Sustainable Electricity Generation with Solar Updraft Towers

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Summary

Present electricity generation using fossil fuels is damaging the environment and is not sustainable, whereas solar radiation is an inexhaustible source of energy. Harnessed at reasonable costs, it can provide prosperity and a livable environment for mankind. Solar updraft towers – sometimes also called 'solar chimneys' – promise sustainable solar electricity at low costs. Solar updraft towers are solar thermal power plants utilizing a combination of a solar air collector and a central updraft tube to generate a convective flow which drives pressure staged turbines to generate electricity.

Introduction

Current energy provision systems based on exhaustible fuels like coal, hydrocarbons and uranium are damaging the environment and are not sustainable. Increasing prices due to limited resources and rising demand pose serious problems even to rich countries. *Fig. 1* shows the historic production rate of fossil hydrocarbons and an extrapolation into the future. A drastic production decrease in the near future is clearly visible. Experts are still discussing the exact position of the peak controversially, but not its existence. Production is already declining in some oil fields, e.g. in the North Sea [1].

Poverty, population explosion and migration are, amongst other reasons, also a consequence of insufficient energy supply and high energy costs. According to a study of the International Energy Agency about 1,6 bn people have no access to electric energy, and about 2,4 bn have to rely on biomass for cooking and heating, and the numbers are increasing [2]. All these fellow human beings want to, and should be able to, use electricity in the future. Hence demand for electricity will dramatically increase, especially in developing and emerging nations. It would be very shortsighted to rely on coal and oil or even nuclear power here. A clean inexhaustible source of energy is needed: the sun.

The Solar Updraft Tower

Solar energy can be used in various indirect (biomass, hydro-power, wind) and direct forms (solar thermal power, photovoltaic systems). Sensible technology for the wide use of renewable energy must be simple and reliable, accessible to the technologically less developed countries that are sunny and often have limited raw material resources. It should not need cooling water and it must be based on environmentally sound production from renewable, reusable or recyclable materials.

The solar updraft tower meets these conditions. Its three essential elements – solar air collector, chimney/tower, and wind turbine – have been familiar for centuries. Their combination to generate electricity has already been described in 1931 [3]. Currently several solar updraft tower projects are being developed, the most advanced being a 200 MW system in Australia.

The solar updraft tower's principle is shown in *Fig. 2*. Air is heated by solar radiation under a low circular transparent roof open at the periphery; the roof and the natural ground below it form an air collector. In the middle of the roof is a vertical tower with large air inlets at its base. The joint between the roof and the tower base is airtight. As hot air is lighter than cold air it rises up the tower. Suction from the tower then draws in more hot air from the collector, and cold air comes in from the outer perimeter. Continuous 24-hour operation can be achieved by placing tight water-filled tubes or bags under the roof. Since the heat capacity of water is about five to six times higher than that of soil, the water inside the tubes stores a large part of the daily solar heat and releases it during the night. Thus solar radiation causes a constant updraft in the tower. The energy contained in the updraft is converted into mechanical energy by pressure-staged turbines at the base of the tower, and into electrical energy by conventional generators [4, 5, 6].

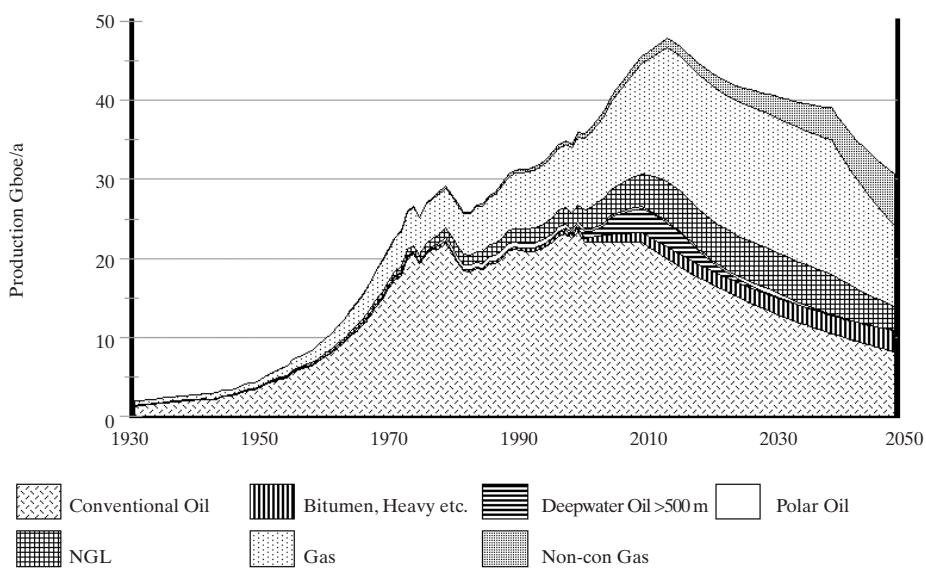

Fig. 1: Past and forecast production of all hydrocarbons under a base case scenario [1]. Unit of production is Gboe/a = 10^9 barrel of oil equivalents per year.

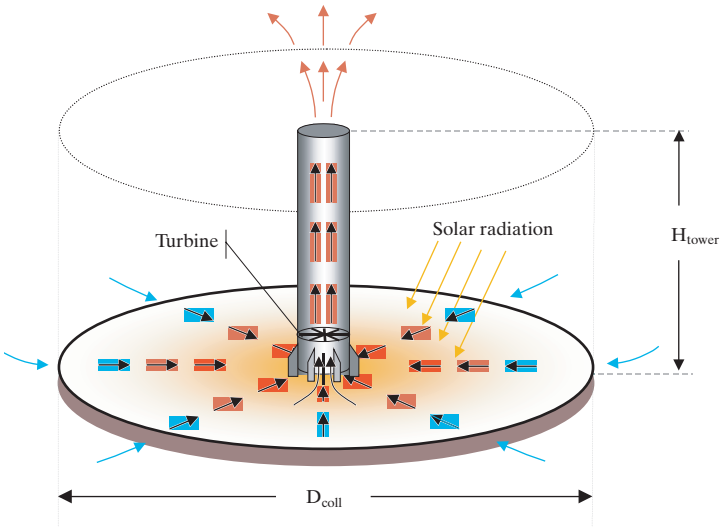

Fig. 2: Solar updraft tower principle

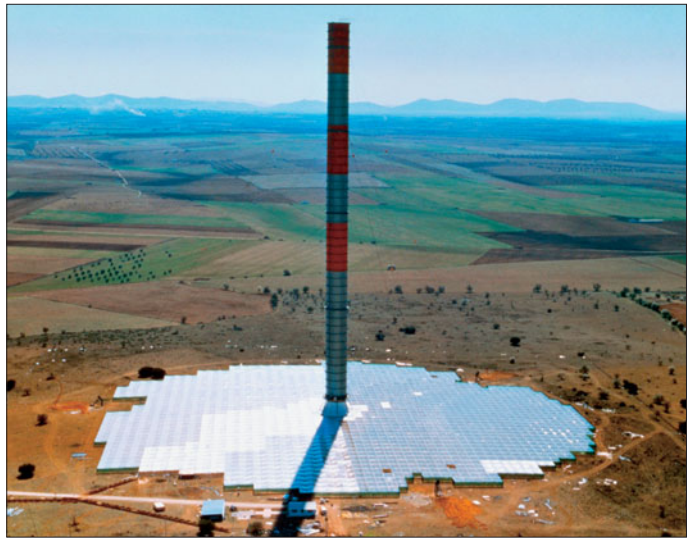

Fig. 3: Prototype Manzanares

Prototype

Detailed theoretical preliminary research and a wide range of wind tunnel experiments led to the establishment of an experimental plant with an output of 50 kW in Manzanares, about 150 km south of Madrid, in 1981/82. The tower height was about 200 m with a collector area of 45 000 m² [7, 8].

Completion of the construction phase in 1982 was followed by a successful experimental phase, the purpose of which was to demonstrate the operating principle of a solar updraft tower. The goals of this phase of the project were (1) to obtain data on the efficiency of the technology developed, (2) to demonstrate fully automatic, power-plant-like operation with a high degree of reliability, and (3) to record and analyze operational behavior and physical relationships on the basis of long-term measurements.

From mid 1986 to early 1989 the plant was run on a regular daily basis. During this 32 mo period the plant ran, fully automatically, an average of 8,9 h per day. In 1987 there were 3067 h with a solar global horizontal irradiation of over 150 W/m² at the Manzanares site. Total operation time of the plant with power to the grid was 3157 h, including 244 h of net positive power to the grid at night. Plant reliability was over 95%. The 5% non-operational period was due to automatic plant switch-off at the weekend when the grid occasionally failed. These results show that the system and its components are dependable and that the plant as a whole is capable of highly reliable operation. Thermodynamic inertia is a characteristic feature of the system, continuous operation throughout the day is possible, and for large systems even abrupt fluctuations in energy supply are effectively cushioned.

Large-Scale Solar Updraft Towers

Generally speaking, electrical power output of the solar updraft tower can be calculated as the solar energy input multiplied by the respective efficiencies of collector, tower and turbine(s).

(1) Solar energy input into the collector is the product of global solar radiation and collector area.

(2) Tower efficiency is proportional to tower height.

Combining (1) and (2) we find that solar updraft tower power output is proportional to collector area and tower height, i.e. proportional to the cylinder depicted in *Fig. 2*. Therefore the same output may result from a large tower with a small collector area and vice versa.

Engineering

Tower

Towers 1000 m high are a challenge, but they can be built today. The CN tower in Toronto, Canada, is 553 m high, the Taipei Financial Center, an office building, 508 m, and serious plans are being made for 2000 m skyscrapers in earthquake-ridden Japan. What is needed for a solar updraft tower is a simple, large diameter hollow cylinder, not particularly slender, and subject to very few demands in comparison with inhabited buildings. There are different ways of building this kind of tower: free-standing in reinforced concrete, guyed tubes with skin made of corrugated metal sheets, or also cable-net designs with cladding or membranes. The respective structural approaches are well known and have been used in cooling towers. If sufficient concrete aggregate materials are available and expected seismic acceleration is moderate, then reinforced concrete tubes are the most suitable design.

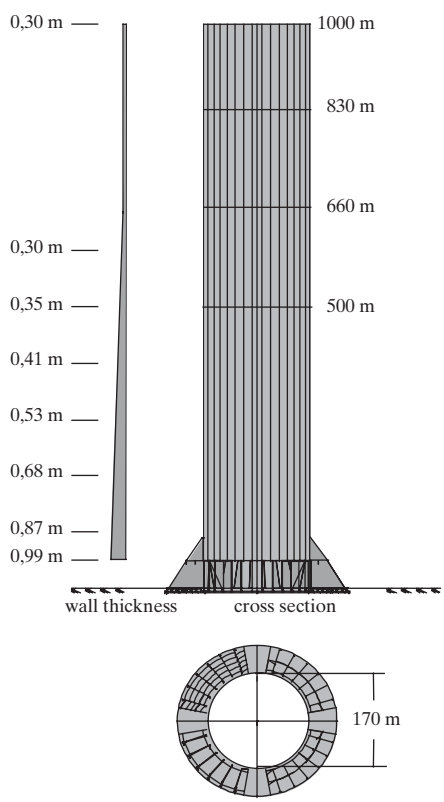

Fig. 4: Wall thickness of a tower 1000 m high, diameter 170 m (example).

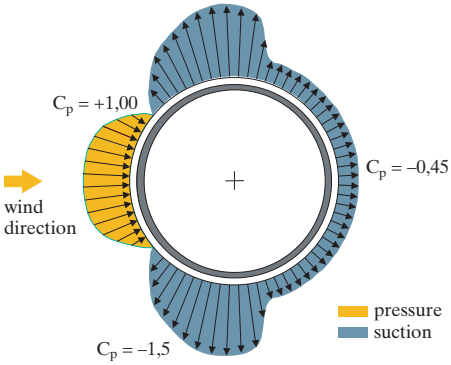

Fig. 5: Typical pressure/suction distribution around the circumference of a cylindrical tube.

Technologically speaking, the updraft towers are nothing but cylindrical natural draft cooling towers with large diameters and a height of up to 1000 m or even more. The wall thickness decreases from about 1 m just above the support on radial walls to 30 cm halfway up, then remaining constant all the way to the top (*Fig. 4*).

Such thin-walled tubes will oval due to the wind suction especially at the flanks (*Fig. 5*). This dramatically increases the meridional compressive and tensile stresses if compared with the linear bending stresses of a cantilevering beam (*Fig. 6*, top left). The resulting loss in stiffness, due to cracking of the reinforced concrete and the danger of buckling, limit the height of natural draft cooling towers to about 200 m. Detailed statical/structural research showed that it is appropriate to stiffen the updraft tower at several levels with cables arranged like spoked wheels within the tower, so that ovalling is efficiently counteracted and thinner walls can be used. The spoked wheels statically function like a bulkhead, but let the air stream pass through practically unhindered (*Fig. 7*).

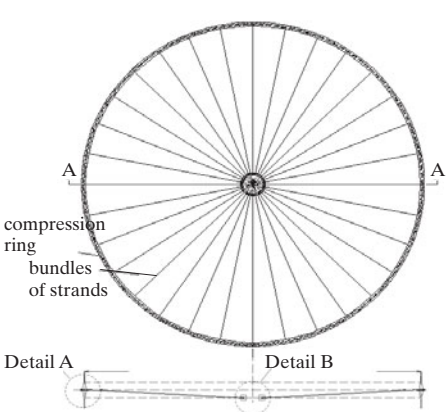

Fig. 6: Meridional stresses in the tower around its periphery and along its height depending on the number of stiffening spoked wheels (tower geometry according to Fig. 4).

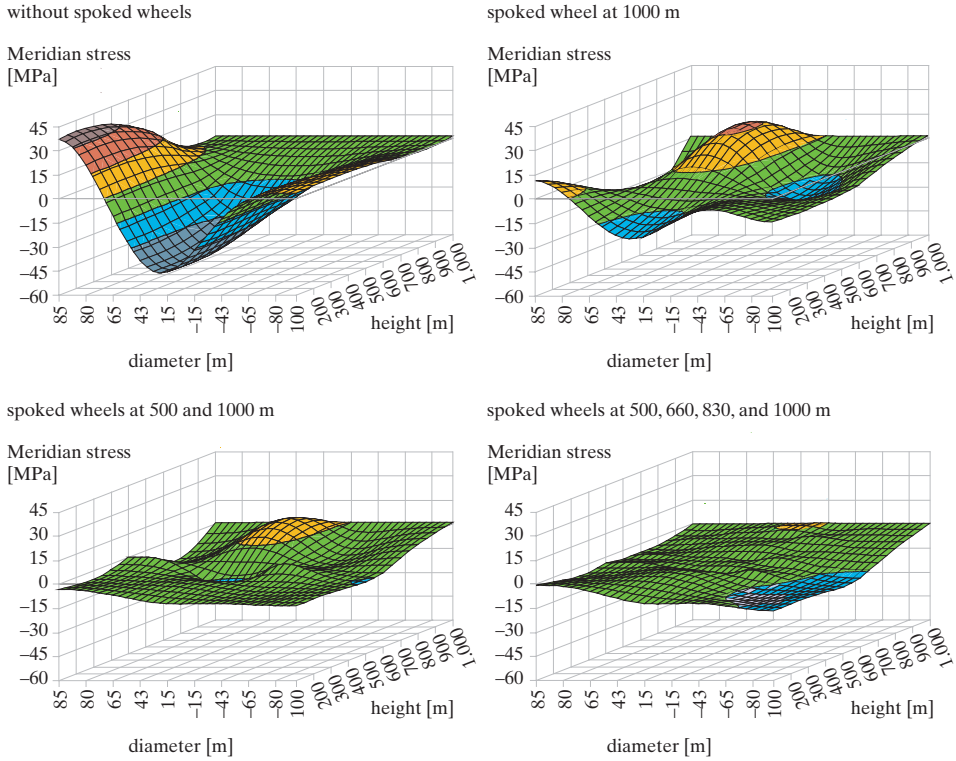

Fig. 7: Spoked wheel; the spokes are made of bundles of strands.

One spoked wheel at the top and, e.g., three more distributed over the height of the tower do reduce the meridional stresses to an extent that tension disappears completely, succumbed by the tube's dead load. Considering that the absolute volume under the stress diagrams in *Fig. 6* is somehow proportional to the consumption of concrete and reinforcing steel, one arrives at the conclusion that these spoked wheels make such high towers for solar updraft towers feasible. Perhaps the spoked wheels, nevertheless important, are the only really new feature of solar updraft towers compared to existing structures.

Collector

The air in a solar updraft tower power plant is heated by the greenhouse effect in a simple air collector, about 3 m high, consisting only of a glass, plastic-sheet or membrane roof, and the radiation absorbing ground beneath it (*Fig. 3, 8*). Only near the tower base does the roof rise to about 15 to 25 m to keep up the flow rate and thereby reduce friction losses, afterward redirecting the air upward. The collector roof allows the short-wave rays from the sun to pass through it while at the same time trapping the long-wave heat re-radiation from the heated soil. Thus the ground under the roof heats up and transfers its heat to the air flowing radially above it from the outside to the tower. The ground functions as a natural thermal storage, heating up during the day and releasing the day's heat at night. Thus the solar updraft tower works 24 h per day, albeit at significantly reduced output at night. If additional thermal storage capacity is desired to smoothen the electricity out-

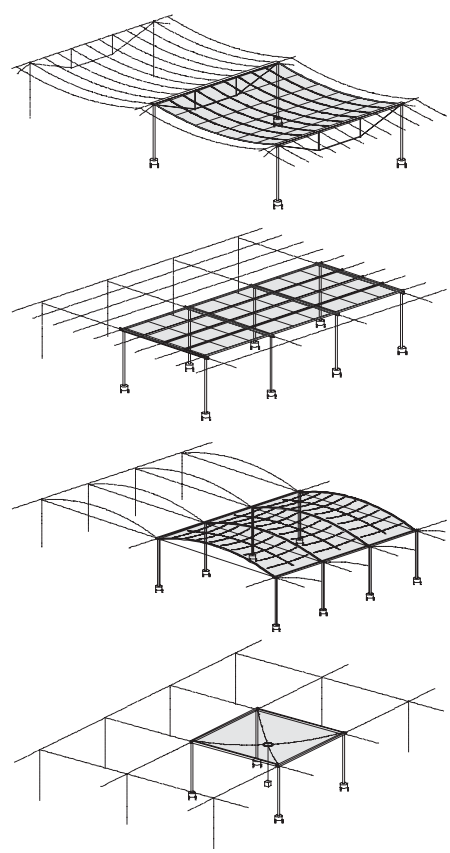

Fig. 8: Collector design options

Capacity	MW	5	30	100	200
tower height	m	550	750	1000	1000
tower diameter	m	45	70	110	120
collector diameter	m	1250	2900	4300	7000
electricity output [1]	GWh/a	14	99	320	680
[1] at a site with an annual global solar radiation of 2300 kWh/(m^2a)					

Table 1: Typical dimensions and electricity output for solar towers without additional thermal storage

Capacity	MW	5	30	100	200
tower cost	Mio. €	19	49	156	170
collector cost [1]	Mio. €	13	59	131	318
turbine cost	Mio. €	8	32	75	133
engineering, tests, misc.	Mio. €	5	16	40	42
total	**Mio. €**	**45**	**155**	**402**	**662**
annuity on investment	Mio. €/a	3,2	11,3	29,2	48,1
annual operation & maintenance cost	Mio. €/a	0,2	0,8	1,9	3,4
levelized electricity cost (LEC)[2]	**€/kWh**	**0,25**	**0,12**	**0,10**	**0,08**
[1] cost for unskilled labor assumed to be 18 €/h [2] at an interest rate of 6 % and a depreciation time of 30 years					

Table 2: Investment cost and Levelized Electricity Cost (LEC) for solar towers without additional thermal storage. LEC for solar towers with thermal storage are approtimately 10% less.

put curve, water filled black tubes are laid down side by side on the radiation absorbing soil under the collector. The tubes are filled with water once and remain closed thereafter, so that no evaporation can take place.

Turbines

For mechanical turbine design, it is possible to use a great deal of experience from hydro and wind power stations, cooling tower ventilation technology and the Manzanares solar updraft tower's years of operation. Although one single vertical axis turbine arranged at the base of the tower may appear to be the straightforward solution, current cost estimates are based on 24–36 horizontal axis turbines arranged concentrically at the periphery of the tower in order to utilize turbines of existing sizes – particularly with regard to rotor diameter. Additionally, this configuration offers redundancy and excellent partial load behavior, because during times of lower solar radiation and especially at night several turbines can be shut off while the rest operates under design conditions, and therefore at high efficiency. Aerodynamic design for entrance area and turbines was achieved by means of wind tunnel airflow experiments and computer fluid dynamics.

Investment Cost and Levelized Electricity Cost

Typical dimensions for selected solar updraft towers are given in *Table 1*. The numbers are based on typical material and construction costs. Based on specific costs and the dimensions from *Table 1*, investment costs were calculated. With the respective annual energy outputs from simulation runs, levelized electricity costs (LEC) are calculated using an interest rate of 6% and a depreciation time of 30 years (*Table 2*).

From *Table 2* it becomes obvious that LEC for a small 5 MW solar updraft tower are relatively high, comparable e.g. to a Photovoltaic-system. With increasing plant size, a significant reduction of electricity generation cost is associated, leading to LEC of 0,08 €/ kWh for a 200 MW plant in the given example at an interest rate of 6%. Further cost reduction will be achieved in countries with low labor costs.

Ecological Analysis

The two most interesting values in this context are greenhouse gas emissions, expressed in CO_2-equivalents, and energy payback time. The reduction of Greenhouse Gas (GHG) emissions and the saving of limited fossil resources is an explicit goal of governmental action today. To accomplish this task, the increased utilization of renewable energy technologies can be a major contributor. As no fuel is burned during operation, there are no greenhouse gas emissions due to operation of the solar updraft tower or other solar power plants. Still, emissions related to construction of the plant (due to the provision of building materials and the operation of construction machines) must be attributed to solar updraft tower electricity. Hence, for a fair comparison of various power plant types, a life cycle assessment (LCA) must be performed, which considers all material and energy streams related to construction, operation and dismantling of the power plant ('cradle to grave'). Then the resulting sums are divided by the produced electricity to obtain specific numbers, e.g. kg of greenhouse gas emissions per kWh. The results of such a LCA (*Fig. 9*) show that specific GHG emissions of a large scale solar updraft tower are about 60g/kWh_{el}, compared to roughly 1000 g/kWh_{el} of a coal fired power plant, i.e. about 94% less!

Energy payback time is defined as the period for which the power plant has to be in operation to save as much primary energy as was expended in plant construction. A look at this index shows that it only makes sense with renewable energy sources, as only with them is it possible to use less exhaustible energy than the amount of energy generated. Exhaustible-fuel plants (e.g. coal and nuclear power plants) always require more primary energy for construction and especially operation than the electrical energy generated by them (as they have an efficiency <1). To calculate the amount of primary energy saved, it is assumed here that "solar electricity" replaces electricity from fossil-fuel plants with a medium efficiency of 40%, i.e., 1 kWh (3,6 MJ) of solar power saves 2,5 kWh (9 MJ) of inexhaustible energy. After three years the solar updraft tower has paid back the energy invested in its construction, from then on, for at least another 80–100 years, it is a net source of clean electricity (*Fig. 9*).

Conclusion

A solar updraft tower generates electricity using direct and diffuse solar radiation. It is based on a simple principle, its physics are well understood. As thermodynamic efficiency increases with tower height, solar updraft towers must be large to generate electrici-

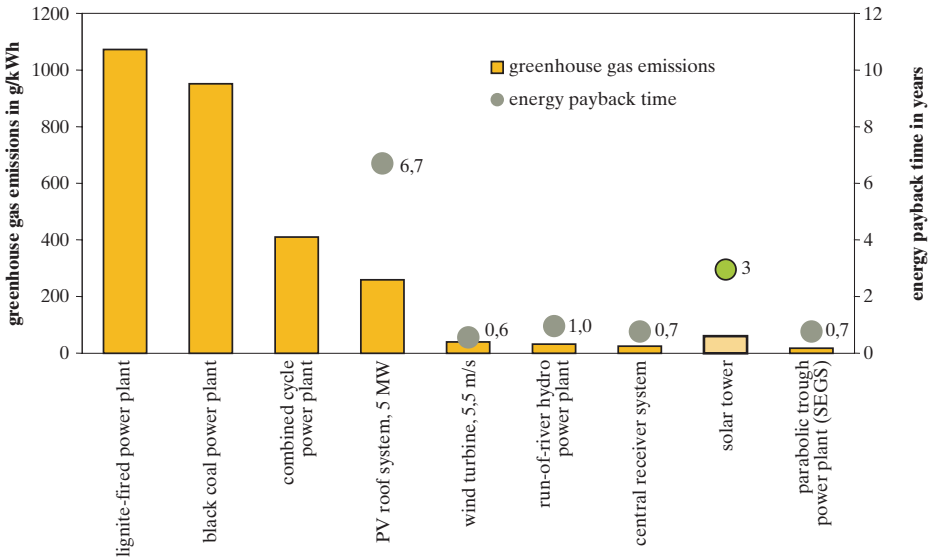

Fig. 9: Comparison of related greenhouse gas emissions and energy payback time (Sources: [9, 10, 11, 12], own calculations)

ty at competitive cost. Large power plants mean high investment cost, to a large extent due to the many construction workers required. This in turn means the creation of many jobs, an added value in the country itself. Solar updraft towers reduce the environmentally disastrous utilization of dwindling fossil fuels, while removing the need for costly imports of coal, oil, or gas which is especially beneficial for the developing countries releasing means for their development.

The construction of solar updraft towers is not associated with resource consumption; resources are merely bound for a certain time. As solar updraft towers mainly consist of concrete and glass, which is sand plus (self-generated) energy, they can reproduce themselves in the deserts – a truly sustainable source of energy.

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IABSE Declaration for Sustainable Development

The Permanent Committee approved the following declaration at its meeting of June 21, 1996, in Copenhagen, Denmark:

IABSE pledges to further the aims of sustainable development as defined by the United Nations World Commission on Environment and Development: *"Sustainable development meets the needs of the present without compromising the ability of future generations to meet their own needs."* IABSE recognises the interdependence of the planet's diverse ecosystems and their finite capacity to assimilate changes due to human activities. IABSE urges its members to identify and act to minimise potentially damaging environmental impact stemming from their work. In their professional activities, IABSE desires that its members promote:

– the full understanding of the interdisciplinary actions required to sustain and optimise the natural, built and socio-economic environment

– the increased use of renewable and recycled non-renewable materials in the construction and operation of structures

– the conscientious assessment of the environmental impact of projects, basing recommendations on environmental soundness.

IABSE members will urge the incorporation of environmental objectives into design, planning, construction and operational criteria. IABSE members will continue to educate themselves and their students on issues relating to sustainable development, and to freely transfer this knowledge to society. Finally, IABSE strongly encourages its members to decline association with engineering activities, in developed and in developing countries, that are contrary to sustainable development.