terms :

$$\text{Knowing that } M = \left[\begin{array}{c|c|c} E & {}^tH & {}^tI \\ \hline H & F & {}^tJ \\ \hline I & J & A \end{array} \right] = \left[\begin{array}{c|c} B & {}^tD \\ \hline D & A \end{array} \right], \quad B = \left[\begin{array}{c|c} E & {}^tH \\ \hline H & F \end{array} \right] \text{ and } D = \left[\begin{array}{c|c} I & J \end{array} \right]$$

and that, from the mere definition of P,
$$P = \begin{bmatrix} C \\ T \end{bmatrix} \quad \text{and} \quad G_p = \begin{bmatrix} G_c \\ G_t \end{bmatrix}$$

relation (78) can be expanded as follows :

$$\begin{aligned} f(P) &= f_0 + {}^tG_p.P + \frac{1}{2} {}^tP.B.P - \frac{1}{2} ({}^tG_r + {}^tP.D).A^{-1}(G_r + DP) \\ &= f_0 + {}^tG_c.C + {}^tG_t.T + \frac{1}{2} {}^tC.E.C + \frac{1}{2} {}^tT.F.T + {}^tC.H.T - \frac{1}{2} ({}^tG_r + {}^tC^tI + {}^tT^tJ).A^{-1}(G_r + IC + JT) \end{aligned} \quad (80)$$

which we can order by "growing powers of T" :

$$\begin{aligned} f(C, T) &= \{f_0 + {}^tG_c.C + \frac{1}{2} {}^tC.E.C - \frac{1}{2} ({}^tG_r + {}^tC^tI).A^{-1}(G_r + IC)\} \\ &\quad + \{ {}^tG_t + {}^tC^tH - ({}^tG_r + {}^tC^tI).A^{-1}J \}.T + \frac{1}{2} {}^tT. \{F - {}^tJ.A^{-1}J\}.T \end{aligned} \quad (81)$$

Still according to page 89 diagram, we must now gather these results, after weighting them with the density $\rho(T)$, which will give three categories of integrals :

- the T-independent term, which, besides, is a scalar, is just to multiply by $\int \rho(T) d^m T = \rho_t$ (the $\int d^m T$ symbol means m^{th} order multiple integral, where m is the total number of "temps" parameters ; from now on, we only write it $\int d^m T$). (For a normed distribution, ρ_t could be = 1).

- for the T^1 -dependent term, the integration will commute with the matricial calculation, i.e. :

$$\int [\{ {}^tG_t + {}^tC^tH - ({}^tG_r + {}^tC^tI).A^{-1}J \}.T] \rho(T) d^m T = \{ {}^tG_t + {}^tC^tH - ({}^tG_r + {}^tC^tI).A^{-1}J \}. \int T. \rho(T). d^m T .$$

The $\int T. \rho(T). d^m T$ term which appears on the right hand side is a column matrix which can be computed as soon as we know the distribution ρ . From now on, we name it T_i ¹³⁸ : $T_i = \int T. \rho(T). d^m T$ (82)

- oppositely, integration can't commute with a right-hand multiplication by T and a left-hand one by tT , but this isn't a problem, as the relevant term doesn't depend on C which will be used for the final optimization. We can simply write :

$$\int \frac{1}{2} {}^tT. \{F - {}^tJ.A^{-1}J\}.T. \rho(T). d^m T = K \quad (83) ,$$

which is a constant scalar that we can compute as soon as we know the distribution ρ and all the second partial derivatives of f around the point V_0 .

We can see that expression (81), after the integration with respect to T and with the density $\rho(T)$ weighting, gives an expression of f which only depends on C and on various constants : (84)

¹³⁸ as "integral"

$$f(C) = \rho_t \{f_o + {}^tG_c.C + \frac{1}{2} {}^tC.E.C - \frac{1}{2} ({}^tG_r + {}^tC.T).A^{-1}(G_r + IC)\} + \{{}^tG_t + {}^tC.H - ({}^tG_r + {}^tC.T).A^{-1}J\}.T_i + K$$

We must now order it by growing powers of C so that we can realize the final optimization forecast page 89 :

$$f(C) = \{\rho_t.f_o + K + {}^tG_t.T_i - {}^tG_r.A^{-1}.J.T_i - \frac{1}{2}\rho_t {}^tG_r.A^{-1}.G_r\} \\ + \{\rho_t({}^tG_c - {}^tG_r.A^{-1}.I) + {}^tT_i(H - {}^tJ.A^{-1}.I)\}C + \frac{1}{2}\rho_t {}^tC\{E - {}^tI.A^{-1}.I\}C \quad (85)$$

$$\text{which we can write as :} \quad f(C) = f'_o + {}^tG'_c.C + \frac{1}{2} {}^tC.E'.C \quad (86)$$

where the three constants f'_o , G'_c and E' are directly drawn from the comparison of (85) and (86), with the transposition of ${}^tG'_c$ into :

$$G'_c = \rho_t(G_c - {}^tI.A^{-1}.G_r) + ({}^tH - {}^tI.A^{-1}.J)T_i \quad (87)$$

Then, we can very simply operate the final optimization : as we saw it on the fake example (74) of an optimization with regard to the whole vector V, the derivation with respect to C yields : $\partial f/\partial C = {}^tG'_c + {}^tC.E'$, which is equated to zero, classically, for ${}^tC = - {}^tG'_c.E'^{-1}$, i.e. :

$$C_{opt} = - E'^{-1}.G'_c \quad (88)$$

Therefore, we've indeed found a way to determine the optimal construction parameters and, for each "temps" configuration, the optimal operating control ; then, the economical indicator results from the combination of (86) and (88) :

$$f_{max} = f'_o + {}^tG'_c.C_{opt} + \frac{1}{2} {}^tC_{opt}.E'.C_{opt} = f'_o - {}^tG'_c.E'^{-1}.G'_c + \frac{1}{2} {}^tG'_c.E'^{-1}E'.E'^{-1}.G'_c \quad (89)$$

$$f_{max} = f'_o - \frac{1}{2} {}^tG'_c.E'^{-1}.G'_c \quad (90)$$

The only reservation is that this result is correct only if the 2nd order expansion in series approximation doesn't bring too much errors. Four remarks about this :

① - for construction parameters C, the more we refine the optimization process, the closer we get to the optimum, and the better this approximation becomes. Therefore, we can take the first V_o values quite at random, and then, after a 1st optimization, start from the C_{opt} construction parameters we've just found. The 2nd optimization will be even more precise.

② - oppositely, for the "temps" parameters, and thus for the control variants, the model must inevitably operate on a wide range of values. The most serious problem would be to have non negligible errors for a very low (cloudy weather) or null (by night) lighting, for example a negative output instead of being quasi-null !

The solution is probably to take for these conditions a null occurrence probability $\rho(T)$. A consequence is that, even if in theory ρ is a probability function, the sum of all the other cases will

be lower than 100 %. That's why, instead of taking a normed probability function and lighten the previous calculation with $\rho_t = 1$, we kept this term in the final formulas (85) and (87).

This problem being solved, we can locate the point V_o at sunny weather mean conditions. Therefore, most of the relevant points will induce little errors : the sunny points because they're not very far from V_o , and the dark points because of their zero weighting.

③ - a theoretically important limitation of expansion in series models comes from some equipments' capacity. For example, if we use a 1 MW turbine, not much is changed if the air flow energetic potential moves from 800 to 900 kW, but all changes if it moves from 1000 to 1100 kW. However, this seems to concern mainly the turbines and pumps, which can be dealt with rather independently from the remaining. We saw that the solar chimney depression isn't a limiting parameter of its mechanical bearing, there should be no temperature limitation for the black bodies we lie under the collector, etc...

④ - finally, other non-continuities result from qualitative options : glass or polycarbonate, steel or concrete, etc. In this case, we'd optimize each hypothesis, and compare them at the end. We can also take this into account by juxtaposing both materials, as, in introduction, I chose the "percentage of double glazing collector" as a construction parameter example.

To conclude, are the needed calculations very heavy ? As the total number of parameters is s (for example twenty) we've mainly around $s^2/2$ $\partial^2 f / \partial x \partial y$ to compute, each one from four points :

$$\partial^2 f / \partial x \partial y = \{f(x_o + \Delta x, y_o + \Delta y) - f(x_o + \Delta x, y_o - \Delta y) - f(x_o - \Delta x, y_o + \Delta y) + f(x_o - \Delta x, y_o - \Delta y)\} / 4\Delta x \Delta y. \quad (91)$$

Therefore, we've got to compute $2s^2$ internal rates of return, for each optimization phase ; in each case, we must model the system's physical behaviour and its cost, and compute the IRR : the difficulty is probably in the physical modelling itself and in the economical information (costs, etc.) research, and not in these results application to $2s^2$ different case, or $4s^2$ if we make two successive optimizations, as previously suggested.

Equally, we shouldn't be frightened by what we must calculate from these second partial derivatives : invert two symmetrical matrices, whose size is for A the number of control variants (1 or 2) and for E' the number of construction parameters (perhaps a dozen) : computers easily operate such inversions ; calculate $m+2$ integrals (a vector T_i and two constants ρ_t and K), in a m -dimension space, which bears no theoretical difficulty as soon as we've realistically described the occurrence probabilities of the weather conditions and of the power output sale prices ; at last, multiply a lot of matrices, which is in the scope of any PC.

Therefore, unless we'd be unhappy with a 2nd order ES and we'd want to work with 3- or 4-dimension matrices, the optimization procedure described in page 89 diagram isn't what must frighten us : the relevant information collect is a much more limiting factor than the optimization process itself, and this is true whatever the number (reasonable, probably not more than hundred) of parameters we want to vary together.

Optimization with energy storage, such as described page 85, is more complex from a theoretical point of view, but some approximations can be found, and based on the present techniques, as shown next point.

V.D.2 Appendix 4b : systems with heat storage

The general optimization principles of a system with heat storage are defined pages 90 and 91. They're much different from page 89 algorithmic diagram, which is the basis of the matrical calculations we've just done in appendix 4a. However, on a particular example (with some interest as it is the Australian solar chimney, with 24 h operating), we can come back to a rather close optimization mode.

We start with the system's physical analysis :

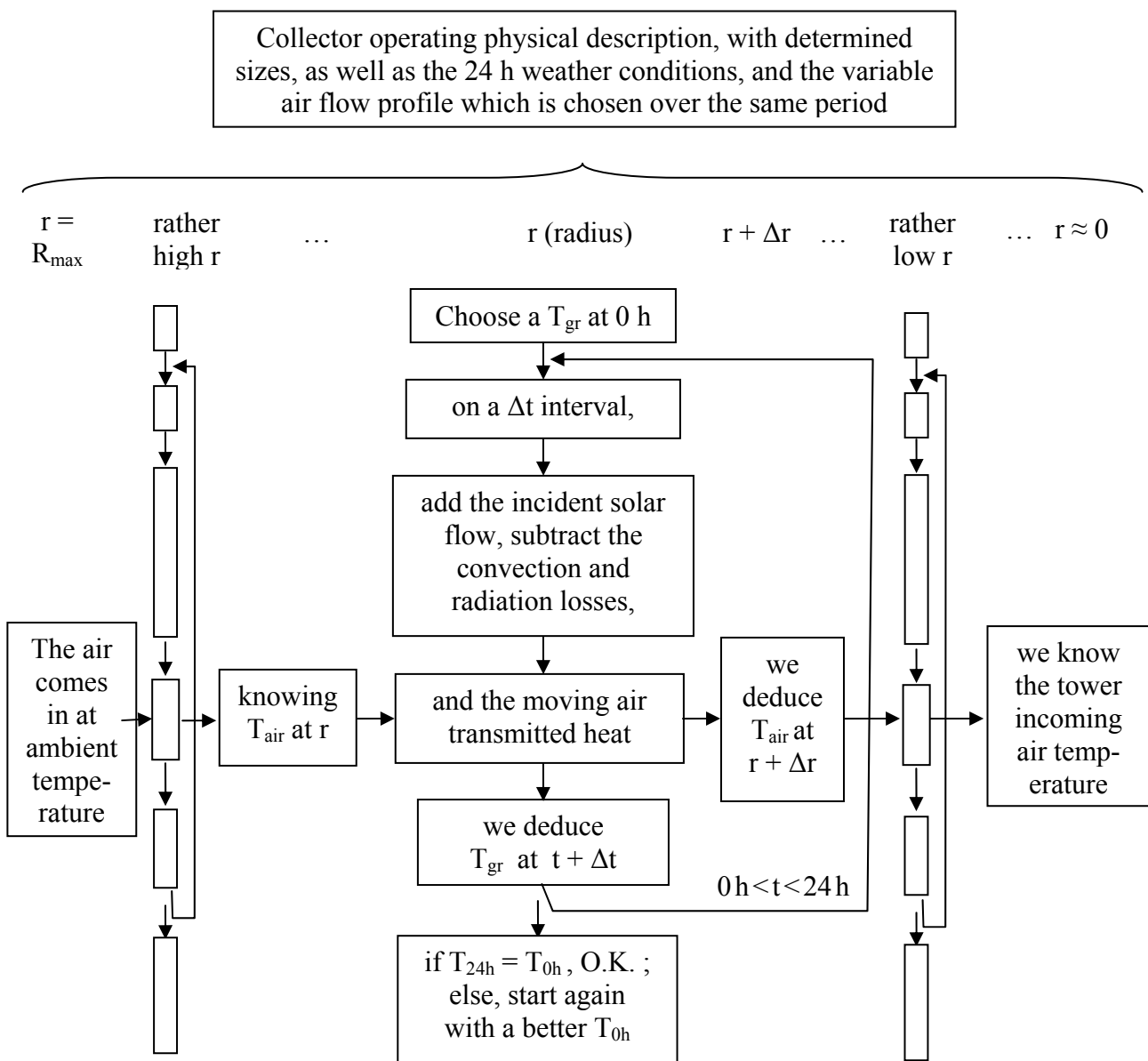


Figure 52

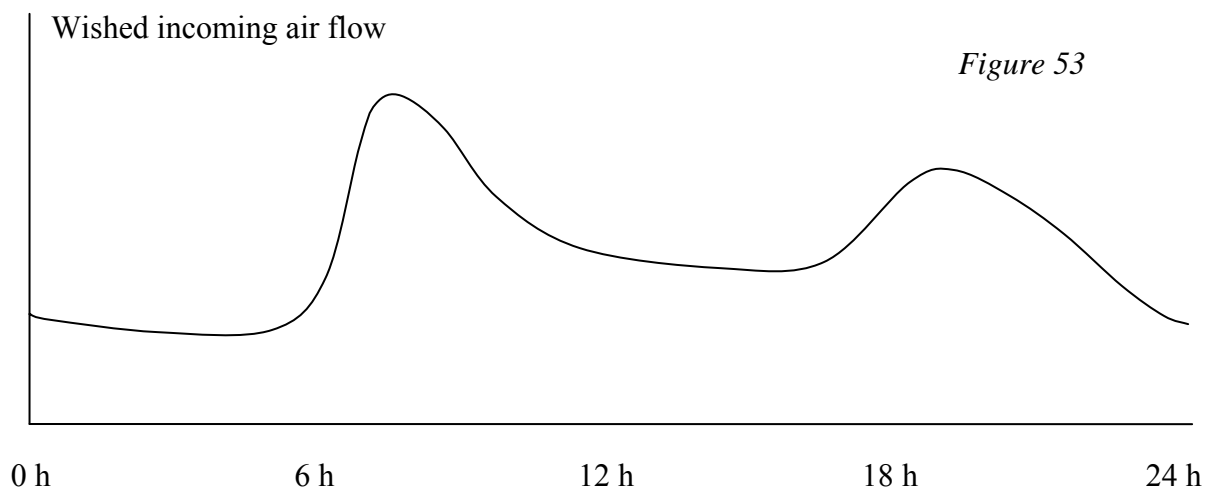
On each Δt time interval and each Δr collector radius interval (computer grids, i.e. sizes of the system representing cells), the ground (more or less complex) absorbs part of the incident solar flow, loses some heat by radiation and convection, and gives some to the incident air flow. So far, not much difference with what dos S. Bernardes, Voß and Weinrebe^{iv} do, Cf. figure 3, page 10. However, two remarks :

- here, we keep the highest freedom to choose the incoming air flow (while remembering that the efficiency will be low if this flow is too high or too low), in particular for the reasons given pages 93, 94 and previous ;

- the evaluation is correct only if we check that at the end of the day, for each distance r from the collector centre, the stored heat equals what it was 24 h earlier. In the dos S. Bernardes and alii's article we've just quoted, this condition seems to be fulfilled on the results curves, but nothing in the algorithm description corresponds to such a check. The authors may have bypassed this problem by operating their software 2 or 3 times longer, which, if the thermal inertia isn't too great, should rapidly converge to the steady-state solution we look for. However, if the computing time is expensive, it would be better to use convergence accelerating methods, which include the figure 52 steady-state test, and improve it for retroaction.

Then, we must insert this physical modelling into a larger optimization system, such as what we saw in appendix 4a. This will be shown in figures 54 and 55. Then, we'll be able to make matrical computations with the three variant categories : control, "temps", and construction. Here, control is the choice of a 24 h air flow profile. But 1 or 2, or even 15 parameters, aren't enough to describe the infinite choice we have to find this optimal profile : the vectorial space of the continuous real functions on the $[0, 24 \text{ h}]$ interval, has an infinite dimension. But we can't think of adapting appendix 4a matrical method, to work in such an infinite dimension !

Therefore, we must limit our freedom to choose any 24 h air flow profile, and be happy with functions rather close to what, intuitively, an optimal flow could be. From the day phases analysis we made previously (pages 93-94), we can imagine a profile such as :



What can we say about such a curve, which looks like nothing well known, and thus could be characterised by a quasi-infinite number of parameters ? That, after 24 h, it comes back to its starting point. Therefore, we could consider it as a periodical function restriction to one day. But all continuous periodical functions can be split into a Fourier's series.

And, if there aren't too sudden variations, the very high rank harmonics become negligible. A function such as in figure 53, which shows no strong features within a lower than 1 h time interval, could be quasi-perfectly approximated by the 25 first terms of its Fourier's series, i.e. at most 50 parameters (and probably very correctly with the first 10 terms, i.e. 20 parameters). This is more than the 1 or 2 control variants we assumed in appendix 4a, but less than the infinity we were afraid of last page.

Therefore, we only have to put the sum of some dozens of sinusoids whose periods are 24 h divisors, in figure 54 hereunder, in the cases "Choice of a 24 h air flow profile with respect to t". The remainder of the figure bears no particular difficulties, except the two following points :

① - the air flow profile is chosen from an optimization which is based on a "hypothesis for 24 h weather and economical conditions". Said differently, a meteorological forecast intervenes. But the "mean income" we get at the end of the day results from the real weather conditions that will occur. The difference between forecast and reality will slightly lower this real income (we can also wonder whether the system could be refined with a real time correcting device, to marginally vary the initial daily choices. This is well beyond the scope of the present study).

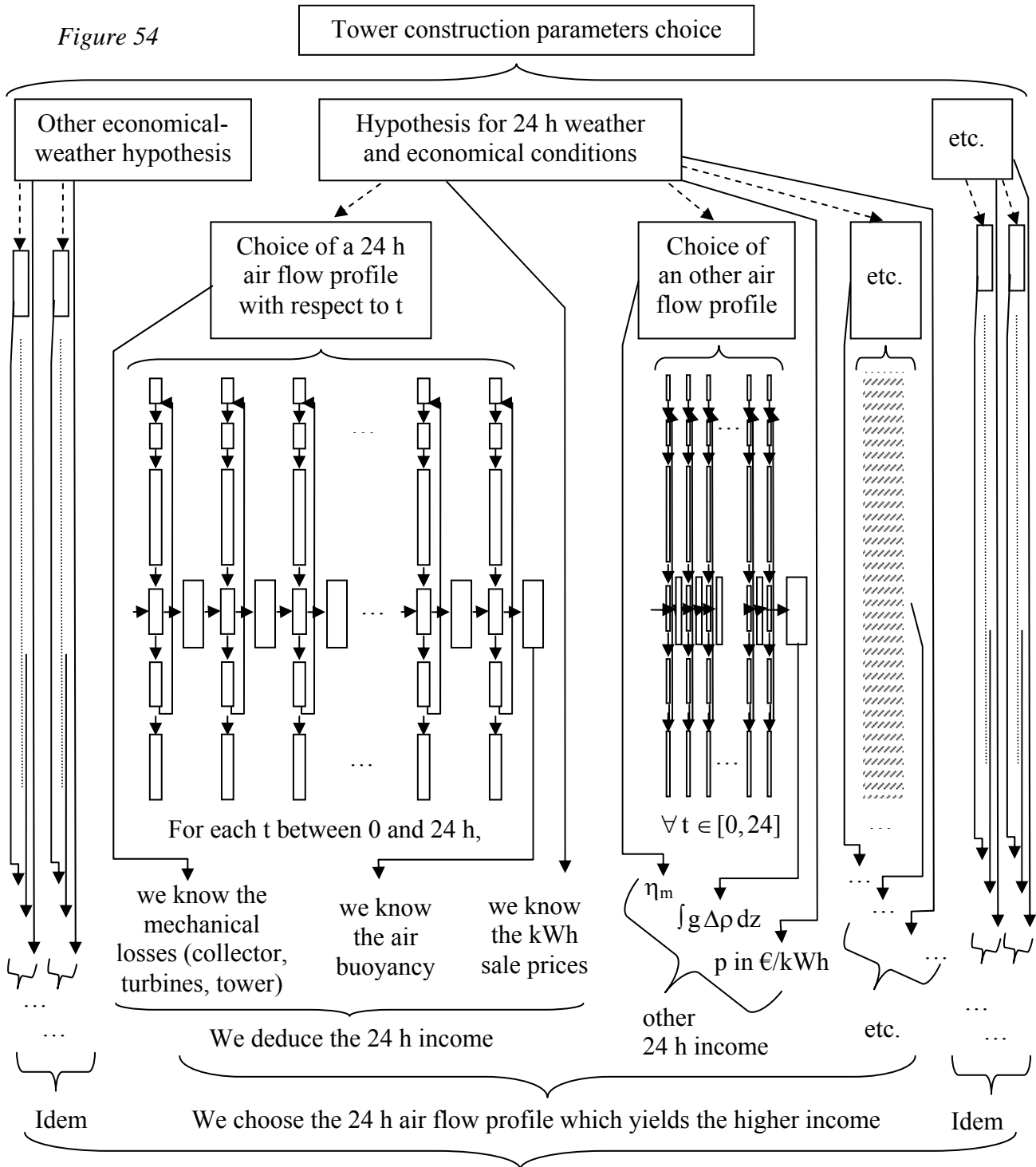
② - when we say "occurrence probabilities of the various 24 h weather and economical conditions hypotheses", it isn't as simple as for a storageless system, where we just had to characterize the incident solar flow, the ambient air temperature, this temperature's gradient up to 1 km high, and the kWh sale price, all of it at a t time. Here, we must work with 24 h profiles precise features, and for example being able to distinguish a 5 mn period cloud-sun alternation regime, from the same regime but with 3 h or 12 h periods.

Therefore, the vectorial space of the "temps" conditions has, one more time, a theoretically infinite dimension, and we must bring it back to a finite dimension. The solution may be to define some "typical days" which would be the vectorial base of an finite dimension sub-space of this infinite vectorial space. The difficulty could be to find the good norm (definition of a scalar product) so that this base could be orthonormal and that any real weather profile could be correctly projected upon this finite dimension sub-space.

With these reservations, we can see that figure 54 hereunder perfectly includes figure 52 which was describing this diagram centre (physical behaviour) ; and that the same figure 54 can be included in figure 55, itself only a variant of figure 30, page 89, which was the basis for appendix 4a matricial calculations. Therefore, an analogous optimization really seems possible even with a heat stock rational management, aimed to ever enhance the tower economical performance.

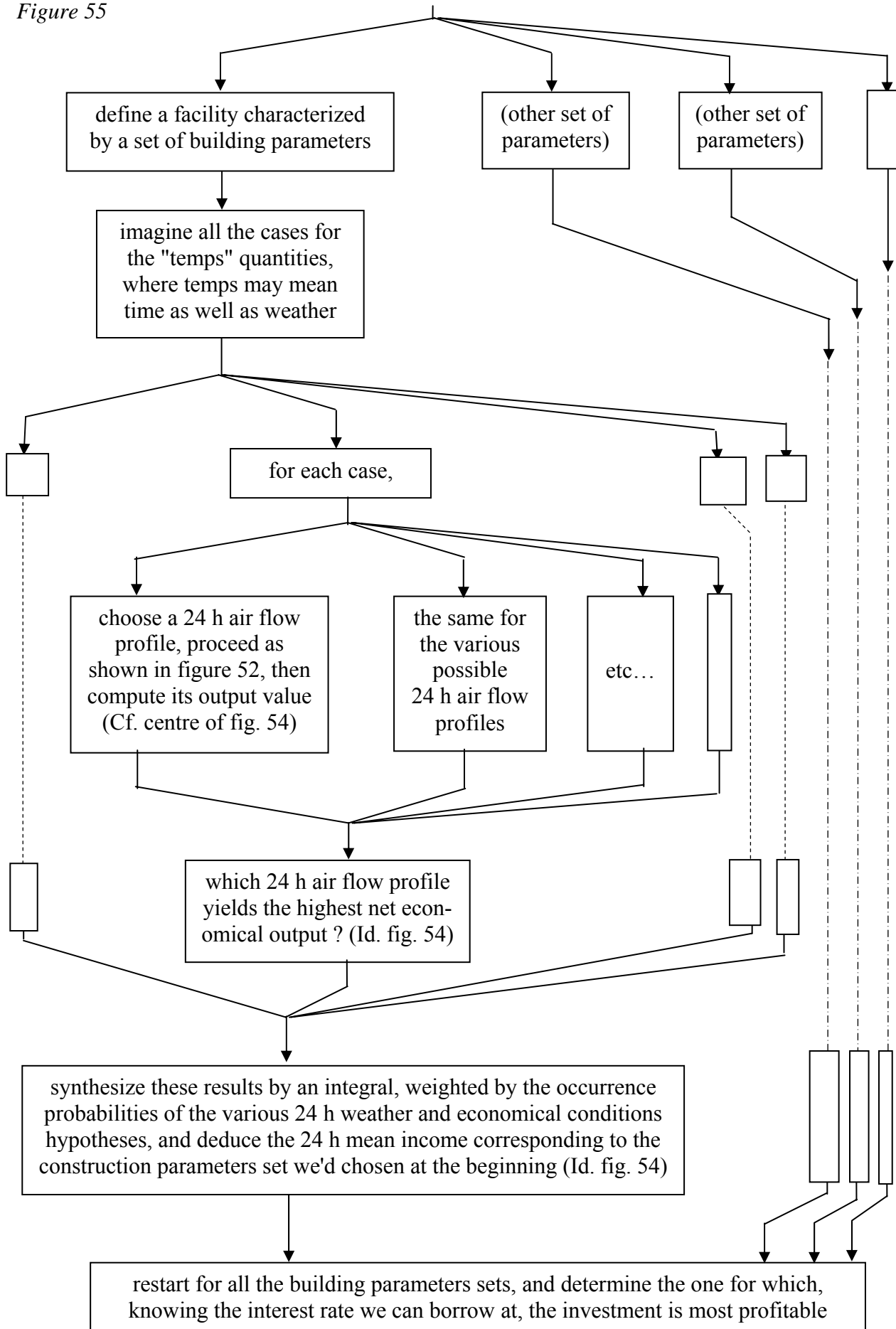
A last detail : when we write, in figure 54, "we know the kWh sale price", this is true for towers which provide a low part of the electrical power which is bought in a given region : they are "price-taker". But with the ambition to match the largest part of the power demand, we also should think about the opposite hypothesis : that they'd be "price-maker". In this case, we must begin by

the offer / demand equilibrium, i.e. the intercept of a power/price relation for the towers, and the same relation for the buyers : the difference is that the latter is an oblique curve, whilst, to optimize a "price-taker" system, we view this demand curve as a horizontal : price = cte. But we can say that when this question is on the agenda, it'll mean that the solar chimneys have proven their adequacy, and it'll be a pleasure to even more sophisticate the optimization process !



We weight these various results by the occurrence probabilities of the various 24 h weather and economical conditions hypotheses, and we get the mean income for the tower as it had been defined (construction parameters)

Figure 55



V.E Appendix 5 : Larsen's effect origin (Tel Aviv university Energy towers)

I wrote in pages 41-42 that "The inlet area is exactly equal to the outlet area, but their shapes are different (plane circle / cylinder slice). At the outlet, the velocities profile is approximately parabolic with respect to the altitude z ; if we call the highest 40 % "the parabola's top", they fill 40 % of the cylindrical diffuser's area.

At the inlet, there is a comparable parabolic profile, but with respect to the radius r . So, the central 40 % top of the {velocity / horizontal co-ordinate} curve, obeys the πr^2 law, and it accounts only for $(40\%)^2 = 16\%$ of the cross-section's area. As we have such maximum velocities only through a lower fraction of this area, they must be faster, for the total flow to be the same. ...

This modifies the energy balances that we can make, among entrance and exit, for the same total air flow, but with volume elements contributions which are now weighted by $\frac{1}{2}mv^2$: in the integral calculations, where v was low, the result is even lower than for the air flow, i.e. still near to 0, thus not very different ; but, where it is higher, this difference is amplified by this integration. So, the inlet's freely borrowed energy will be higher than what is handed back at the outlet. "

The precise calculation is the following :

$$\text{At the inlet, the velocity is: } v_{in}(r) = V_{o,in} \cdot \{1 - r^2/R_t^2\} \quad (92) ;$$

$$\text{at the outlet: } v_{out}(z) = V_{o,out} \cdot \{1 - (z-z_0)^2/z_0^2\} \quad (93)$$

As the inlet and outlet areas are the same : $\pi R_t^2 = 2\pi R_t \cdot 2z_0$, we can substitute z_0 by $R_t/4$ in (93), which yields :

$$v_{out}(z) = V_{o,out} \cdot \{1 - (4z-R_t)^2/R_t^2\} \quad (94)$$

The incoming and outgoing air flows are assumed to be identical in volume¹³⁹, so that :

$$\int_0^{R_t} v_{in} \cdot 2\pi r dr = \int_0^{R_t/2} v_{out} \cdot 2\pi R_t dz = 2 \int_0^{R_t/4} v_{out} \cdot 2\pi R_t dz \quad (95)$$

$$\text{hence : } \int V_{o,in} \cdot \{1 - r^2/R_t^2\} 2\pi r \cdot dr = 2 \int V_{o,out} \cdot \{1 - (4z-R_t)^2/R_t^2\} 2\pi R_t \cdot d(4z)/4$$

$$V_{o,in} \int \{d(r^2/2) - d(r^4/4R_t^2)\} = 2R_t V_{o,out} \int \{ dz - d((4z-R_t)^3/12 \cdot R_t^2)\}.$$

With the integration intervals $[0, R_t]$ and $[0, R_t/4]$, this yields :

$$V_{o,in} \cdot \{R_t^2/2 - R_t^4/4R_t^2\} = 2R_t V_{o,out} \cdot \{ R_t/4 - (R_t)^3/12R_t^2\}, \text{ i.e. : } R_t V_{o,in} /4 = R_t V_{o,out} /3 \quad (96)$$

which confirms that the incoming peak value is higher than the outgoing one.

¹³⁹ This "error" also takes part in the Larsen's effect generation, Cf. p. 43, 2nd and 3rd §.

We can now compute the incoming and outgoing kinetic energies. The previously used products of a velocity and an areal element, came in fact from the volume element : $d^3V = v.dt.d^2S$. Its mass is $\rho.d^3V$, thus its kinetic energy will be $\frac{1}{2} \rho.d^3V.v^2 = \frac{1}{2} \rho.v.dt.d^2S.v^2 = \frac{1}{2} \rho.dt.d^2S.v^3$. Still with the same $\rho = \text{cst}$ assumption, we can simplify the terms which will be the same at the inlet and at the outlet, and we'll only have to compare integrals with $v^3.dS$ instead of the $v.dS$ we had in (95) : this is the precise meaning of the idea of "weighting this integral by v^2 ".

$$\text{So, we'll have to compare : } E_{in} = \int_0^{R_t} v_{in}^3 \cdot 2\pi r dr \quad \text{and} \quad E_{out} = 2 \int_0^{R_t/4} v_{out}^3 \cdot 2\pi R_t dz \quad (97)$$

$$\text{or : } \int V_{o,in}^3 \cdot \{1 - r^2/R_t^2\}^3 \cdot 2\pi r.dr \quad \text{and} \quad 2 \int V_{o,out}^3 \cdot \{1 - (4z-R_t)^2/R_t^2\}^3 \cdot 2\pi R_t.dz \quad (98)$$

From (96), the comparison is the same if we substitute $V_{o,in}$ by 4 and $V_{o,out}$ by 3, so we're left with :

$$64 \int \{1 - r^2/R_t^2\}^3 \cdot r.dr \quad \text{and} \quad 54 R_t \int \{1 - (4z-R_t)^2/R_t^2\}^3 \cdot d((4z- R_t)/4) \quad (99),$$

or (with the change of variant : $4z- R_t = u$) :

$$64 \int \{r - 3r^3/R_t^2 + 3r^5/R_t^4 - r^7/R_t^6\}.dr \quad \text{and} \quad 54 R_t \int \{1 - 3u^2/R_t^2 + 3r^4/R_t^4 - r^6/R_t^6\}.d(u/4)$$

Finding the primitives isn't difficult, and, thanks to the change of variant, the integration intervals will be $[0,R_t]$ for both integrals, so that we finally have to compare :

$$64 \{R_t^2/2 - 3R_t^2/4 + 3R_t^2/6 - R_t^2/8\} \quad \text{and} \quad (27R_t/2) \{R_t - 3R_t/3 + 3R_t/5 - R_t/7\}$$

$$\text{i.e. : } 64R_t^2/8 \quad \text{and} \quad (27R_t/2) \{16R_t/35\}, \text{ or finally :}$$

$$8 R_t^2 \quad \text{and} \quad 8 \cdot \{27R_t^2/35\} \quad (100)$$

The left-hand term is clearly higher than the right-hand one, so we have precisely established, as announced, that, although a first integral calculation has been done to equate the volume flows at the inlet and the outlet, whose areas are also equal, the v^2 -weighted integrals differ, the inlet being around 30 % higher than the outlet.

From a physical point of view, this shows that, from the boundary conditions the authors have put in their algorithms, an artefact has been generated which is equivalent to borrowing a 130 energy and handing back only 100 at the outlet. This is exactly the origin of Larsen's effect which, for nominal values, generates very high power output figures, and, for slightly different values of sensitive parameters (tower height, droplets radius, and probably inlet/outlet areas ratio), leads to computational instability.

V.F Appendix 6 : Ideas for further studies

V.F.1 Appendix 6-a - Droplets jets physics and optimization in an energy tower

As we saw page 66, if we want to define the characteristics of the water sprayers we'll set at an energy tower top, we must choose between contradictory requirements :

- for an efficient water evaporation, so that the air can be quickly cooled down and weigh on the turbines, we need tiny droplets ;

- but, if we don't want millions of sprayers, the water jets must have a large range and, in order not to waste too much initial kinetic energy, they mustn't be too quickly slowed down by the air. This is possible, either if they don't break up too early in droplets (is this realistic is an air flow around 50 m/s ?), or if these droplets are large enough ;

- it would probably be necessary to give the droplets quite the same size, to avoid that some of them "fall" faster than others, catch them up, and that their coalescence reduce the lot's evaporation area ("falling" is not only gravity, but also the inertia they oppose to the air turbulence); this problem is self-maintained : coalescence resulting droplets would have an even greater mass difference with the smallest, so their cannibalism will keep growing, unless it never begins ; hence, the usefulness of a precise initial calibration ;

- this calibration, from well defined sprayer holes, could be incrust sensitive ; the same for the generation of perfectly cylindrical jets at the sprayer exit : incrusts could turn them less regular ; but frequent cleaning would generate high expenses ;

- and we'd avoid that some air zones become very droplet-rich while others would be far from the nearest droplet.

We can use the following parameters :

- those we spontaneously consider : holes size, water pressure,

- or less spontaneously : water jets inclination to the vertical, sprayer movement (notably rotation).

First examine these two latter parameters' action in a motionless air. Gravity accelerates an initially horizontal or downwards jet, so that it stretches, which increases its fragmentation risk : it will probably occur at quite the same distance for all the initially comparable jets. The same for rotation, which, besides, is probably useful for a good droplets dispersion : the jet takes a spiral shape, with, again, a stretching effect, and thus fragmentation.

Opposite, an upwards jet without much rotation first slows down, which increases its cross-section area ; it's a good thing if we want to delay its fragmentation, but with a risk of controllability crisis : with sensitive initial conditions, fragmentation could take place either just at the beginning, or much later, with very different results for the droplets ranges and even sizes.

Interaction with an air flow complicates the problem. An accelerating fluid (like the air above the tower, as it converges from every direction to get into it) doesn't seem to develop much turbulence, contrarily to a decelerating one ; but, perhaps, could there remain some, as Reynolds's number is still high ? With what consequences ? Simply the fact that the air's velocity and direction will be neither homogeneous nor constant ? Or will micro-swirls be able to distort the water jets ?

Could we also have, through mechanisms more or less comparable to Kelvin-Helmoltz's instabilities, an interaction between an air flow, even a laminar one, and a water jet, like what happens when air is blown into a musical instrument and interacts with its reed ? How much can a water jet which isn't yet broken up in droplets, and whose cylindrical shape is still stabilised by the surface tension, behave like an "elastic" object such as a reed ?

Liquid jets breaking up studies, both theoretical ¹⁴⁰ and experimental, probably already exist but perhaps mainly about other fluids (fuel-oil in injection engines). The main difficulty is to define the best statistical frame in which we'll describe the system, and, so far, it may not have been done with most satisfying results.

V.F.2 Appendix 6-b - Substituting the many turboalternators and their concurrent horizontal axes, by only one, with a vertical axis, as a circular "sailing train"

From what we saw in page 7, the air mechanical energy conversion into electrical power doesn't raise much theoretical questions : contrarily to wind turbines which probably need costly gearing up devices, the tower turbines can rotate fast enough to spare such an expense.

But the current projects bear the same cost factor as all the systems with the same symmetry as a plane or boat screw, i.e. if the rotation axis and the fluid movement are parallel. The fluid power harvesting system, which is perpendicular to this movement, is also perpendicular to its own symmetry axis, hence belongs to the "disk" category : it's made of points whose distance to the axis, r , is variable. So, these points have r -dependent tangential velocities, contrarily to the fluid.

¹⁴⁰ The cylindrical shape isn't the absolute minimum of a liquid's area, as a division in drops yields a lower area, but infinitesimal variations of this cylindrical shape probably increase its area, so that it is stable as long as it doesn't undergo too large oscillations ; in some cases, a fragmentation back-spreading from downstream, may destabilize the upstream jet.

To have a good efficiency, the quotient of the screw's and the fluid's velocities must command the angle between the blade surface and the disk's plan. That's why this angle varies with respect to r (the blades inclination to the wind must be low at the centre, where a turbine point's velocity is low, and higher at the periphery, as it moves faster), and why any screw has a "buckled" shape, which needs costly sheet-metal work (widely meant : wind turbines blades are now made from polymerised composite materials, but their shape is still buckled and they're probably less simple to make as if they were plane).

Solar chimneys, as well as to energy towers or solar-tower-like steam towers, are lucky enough to have turbines just where the flowing air must anyway undergo a 90° direction change. This opportunity to escape from the boat screw symmetry isn't taken by the Australian project and its 32 turbo-alternators with radial-horizontal axes rotating disks. However, it was possible, with a cylindrical geometry such as in the drawing hereunder :

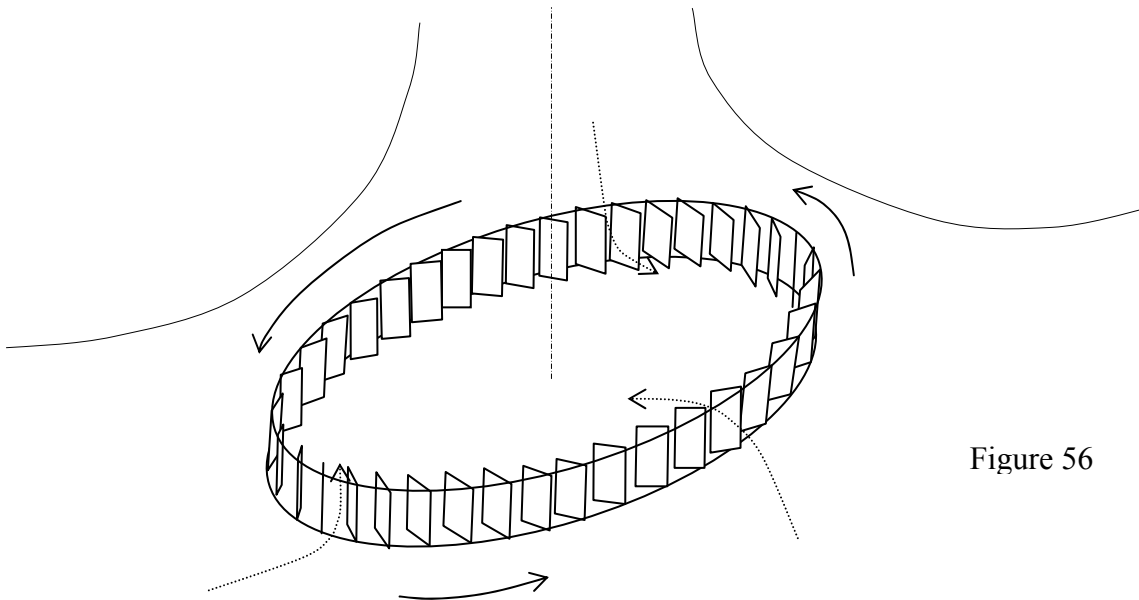


Figure 56

We've got now only one turbine, with a cylindrical shape (occupying more or less the same room), and rotating round the whole tower vertical axis. It looks like a "circular sailing train", and analyses as a turbo-alternator with a great many pairs of magnetic poles (still without gearing up).

The conversion into electrical power takes place, all over the circumference, in the ground (and possibly in the ceiling) where the induced circuit lies. The inductor is solidly linked to the "train", also on the whole circle (it isn't made from one locomotive and wagons, all the wagons are electromechanically active).

Would such a train, around 1 km long, and its track, be too expensive ? We can remember the German magnetic levitation train project, which was also magnetically propelled : it was a linear synchronous engine with a much longer induced circuit than here.

Another comparison, with the current project's turbines. Any electrical machine's economic efficiency depends on the rotor and stator relative velocity. If the turbine is fast enough, as in the current project, we can try to avoid a costly gearing up, and have a all-in turbo-alternator. Thus the alternator's angular velocity is the same as the turbine's. Then, in order not to lose too much linear velocity, the inductor radius mustn't be too short, compared to the mean distance from the axis to the blades.

But, if we add up the circumferences which are described by the blade middles of the current project's 32 turbines, we'll get a perfectly comparable value (even higher) than the perimeter of the unique turbine we propose here. So, a "circular sailing train" doesn't imply a greater circumference for the air gap, for the inductor on one of its sides, and for the induced circuit on the other, than more classical turbines, unless they accept to gear up or to have a lower velocity for the induced electromotive field.

So, this sailing train is not bad for what concerns the direct conversion of its rotation movement into electrical power. Therefore, we can stress its theoretical advantage for the conversion of the air movement into train rotation : the sails, which can be simple metal rectangles (a dozen years ago, there were projects of merchant boats with metallic sails, profiled like aeroplane wings, and engine-piloted¹⁴¹). This generates economies : we no longer need non developable surfaces which require sheet-metal work ; we can transfer the stresses through mainly tension working elements (cables, ...).

It might also help to vary these blade-sails orientation to adapt to variable air velocities (Cf. page 94, the middle §). We can't, by turning a buckled screw blade by x° , vary in the same proportions a $\text{tg}(\alpha) = 3$ just near the axis, and a $\text{tg}(\alpha) = 0.2$ far from it. Here, as the whole sail has the same inclination to the air flow, it could be fine tuned.

Finally, the turbines geometry could perturb the air flow : upstream, we must divide it into 32 pieces, and adjust them to the turbines circular shape ; downstream, the turbine outgoing air has undergone, unless we build a correcting device, the turbine reaction torque, which will give it a rotation movement and, combined with the 31 other air flows, will generate friction and perturbing swirls. This won't let an optimum flow at the tower bottom.

Here, the equivalent movement will be a vertical axis rotation : no friction risk among neighbouring swirls. And even a useful rotation, in one hypothesis : In III-C-2-b, page 125, about the rigid steam saturated air towers, we asked : "*How recover the gravitational energy of the 2 km up condensed water, and prevent these rain drops from falling down to the tower bottom and "eating" the growing uprising droplets (could a spiral internal structure be the solution) ?*" . The idea is, indeed, to develop, inside the tower, a supple structure with an endless screw shape. The rotation movement of the sailing train outgoing (inwards) air, could easily be turned into an helical upwards movement ready to enter this vertical endless screw.

¹⁴¹ Wind power transmission to a wheeled vehicle moving in a perpendicular direction, through oblique panels, also exists in the "sailing karts" which recently appeared on beaches.

V.G Synthesis table

Main category	System components	Technical feasibility	⊕ and ∅ in economics	Localisation / electricity exports	Environmental assessment
Systems without gravity	Collector, water jets evaporation, pistons and turbine	⊕ : can be checked on a small prototype ∅ : gigantic "pistons"	High theoretical efficiency, but mainly by day, no heat storage → difficult to make the mechanical elements profitable	The distance between the massive production sites (very sunny deserts) and the massive consumption sites (developed countries or densely populated developing countries) generally lies between 3000 and 6000 km. Even more for the United States North-East. Few good sites. East-African Rift ; north from Tibet (China & Japan) : low sun in winter	Favourable impact (clouds, rain) but possible problems of hail-stones, collector shadowing
Gravity and solar collector systems (Solar chimneys)	1000 m solar tower (current Australian project)	Should be soon confirmed	Not very low, already studied costs ; the tourist income can't be generalized.		Against the general atmospheric circulation
	2000 or 3000 m towers and very large collectors	"suspended guy rods" "ribs collector"	The kWh cost could be divided by nearly 2		The impact is divided by 2 or more for the same electricity production
	Overpressured modifiable geometry towers, round a fix pole	As above ; very tall internal structure ; very important mobile elements	Also a large theoretical gain potential.		
	Uphill towers	"air penstock" (extension of the ribs collector principle)	Sure gains only for short ducts (abrupt slope)		
Latent heat and gravity systems	Energy towers : water sprayers at the tower top, turbines, diffuser	Incrust risk, need of an enhanced coalescence : two reasons to use not too tiny droplets	Quite free resource, allowing a high air flow (mpp) but the facilities are not used 24h/24 or 365j/365 → problem if the turbines are still expensive	As for the collector systems	Creates a slightly salted cool moist wind. Supports the global atmospheric circulation
	Water freezing warms the polar air	⊕ : the change of state takes place on the ground ∅ : climatic conditions		Complementary with the hot deserts, but still at more than 2000 km from the clients	Globally stabilizes the world climate, in particular the thermohaline circulation.
	Mild, steam saturated and uprising air condensation with a high altitude difference	Artificial hurricanes : very particular constraints	Could be financed by insurance companies	Possibly complementary with others ; better in a "hydrogen economy"	The climate impact is the first goal ; check the sea level
		Very tall solar-tower-like structures	Quite perfectly complementary with energy towers, could turn a 1,000,000 km ² desert into a large oasis		

V.H Symbols

The main symbols which aren't explicitly defined by the text itself, are the following :

\propto : proportionality symbol ; ∇ , gradient (nabla) ; Δ , Laplacian

cst = constant ; mpp : abbreviation of "maximum power point",

A, B, C, D, E, F, G, H, I, J, M, P, R, T, V : in appendix 4-a, matrices, most of them being 2nd order partial derivatives of a financial function, with respect to various variants.

a, b, c : ad hoc coefficients to be adjusted, in particular in appendix 3

A : cross-section area, in particular in some quoted articles (m²)

C, C_t : dimensionless numbers which appear in the turbulent friction calculations

c_p : specific calorific capacity (J/K.kg)

D : diameters (m) ; D_{coll} : solar collector diameter ; D_t : tower diameter

E : steel Young's modulus (Pa) ; or potential electromotive force in electricity (V) ;

E' : electrical receptor's potential electromotive force

F : in a quoted publication (p. 34), cross-section area

g : gravity acceleration, $\approx 10 \text{ m/s}^2$

H (or h) : Heights : H_{coll} : solar collector height ; H_t or h_t : tower height ; p. 140 : Enthalpy (J)

k : thermal conductivity (W/Km) ; or dimensionless multiplying coefficient

I : electrical intensity (A) (otherwise : I = myself)

L : change of state latent heat (J/mol), or cable length (m)

M (in formula (3)) : air molar mass, $\approx 29 \text{ g/mol}$

n : number of moles, in particular gaseous (mol)

N : number of days (p. 83) ; in some quoted publications, N is the power output

P : represents either a pressure (Pa), or a power (mechanical or electrical , i.e. a work per second, in W) ; page 103, a cable's weight (N)

P_a : atmospheric pressure by the ground

P_{dow} : air pressure downstream the turbine

P_h : atmospheric pressure at the tower's top

Q : heat quantity (J) ; in a quoted publication, Q is a volume air flow (m^3/s)

r : variable radius (m) ; R or r_{coll} : solar collector radius ; R or r_t : tower radius

R : perfect gases constant, 8.32 J/K.mol

S : area, often for a cross-section (m^2) ; in fig. 3, S is a solar energy flow (W/m^2)

s : curvilinear abscissa (m) ; in appendix 4 : total number of variants (dimensionless)

t : time (s)

T : p. 59-60, 102, a cable tension (N) ; but most often : absolute temperature, in K unless opposite mention ; in particular, in figures 2 and 46 :

T_o : solar collector incoming air temperature

T_{ups} : temperature upstream the turbine

T_{dow} : temperature downstream the turbine

T_{ex} : solar chimney outgoing air temperature (as in "exit")

T_h : outer air temperature at the tower top height

T_{gr} (fig 52) : ground temperature

U : calorific capacities (uncertain unit, Cf. p. 49) ; or electrical voltage (V)

V : volume of a gas (m^3) ; sometimes, velocity (m/s)

v , and sometimes w : velocity (m/s)

W : work (J)

x : abscissa (m) ; or dimensionless number, in particular in a 1-x coefficient

z : altitude (m)

α, β : angles (rad) ; dimensionless ratios or exponents

γ : c_p/c_v quotient for a perfect gas : $\gamma = 1.4$ for the air.

Φ : voluminal flow (m^3/s)

ρ : voluminal mass (kg/m^3)

λ : dry air adiabatic temperature lapse rate, $\approx 10\text{K/km}$; or cable lineal mass (p. 59-60)

η : thermodynamic efficiency (dimensionless)

ν : cinematic viscosity coefficient ($\nu = \mu / \rho$, in m^2/s , where μ is the dynamic viscosity) ; either laminar, or its turbulent equivalent.

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