Buoyancy Driven Solar Engine

Summary

Warm air rises. In any air-filled configuration, open to the atmosphere, if part of the volume is heated, warm air will rise drawing ambient air from beneath to replace. If entry of air at the base of the configuration is restricted by a constriction/funnel/convergent nozzle, incoming air is accelerated by the geometric constraint. It may thus be possible to produce high air flow velocity using the buoyancy of warm air.

In this paper it is suggested that warm air from a solar absorber/collector flows via a warm air store into the atmosphere. This provides a suction force drawing ambient air from beneath into the absorber. Incoming air is channelled through a convergent nozzle where the narrower is the throat of the nozzle the higher is the air flow velocity. Calculations suggest that at UK maximum summer insolation an air flow velocity of 50 m/s can be achieved. If solar energy can be converted efficiently into the kinetic energy of air flow, this can be harnessed using an air/wind turbine to produce electricity.

No experimental work has been carried out. The author suggests a series of experiments that could validate the approach and describes possible working models. It is the author's belief that the 'buoyancy driven solar engine' outlined will allow conversion of solar energy into electricity with over 50% efficiency and that it is amenable to large scale application.

Introduction

Consider a loosely structured solar absorber inside a tall transparent cylinder as in Figure 1

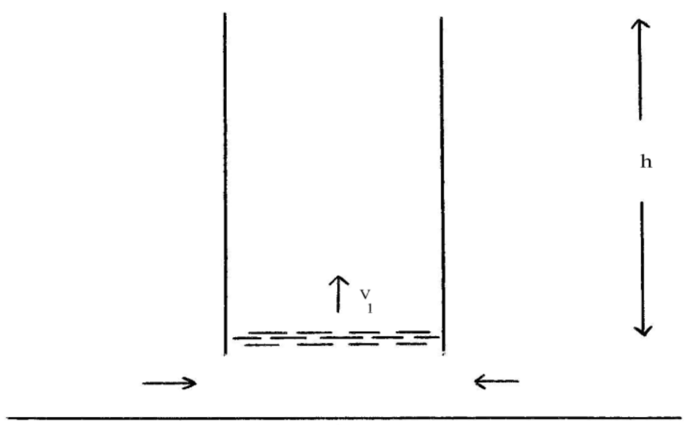


Figure 1

A gap is left between the glass cylinder and the ground to allow entry of ambient air. The absorber is made of metal coated with specialist solar absorber paint and is of a loose, open configuration to allow rapid heat transfer to neighbouring air. The absorber takes up incident solar energy with high efficiency, warming air in its vicinity which rises because of its buoyancy drawing in ambient air to replace. Consider that ambient temperature is T and that there is a gain in temperature ΔT as air travels through the absorber. The chimney above the absorber is then filled with air at a temperature of $T + \Delta T$. At constant insolation, air is drawn through the absorber and chimney with a velocity v_1 where

$$v_1^{\,2} = 2 \frac{\Delta T}{T} gh \qquad (1)$$

where h is the height of the cylinder and g the acceleration due to gravity.

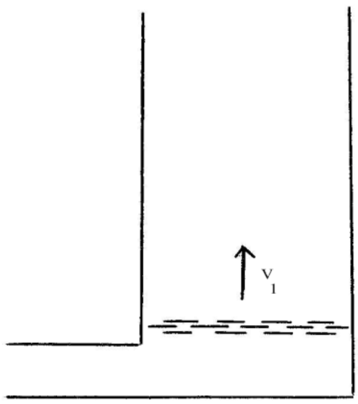


Figure 2

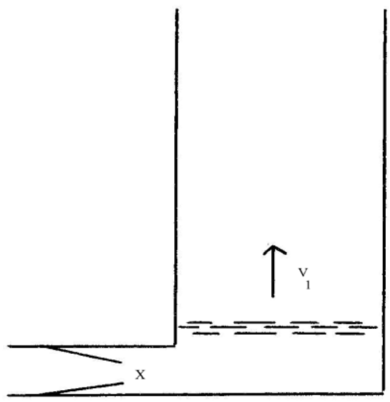


Figure 3

Now consider Figure 2. The solar absorber and glass chimney are as previously but the cylinder is sealed to the ground allowing only the air entry channel shown. The buoyancy of the warm air in the chimney again draws ambient air through the absorber with a velocity v_1 as in equation (1). Next consider restricting the air flow into the entry channel as in Figure 3. The values of h, ΔT and v_1 are as earlier. It will be acknowledged that the narrower is the funnel or constriction for incoming flow the greater will be the velocity at x the throat of the funnel. There is a danger that if the area of the absorber is very large, or if h is too low or if the constriction is very narrow, then atmospheric air from above the chimney will cause a back flow. To protect against this, the chimney is covered as in Figure 4 and has an exit air channel with a flap valve to prevent back flow.

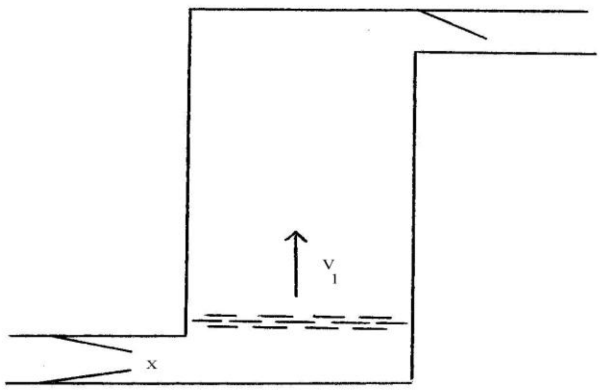
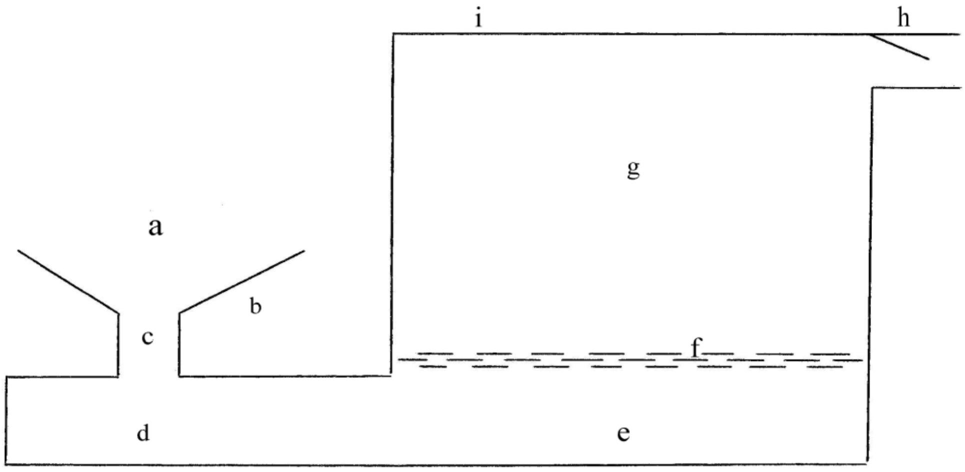


Figure 4

It is speculated that using this configuration it should be possible to accelerate incoming air to high velocity at x using the suction force provided by the buoyancy of air in the warm air store. Now consider Figure 5 where the funnel/constriction is replaced by a convergent nozzle.



a ambient air
b convergent nozzle
c throat of nozzle
d,e ambient air store
f solar absorber
g warm air store
h flap valve
i glass/perspex

Figure 5

Solar energy passes through the transparent containment (i) of the warm air store (g) and is taken up with high efficiency by the solar absorber (f). The absorber warms air in its neighbourhood which rises because of its buoyancy. This draws air from beneath (e) and in turn through the ambient air store (d). Ambient air (a) is thus drawn through the convergent nozzle (b) and through the throat of the nozzle (c) where it reaches high flow velocity. The flap valve (h) protects against backflow.

Physics of the Air Flow

Consider the solar absorber to have area A_1 m^2 and that insolation is I watts/m^2. Consider that ambient temperature is T °K and that air flow through the absorber has an average temperature rise ΔT. The warm air store is of height h metres. The velocity of air flow through the absorber v_1 m/s is given by

$$v_1^{\,2} = 2\,\frac{\Delta T}{T}\,gh \qquad (1)$$

where g is the acceleration due to gravity.

Consider that the cross-sectional area of the throat of the nozzle is A_2 m^2 and that the velocity of air flow through the throat of the nozzle is v_2 m/s. Constant mass flow requires that

$$v_1A_1 = v_2A_2 \qquad (2)$$

As ambient air is drawn into the convergent nozzle it acquires flow kinetic energy. This comes at the expense of its own internal energy. Thus incoming air flowing through the throat of the nozzle at (c) suffers a fall in temperature $\Delta T^{/}$ where

$$\frac{1}{2} v_2^{\,2} = C_p \Delta T^{/} \qquad (3)$$

where C_p is the specific heat of air in J/kg K.

In Figure 5 since no work-producing device is present, the high velocity flow from the nozzle (c) merely discharges into the ambient air store (d) generating turbulence. The kinetic energy is reconverted into internal energy and air enters the solar absorber from (e) at ambient temperature T.

There is one exceptional circumstance in the above model configuration where $\Delta T = \Delta T^{/}$. At this 'point of symmetry' the kinetic energy of the air flow through the throat of the nozzle is exactly equal to the amount of solar energy taken up by the absorber i.e.

$$\frac{1}{2} \rho A_2 v_2^{\,3} = I A_1 \qquad (4)$$

when ρ is the density of air in kg/m^3.

From (1) and (3) eliminate $\Delta T = \Delta T^{/}$ at this point of symmetry

$$\frac{T v_1^{\,2}}{2gh} = \frac{v_2^{\,2}}{2C_p}$$

$$h = \frac{TC_p}{g}\left[\frac{v_1}{v_2}\right]^2$$

From (2)

$$h = \frac{TC_p}{g}\left[\frac{A_2}{A_1}\right]^2$$

Consider $T = 300°$ $C_p = 1005$ J/kg K $g = 9.81$ m/s^2

$$h = \frac{300 \times 1005}{9.81}\left[\frac{A_2}{A_1}\right]^2$$

$$h = 30{,}734\left[\frac{A_2}{A_1}\right]^2$$

It should be noted that if $A_1 = A_2$ $h = 30{,}734$ metres which is in exact agreement with solar chimney theory. Table 1 is derived from the above equation.

A_1/A_2	h
10	307.3 m
40	19.2
100	3.07
200	0.77

Table 1

This gives the critical height for the warm air store at the 'point of symmetry' for different A_1/A_2 ratios. Consider the case where $A_1/A_2 = 100$ and $h = 3.07$ m then in equation (4)

$I = 750$ watts/m^2 at UK maximum summer insolation
$\rho = 1.177$ kg/m^3 at 300°K and atmospheric pressure

$$v_2^{\,3} = \frac{750 \times 100 \times 2}{1.177} = 127{,}483$$

$$v_2 = 50.32 \text{ m/s}$$

From equation (2)

$$v_1 = 0.50 \text{ m/s}$$

From equation (3)

$$\Delta T = \frac{50.32 \times 50.32}{2 \times 1005} = 1.26°C$$

The above calculation indicates that in the configuration described in Figure 5 with $A_1/A_2 = 100$ and a warm air store of height 3.07 metres, at UK maximum summer insolation, natural convection generates an air flow velocity of 0.50 m/s through the absorber and of 50.32 m/s (113 mph) through the throat of the nozzle. The temperature changes involved are remarkably low – a fall of 1.26°C as ambient air flows through the throat of the nozzle, its subsequent recovery to ambient from turbulence in the ambient air store and a gain of 1.26°C as air flows through the absorber. It is the buoyancy of this warm air above the absorber that drives the system.

Buoyancy driven solar engine (BDSE)

If there is a flow of air into the configuration described in Figure 5, it can be intercepted by a wind/air turbine and harnessed to produce electricity. The output of the turbine will be greatest if sited in the throat of the nozzle where air flow velocity is at its highest.

If the turbine absorbs some of the kinetic energy of the air flow then the temperature in the ambient air store will be below ambient, and the temperature in the warm air store is reduced, reducing buoyancy. Thus it would need to be compensated by having greater height.

It is the author's estimate that if the turbine had efficiency 50% then the height of the warm air store would need to be doubled compared to the 'point of symmetry'.

Wind turbines operating in the open air are subject to an upper efficiency limit of 59% (16/27 the Betz limit). Ducted turbines are not subject to this limit and have an efficiency of up to 80%. Wells turbines may also be suitable with a theoretical efficiency of up to 90%.

It is the author's estimate that if the turbine used had an efficiency of 80% then the height of the warm air store would need to be multiplied by 5.

Suggested Experiments

(1) **Air Flow/Temperature Measurement**

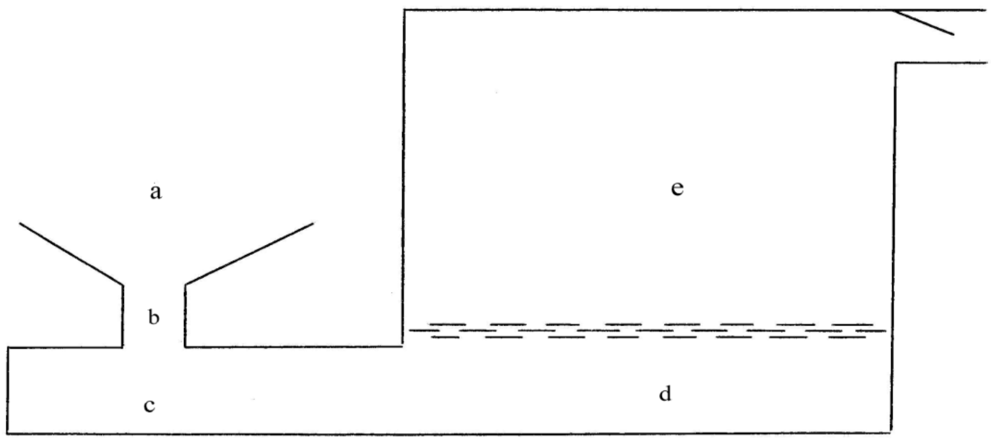


Figure 6

The author asks interested individuals to build a configuration as in Figure 6 of laboratory scale dimensions to assess/confirm the calculations above. The apparatus could be of about one metre dimensions as described later. Temperature and air flow measurements should be made at the points shown. It is expected that temperature $T_e > T_a = T_c = T_d > T_b$. Flow rate measurements should confirm low convection velocity in (e) but that this is multiplied by the ratio of cross sectional areas to give high flow rate at (b).

There are several variables now to investigate – time of day and seasonal variations, the influence of the height of the warm air store and the A_1/A_2 ratio. It should be possible to confirm that very high air flow velocities can be generated at (b), the throat of the nozzle.

(2) **Turbine/Electricity Generation**

When optimal conditions have been established above, it is suggested that an air turbine/wind turbine/Wells turbine be installed with its rotational plane in the throat of the nozzle. Try initially with the optimal A_1/A_2 and h values above. The turbine will take energy out of the system which will need to be compensated by a larger height for the warm air store. Experiments need to be conducted with the optimum height found above increased stepwise to maximise efficiency. It is the author's estimate that if the turbine has 50% efficiency the height for the 'point of symmetry' calculated earlier will need to be doubled.

Additional Comments

(1) Work done before energy input

In all energy conversion at power stations, the motor car, aircraft engine …. combustion produces heat, work is then extracted from the hot combustion products and waste heat dumped into the environment. The energy conversion suggested in this proposal is quite different – if one considers the flow of air – work is done by the turbine before the air is heated by the solar absorber. It is a case of exploiting one of nature's feedback mechanisms but this unusual feature of 'work done before energy input' may allow unusually high efficiency.

(2) Nature of solar absorber

The solar absorber has hitherto been described as of loose configuration and allowing easy air flow. Calculations indicate an extremely low value for ΔT as air flows through the absorber – just 1.26°C at UK maximum insolation. Thus it is vital that there is extremely efficient heat transfer from the absorber surface to the air flow. It is suggested that the absorber could be multi-layered or of metallic honeycomb construction coated with absorber paint. Alternatively it could be of similar construction to the heat exchanger that dissipates heat from a domestic refrigerator … a three dimensional cubic structure of thin metal plates that transfer heat efficiently to stagnant air. The height of the absorber is not a problem – it could be of one metre height but made of metal so that its temperature is uniform allowing the entire warm air store to be at temperature $T + \Delta T$. The metallic absorber is then coated with specialist absorber paint so that it takes up solar energy with over 90% efficiency.

(3) Support for convergent nozzle

Ambient air will be accelerated in the convergent nozzle to a velocity of up to 50 m/s over a very short distance. This implies very high "g" forces. Thus the convergent nozzle may need to be built of steel and have strong vertical support particularly around the throat of the nozzle.

(4) Alternative configurations

The author has drawn up several alternatives to the configurations shown in Figures 5 and 6 that should work by the same principles. In Figure 7 the solar absorber and warm air store are separated:

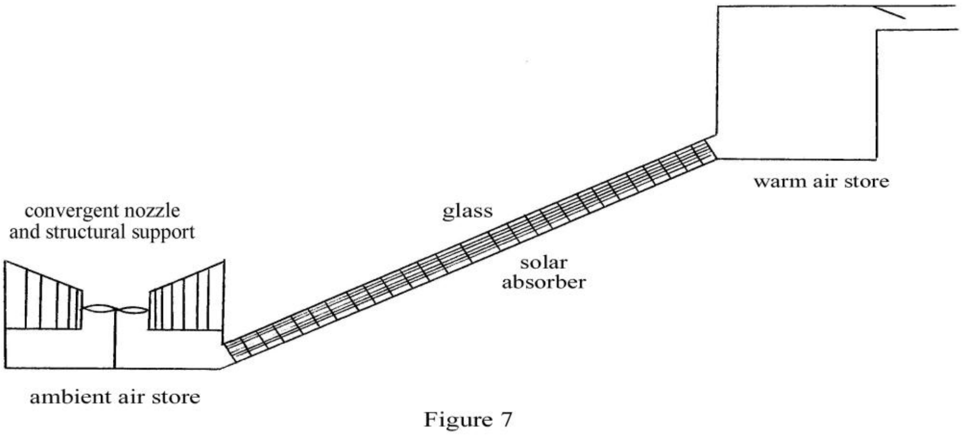


Figure 7

This configuration is based on British Patent Specification No. 15,576 (1904) by H. M Funke, M. P. Funke and E. G. Funke. Their theoretical proposal describes a large scale solar collector built on a South-facing hillside, the force of buoyancy being used to draw incoming air through an air engine.

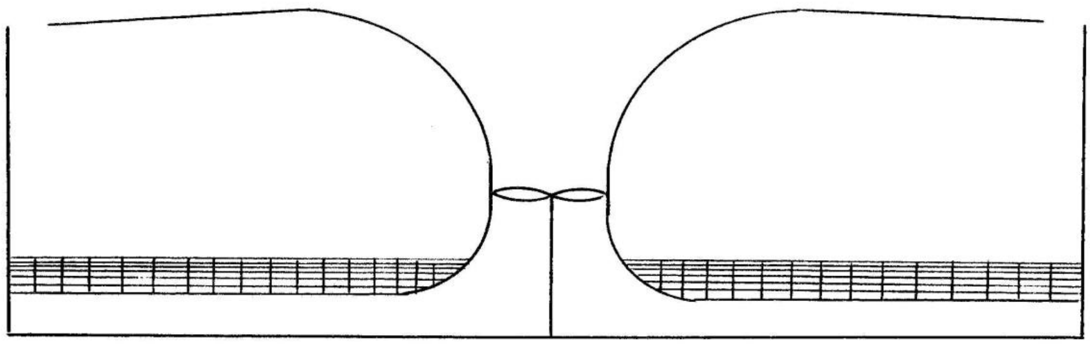


Figure 8

Figure 8 depicts a circular solar collector with transparent roof and sides with the nozzle and turbine for incoming air sited at the centre. The warm air store above and including the absorber provides buoyancy. The physics of the air flow is exactly as outlined earlier.

(5) Laboratory scale experiments

A model based on Figure 5 or Figure 8 could be used for preliminary laboratory work. If the solar absorber is of area 1 m^2 and warm air store of height 1 metre, the calculations leading to Table 1 indicate an A_1/A_2 ratio 175 and a diameter for the throat of the nozzle of 1 metre ÷ $\sqrt{175}$ = 7.6 cm. For insolation 750 watts/m^2 calculation gives v_2 61 m/s, v_1 0.35 m/s and ΔT 1.83°C. If the turbine has 50% efficiency the required height for the warm air store is increased to 2 metres. A maximum output of 375 watts would be expected.

If laboratory experiments proved successful, the above model could be the basis for a solar home system for rural dwellings in developing countries that have no electricity supply. The solar absorber could be increased to 4m^2, the height for the point of symmetry reduced to 0.5m to give a warm air store of height 1 metre. Calculations suggest an A_1/A_2 ratio 248 and diameter throat of nozzle 14.3cm. If the turbine has 50% efficiency then in warm countries with annualised average daily insolation of 6 kWh/m^2 the output of such a system would be 12 kWh/day.

(6) BDSE Prototype Commercial Scale

If early development work described above gave promising results, the model in Figure 8 could be scaled up for large scale generation of electricity using the buoyancy driven solar engine. A commercial prototype could have solar absorber diameter 10 metres, A_1/A_2 100 and throat of nozzle/turbine diameter 1 metre. Earlier calculations show the height at the 'point of symmetry' to be 3.07 metres.

Thus if the turbine has 50% efficiency it would need a warm air store of height 6 metres. In warm countries with day and night annualised average insolation of 250 watts/m^2 such a unit would have an average output of 3.14 x 5 x 5 x 0.5 x 250 watts = 9.8 kilowatts. If we assume electricity value $0.2 kWh it would produce electricity of total value $17,000 year.

(7) BDSE Large scale

The above prototype could be scaled up in stages, increasing the diameter of the absorber and turbine stepwise but maintaining A_1/A_2 100 so that the height of the warm air store remains at 6 metres. The possible prototype stages are illustrated below

diameter solar absorber (m)	10	20	50	100
diameter turbine (m)	1	2	5	10
average output (kW)	9.8	39	245	980

Table 2

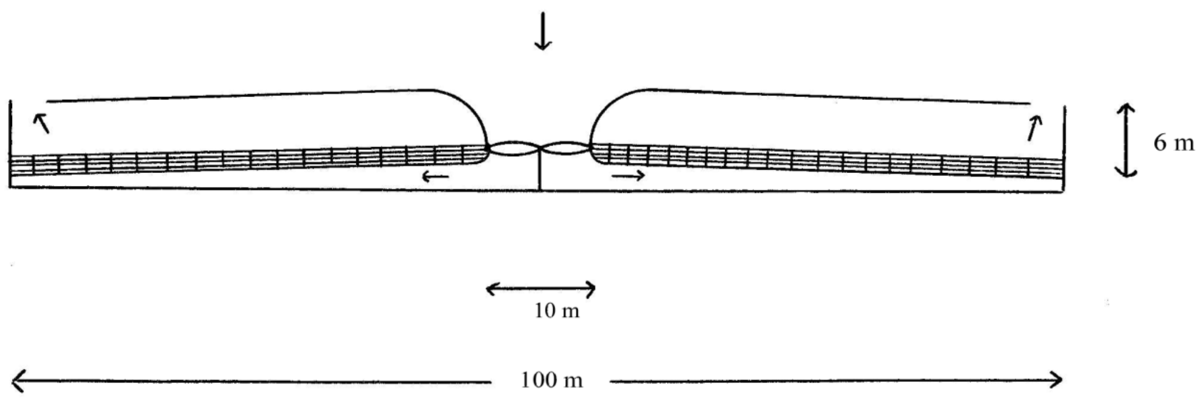


Figure 9

Figure 9 gives an approximate scale impression of the largest BDSE considered. The solar absorber is of diameter 100 metres under a sealed transparent roof which could be of glass, perspex or modern polymer as used in solar panels. The throat of the nozzle and turbine are of diameter 10 metres. The warm air store is of height 6 metres to allow for A_1/A_2 100, a point of symmetry height 3 metres and turbine efficiency 50%. Operating in a warm climate with average annualised daily insolation of 6 kWh/m^2 the large scale buoyancy driven solar engine described would have an AVERAGE output of 3.14 x 50 x 50 x 0.5 x 250 watts = 980 kilowatts. This is output averaged over 24 hours/day and 365 days/year assuming 50% efficiency. Assuming a value $0.2 kWh, total output would have a value of $1.7 million/year. Solar farms could be built of such modular units on low value desert or scrub land producing an average of about 1 Megawatt/hectare or 100 MW/km^2.

Conclusions

The proposal outlined in this paper is entirely theoretical. No experimental work has been conducted to test or verify. The only theoretical work in the literature that is accurately comparable to the proposal is the 1904 patent by Funke, Funke and Funke. This elaborates the broad principles with good practical detail but includes no calculation or experimental results.

The author requests that experimental work be carried out at a university department, energy research institute or industrial company to validate, assess and, if found promising, develop the proposal. Experimental approaches are suggested.

It is the author's belief that the buoyancy driven solar engine will allow the conversion of solar energy into electricity with an overall efficiency of over 50% and that it is amenable to large scale application.

Dr Alan Williams *May 2008*