SOLAR ENERGY CONVERSION

By

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ABSTRACT

The paper presents a survey for the methods of generating the electric energy from the solar energy. These methods are devided according to the influence of incident light on the different materials into direct and indirect methods. In the first, the solar energy is converted directly to electricity by means of solar cells, without any byproducts and without any moving parts. The indirect conversion of solar energy into electricity is done through intermediate stage, such as thermal, mechanical and chemical. Each of these methods is discussed in details and comparison between them is done regarding the conversion efficiency.

1 . INTRODUCTION

The world rate of use of electrical energy has increased from 0.029 x 10^{14} kwh/year in 1850, to 0.498 x 10^{14} kwh/year in 1970, to 0.7 x 10^{14} kwh in 1977, to an estimated rate of 0.844 x 10^{14} kwh in 1980 [3] . Also, sharp rise occurs in fuel prices during the last years due to that fossil reserves are finite and diminshing fast. So, the exis nce of an energy source crisis has become all too clear his seventh decade of the twentieth century. The demand and the fast decreasing of fuel reser tensive search for obtaining new and for the future.

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The solar energy is the chief alternative energy source, because each hour the earth receives 1.73×10^{14} kwh of energy from the sun. Over one year, corresponds to 15177×10^{14} kwh [3] , this is equivalent to about 20000 times the current used sources of energy at the present time [10] . The some of this energy is reflected and used in evaporation of water from seas, lakes and rivers. The remainder, about of 8865×10^{14} kwh, converted into heat, from which the mechanical power can be produced by the solar heat engines. Also, the solar cells converts a fraction of the energy contained in sunlight directly to electric energy. At the present time, the best method for solar energy conversion into electricity is photovoltaic conversion by using solar cells. The solar cell is an electronic device made from semiconductor and it is not a heat engine. So, it is not limited by carnot efficiency factor. Hence, out of the different energy sources, only the solar energy source is best energy source for the future.

2. DIRECT CONVERSION

The solar energy is converted directly to electricity by means of solar cells. This depends mainly on the photoelectric effect, which includes :

(1) The generation of electron-hole pairs in semiconductors subjected to solar radiation. This is known as the internal photoelectric effect and is exploited in the photovoltaic conversion of solar energy into electricity.

(2) The liberation of electrons from a metalic surface under the influence of light, which is known as the external photoelectric effect and is exploited in the photoemissive and the photogalvanic effects. The photoemissive effect is the ejection of electrons from the surface of a solid material by incident solar radiation. But, when aqueous solutions of some with suitable reducing agents are illuminated, the red- ent reduces the dye by transferring an electron to it,

this phenomenon is called the photogalvanic effect.

Consequently, the direct conversion of solar energy into electricity can be subdevided according to the photoelectric effects into three methods; photovoltaic, photoemissive and photogalvanic conversion.

2.1 Photovoltaic Conversion

The photovoltaic cells are constructed from semiconductors, and serve to convert solar radiation energy to electricity, more commonly called solar cells. In order to obtain useful power from photon interactions in a semiconductor, three processes are required :

(1) The photon has to be absorped to give electrons being excited to a higher potential.

(2) The electron-hole charge carriers created, by the absorption must be separated and moved to an edge for collection. This is done by the use of a PN junction. This junction provides an electric field which sweeps the electrons in one direction and the positive holes in the other. If the junction is in a thermodynamic equilibrium, then the Fermi energy must be uniform throughout. Since the Fermi level is near the top of the gap of an N - doped material and near bottom of the P - doped side, an electric field must exist at the junction providing the charge speration function for the cell.

(3) The charge carriers must be removed to a useful load before they recombine with each other and loose their added potential energy.

Hence, the photovoltaic cell is a PN junction , which subjected to solar radiation, as shown in Fig. (1). The incoming photons with energies, h_v , greater than the forbidden energy, E_G (minimum vertical distance between the bottom of the conduction band and the top of the valence band), can be completely absorped by an electron as [1] :

$$h_v = \frac{h.c}{\lambda} \quad (ev) \quad ...... \quad (1)$$

Where h is plank's constant,

c is the velocity of the light

& λ is the wavelength of the incident light.

The absorption of photons in a material is given as a function of distance into the material, x , as [2] :

$$\phi\ (x) = \phi_{(o)} \cdot e^{-ax} \quad ...... \quad (2)$$

Where $\phi_{(x)}$ is the intensity of photons at depth x,

$\phi_{(o)}$ is the intensity of a incident on the solar cell surface

& a is the absorption coefficient of the solar sell material.

If the absorption coefficient is of $10^4 cm^{-1}$, then 90 percent of the photons would be absorped in the first 2.3 m of the material.

Any excess energy the photon has over the minimum required (h_v-E_G) is quickly given up to the lattice as thermal energy. As the electron drops down to the bottom of the conduction band, the electrons jump the forbidden gap and enter the conduction band left behind a hole. So, electron-hole pairs being to appear in the immediate vicinity of the PN junction . These particles move in opposite directions, the electrons pulled to the N - region and the holes to P - region. This flow constitutes an electric current and an e.m.f. develops between P and N sides. This voltage depend on the height of the barrier. The photocurrent-density, J_{ph} , produced is proportional to the number of photons absorped, which have energy to generate electron-hole pairs.

Assuming, one electron-hole pair created for each incoming photon with $h_v > E_G$, the maximum generated photocurrent density, J_{ph} max. , for a solar cell is equel to the short-circuit current density, J_s , for this cell [3] :

$$J_{ph\ max.} = J_s = qN_{ph} \quad A/cm^2 \quad \ldots\ldots \quad (3)$$

Where q is the electronic charge
&
N_{ph} is the number of photons (photons/cm^2. sec.)

The electrical choractersitic of a solar cell can be understood from Fig. (2), which shows the solar cell equivalent circuit. It consists of a constant current generator, a nonlinear junction impedance and a load. Light causes a current, I_L, to flow in the load, the magnitude of this current is the difference between the generated current, I_s , and the current flowing in the nonlinear junction , I_j. The actual junction current is given by [4]

$$I_j = I_o \left(e^{\frac{qv}{kT}} -1\right) \quad \ldots\ldots \quad (4)$$

Where I_o is the dark or reverse saturation current,
v is the voltage applied to the junction,
k is Boltzmann constant
& T is the absolute temperature.

Since

$$I_j + I_L = I_s \quad \ldots\ldots \quad (5)$$

The current-voltage characteristic may be written in the form

$$I_L = I_s - I_o \left(e^{\frac{qv}{kT}} - 1\right) \quad \ldots\ldots \quad (6)$$

The open-circuit voltage of the solar cell can be easily found from eq. (6) by setting $I_L = o$, so

$$v_{o.c.} = \frac{kT}{q} \ \ln \left(\frac{I_s}{I_o} + 1 \right) \qquad \ldots\ldots (7)$$

Fig (3) shows the current-voltage characteristic of a solar cell . The dark-current characteristic is given by eq. (4) . The lower curve shows the performance when the cell is exposed to light, The point of inter-section of each curve with the current axis correspond to short-circuit conditions ($R_L = o$) and that with the voltage axis, to open-circuit conditions ($R_L = \infty$).

The expression for the maximum conversion efficiency of a solar cell is given by [5]

$$\eta_{max.} = A \left(\frac{n_{ph(E_G)} \cdot v_{mp}}{N_{ph} \cdot E_{av}} \right) \left(\frac{\lambda \, v_{mp}}{1 + \lambda \, v_{mp}} \right)$$

Where

$$\lambda = \frac{q}{kT} , \qquad \ldots\ldots (8)$$

A is a constant depending on the reflection and transmission coefficients and the collection efficiency of the cell,

v_{mp} is the voltage at maximum power transfer,

E_{av}, N_{ph} are the average energy and the number of incident photons

&

$n_{ph}(E_G)$ is the number of photons per second per unit area of PN junction whese energy is great enough to generate hole-electron pairs in the semiconductor of energy gap E_G .

Since v_{mp} is usually much greater than unity and A 1, eq(8) can be written [4] as :

$$\eta_{max.} = \frac{n_{ph}(E_G) \cdot v_{mp}}{N_{ph} \cdot E_{av}} \qquad ...... (9)$$

The low values of efficiency are due to the radiant energy losses that results in decreasing generation of electron-hole pairs. These losses may be divided into two groups:

(1) Radiant energy loss by reflection.

(2) Energy loss due to recombination of electron-hole pairs out side the PN junction .

The conversion efficiency of solar cells, Ga Al As/ Gs As (gallium-aluminium-arsenide / galliun-arsenide), Si/Si (silicon), Cd S/In P (cadmium - sulphide/indium phosphor), Cd S/ Cu_2 S, Cd Te (cadmium - tellurium), Cd S, Cd S/Cd Te and Ga P, are 24,20,12.5,8,6,5.1,4 and 3 percent respectively 6, 7 .

2.2 Photoemissive Conversion

A photoemissive cell consists of an emitter as a surface of a solid material whose work function is E_W (electron volts), corresponding to U_W (joules), and a collector. If solar radiation of frequency f, falls upon the emitter suface, the most energetic electron would absorp photon and eventually escape from the material surface with a kinetic energy $\frac{1}{2} mv^2$, and migrate to the anode with velocity v , which condensed, and thus an e.m.f. is developed between the cathode and anode. Then, electric current will flow through external load. The kinetic energy of the emitted electrons is given by :

$$\frac{1}{2} m \ v^2 \leqslant hf - U_W \quad \text{joules} \qquad ..... (10)$$

Where m is the mass of electron,

v is the velocity of emitted electrons

&

h is plank's constant.

The maximum energy of the electrons liberated is independent on the light intensity and varies linearly with the frequency of incident light, the maximum energy occurs at maximum velocity, V_{max} , where

$$\frac{1}{2} m v^2_{max} = hf - U_W \qquad \ldots\ldots (11)$$

Fig.(4) indicates four possibilities for the configurations of the photoemissive cell, which are :

(a) The cell collector is rod and is surrounded by a shell-like emitter.

(b) The emitter is rod and surrouned by a shell-like collector-mirror. In this case solar energy would be reflected on the emitter by the collector-mirror which in turn would collect the emitted electron.

(c) The collector is grid covering the emitter, thus allowing passage of sun rays.

(d) The collector and emitter placed side-by side or at an engle, which use magnetic fields to transport electrons from emitter to collector.

2.3 Photogalvanic Conversion

A photogalvanic cell consists of two inert electrodes immersed in an aqueous solution of the dye and reducing agent. One electrode is subjected to solar radiation, while the other is left in the dark. Under the effect of solar radiation , electrons are generated at the illuminated electrode, and a difference of potential appears between the two electrodes.

When an external load is placed between the dark and the illuminated electrode, a current flows in this external circuit due to the motion of electrons toward the dark electrode.

For example of thionine is used as dye and ferrous ions (Fe^{2+}) as reducing agents. Thionine is purple in colour, but when illuminated the ferrous ions reduce it to a colourless leukothionine. Thus, each ferrous ion loses an electron and becomes a ferric ion. In the dark , the reaction reverses itself in several minutes, thus,

$$2Fe^{2+} + \text{thionine} \underset{\text{dark}}{\overset{\text{light}}{\rightleftharpoons}} \text{leukothionine} + 2Fe^{3+} \qquad (12)$$

The potential of the bleached solution is up to 0.4 volt more negative than that of the purple solution.

3. Indirect Conversion

The indirect methods of generating the electic energy in- from the solar energy can be devided according to the intermediate stage into thermal, mechanical and chemical conversion.

3.1 Thermal Conversion

The solar energy can be absorped by a material surface and converted to heat. This heat is converted to electricity by the use of thermoelectric and thermionic devices.

3.1.1 Thermoelectric Conversion

Seebeck discovered that a the ends of circuit composed of dissimilar materials, there appears an electromotive force if the junctions of the conductors are held at different temperaures. The value of this thermal e.m.f. depends on the temperature difference between the cold and the hot junction and may by expressed as

$$E = a_T \ (T_h - T_c) \qquad \ldots\ldots \quad (13)$$

The positive elements can be made from compounds with general formula T_{1-m} X, and the negative elements [8] can be made from compounds of $Al_m\ T_{1-m}$ X , where :

T is one of the transition metals(manganese-iron-nickel-cobalt-copper or lead),

X is oxygen, sulfar, setenium or tellurium

&

m lies within the limits 0.1-0.001.

The actual ouput voltage and the efficiency as a function of temperature for lead and selenium theremo-junction are shown in Fig.(6), the conversion efficiency is low ranging from 1.8 percent at a temperature difference of 195°c to 2.5 percent at 350°c [7] .

The main problems for thermoelectric conversion are :

(1) The technical difficulties to attach junction, which meed to maintain a large thermal difference between the hot and cold junctions.

(2) The high temperature, T_h, required to attain reasonable efficiency.

3.1.2 Thermionic Conversion

Fig.(7) shows thermionic device which consists of a cathode and node. At a high temperature, electrons are emitted from the cathode (emitter) and moves towards the anode. On the anode, the electrons are condensed, a part of the potential energy aquired for electron escaping from the cathode is converted to heat and a part of the heat will be converted to electrical energy. So, electric current, I_s, will flow through the external load, with conversion efficiency, η , given by$^{(9)}$:

$$\eta = \frac{I_s\ (v_k - v_a)}{I_s v_k + I_s \dfrac{2k\,T_k}{e} + Q_R + Q_T} \qquad (16)$$

Where v_k and v_a are the work functions of the cathode and the anode,

Q_R and Q_T are the heat expended on the radiation and on thermal conduction

&

T_k is the cathode temperature.

The efficiency of thermionic device has been reported as 4% at 2600 °c [7].

The basic problems in making a practical thermionic device are :

(1) The high temperature (2000 - 2700°c) need to get high rates of electron emission.

(2) Maintaining a high temperature difference between the cathode and the anode is difficult, because the spacing between them is generally very small (10-20 m).

(3) The space-charge (negative) in the space between the cathode and the anode limits the net current.

In general, a solar thermionic system would consist of a solar concentrator, a cavity-type thermionic engine, and a tracking device to follow the sun.

3.2 Mechanical Conversion

The solar energy is converted, by a solar-heat angines or heliohydroelectric, to mechanical energy and it is converted into electricity through a conventional power plant.

3.2.1 Solar-heat engine (10)

A schematic heat engine use solar energy and based on the thermodynamic cycle(Rankine-cycle) is shown in Fig.(8) . The flat plate is used as a collector. The fluid (water)is heated to high temperature, and contracts by liberating heat at low temperature. The difference between the input heat and the rejected heat will be converted to mechanical energy that would drive a turbine wheel. Electric generator coupled with the turbine wheel, converts the mechanical energy to electricity.

If the incoming solar energy flux on the flat plate collector is P (in W/m^2), the equilibrium temperature of the plate, T , is :

$$T^4 = \frac{a}{\varepsilon} \quad \frac{P}{\sigma} \qquad \ldots\ldots (17)$$

Where a and ε are the absorptivity and emissivity of the flat plate respectively

σ is stefan's constant .

The practical difficulties of heat engine lie in designing suitable regenerators and the producing devices which will allow the expansion and compression stages to take place at almost constant temperature.

The overall conversion efficiency of a flat plate collector driven heat engine will be only 5 percent. But, when concentraters are used to raise the temperature of the collector, with a concentration ratio of 1000, the efficiency can be increased to 30 percent.

To improve the conversion efficiency of the solar-heat engine, the absorpers can be selectrively chosen so that their $\frac{a}{\varepsilon}$ ratio is high, and by increasing the incoming solar flux using the concentrators.

A graph showing the equilibrium temperature for different rates of power production is shown in Fig.(9), for different values of the incident solar flux and for a neutral absorber ($a = \varepsilon = 0.9$) . The corresponding results for the selective absorper used earlier with $\varepsilon = 0.1$, are shown in Fig.(10).

3.2.2 Heliohydroelectric Power Generation

There are many natural depression with an average depth below sea level, admitting sea water into these depression through hydroelectric turbines, and with a reasonable physical head, which warer is dispossed off by gravity to the sea, the electric energy may by generated. When use the reaction of the sun, the water is dispossed off a evaporation, utilize the conversion of solar energy of evaporation to hydraulic energy and then to electricity, it is called "heliohydroelectric power generation ". The power produced by this method is given $^{(6)}$:

$$P = G.\ \eta\ .\ P_i\ .\ \gamma_s\quad S.\ H_e \qquad \ldots. \quad (18)$$

Where g is the acceleration of gravity,
η is the conversion efficiency,
P_i is the density of the incoming water,
$\dot{\gamma}_s$ is the net evaporation rate,
S is the area of lake presented for evaporation
&
H_e is the hydraulic head.

In Egypt " The Qattare Depression Project " is an example for the possibility of the utilization of solar energy effect for evaporating sea water. With a discharge of 600 m^3/sec from the mediterranean sea into the Depression, by means of tunnels and open channels of 80 km length, equilibrium prevails between the discharge and the evaporation by solar energy from the lake thus created with its surface level 60 meters below sea level.

3.2.3 Chemical Conversion

Photosynthesis occurs in the presence of chlorophyll. Visible light having a wavelength below 0.68 microns is absorbed by the green chlorophyll which becomes activated and passes its energy on to the water molecules. A hydrogen atom is then released and reacts with the carbon dioxide molecule to produce H_2CO, the basic molecule forming carbohydrates, and oxygen. This reaction can be summarized as :

$$CO_2 + H_2O + \text{Light} \longrightarrow H_2CO + O_2 \qquad \ldots\ldots \quad (19)$$

H_2CO breaks at high temperature releasing an amount of heat equal to 112000 calories per mole, where

$$H_2CO + O_2 \longrightarrow CO_2 + H_2O + 112 \text{ kcal /mole} \qquad \ldots\ldots \quad (20)$$

This heat would be converted into electricity by conventional methods. In nature, photosynthesis is not optimized for energy conversion.

A detailed schematic diagram to produce electric power from methane obtained by an algal-bectrial system is shown in Fig.(11). Alglae grown in the pond, with depth of 8 inches in the winter and 12 inches in the summer, are harvested and then placed in a digester for formentation. When the harvested algae are introduced into the digestor, acidforming bacteria break them down, and in so doing, synthesize organic acids, specially the short, straight-chain fatty acids. The acids together with carbon dioxide released by the acid forming bacteria, are converted into methane by methane-forming bacteria. Methane gas produced is burned and the heat energy is used in conventional plant to generate electricity. The conversion efficiency [3] of solar energy into electricity using methane fuel cycle as chemical conversion is about of 2 percent.

Fig. (12) , shows the classification of the different methods of solar energy conversion.

4. Conclusion

From the foregoing study, it could be concluded that :

(1) The solar cells in the photovoltaic conversion were capable of reaching an efficiency of 24 percent.

(2) Thermoelectric devices have not found widespread utilization in solar energy conversion because of a combination of technical difficulties and cost in terms of conversion efficiency. Where the effciency is ranging from 1.8 percent at a temperature difference of 195° c to 2.5 percent at 350°c.

(3) Thermionic devices have conversion efficiency 4 percent at 26000°c. It needs high temperature (2000-2700°c) and high rates of electron emission. Also, the space-charge in it reduces the net current.

(4) The mechanical conversion using solar-heat engine is expensive. It needs flat plate collectors and conventrators for improvement conversion efficiency from 5 percent to 30 percent.

(5) The conversion efficiency of solar energy into electricity using biological reaction as chemical conversion to produce methene fuel is about of 2 percent.

Consequently, the solar cells are the most efficient converters of solar energy conversion.

References :

1 . MILLMAN and HALEIAS : " Electronic devices and circuits", Mc-Graw-Hill Book company, New-York, (1967).

2 . V. STUPELMAN : " Semiconductor devices ", Mir Publishers, Moscow, (1976).

3 . RICHARD C. NEVILLE : " The solar cell ", Elsevier Comp., New-Yourk, (1978).

4 . CHARLES E. BACKUS : " Solar cells ", IEEE Press, New-York, (1976).

5 . JOSEPH J. LOFERSKI : " Theoretical considerations governing the choice of the optimum semiconductor for photovoltaic solar energy conversion", J.appl. Phys., V.27, 777, July (1965).

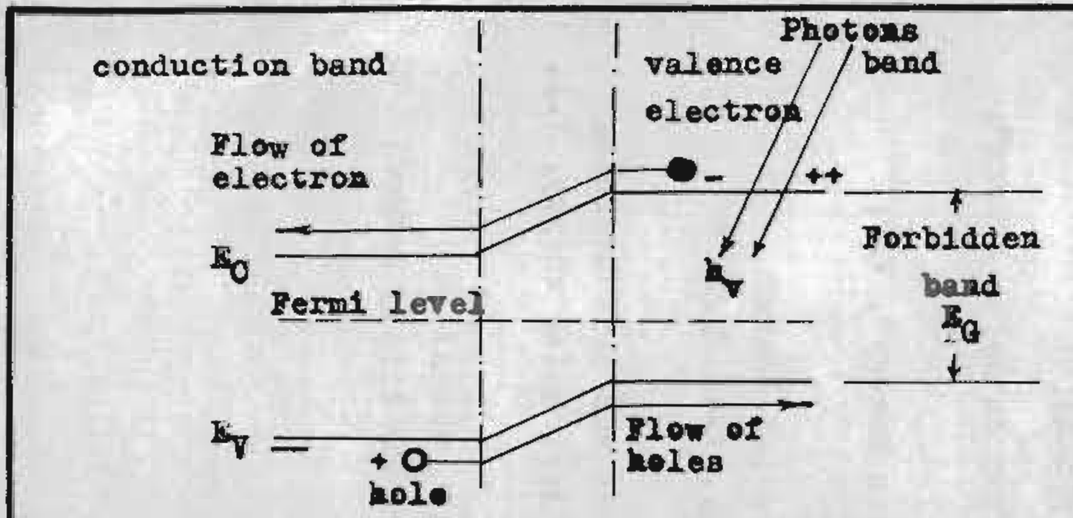
6 . " International Symposium-Workshop on Solar Energy", EGYPT - Cario, June, (1978).

7 . " Internation Conference on Solar Energy", V.2, Nice-France, January, (1977).

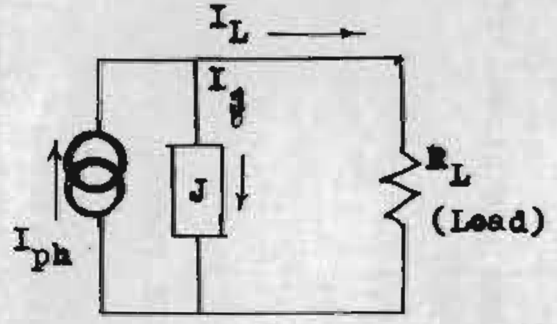
8 . U.A. ARIFOV : " Thermoelectric solar energy converters " , App. solar energy, V.1, No.1, 6 January (1965).

9 . U.A. ARUFOV : " The thermionic method of converting solar energy to electricity ", App. solar energy, V.1, No. 6,5, (1965).

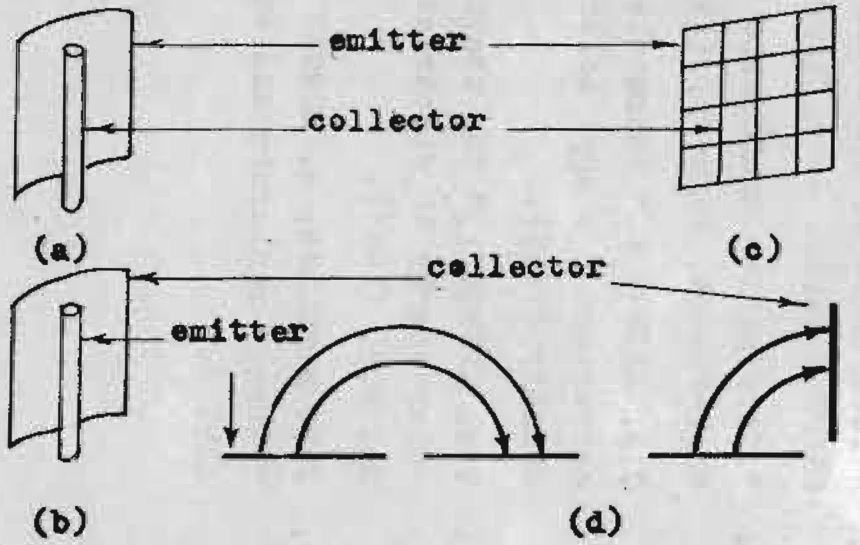
10 . J.T. MCMULLAN, R. MORGAN and R.B. MURRAY : " Energy resources and supply ", Jo Wiley, London, (1976).



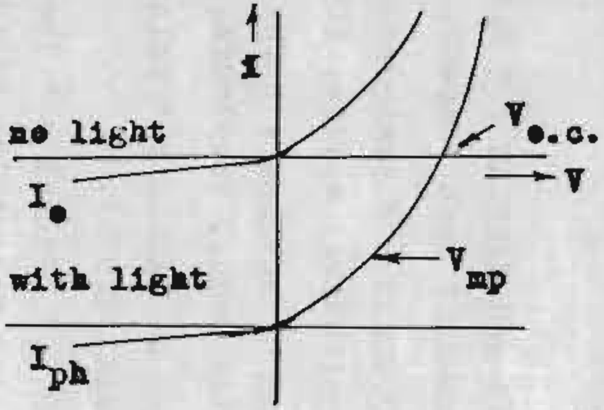
Fig(1): Energy band digaram for PN junction Photovoltaic cell under illumination.



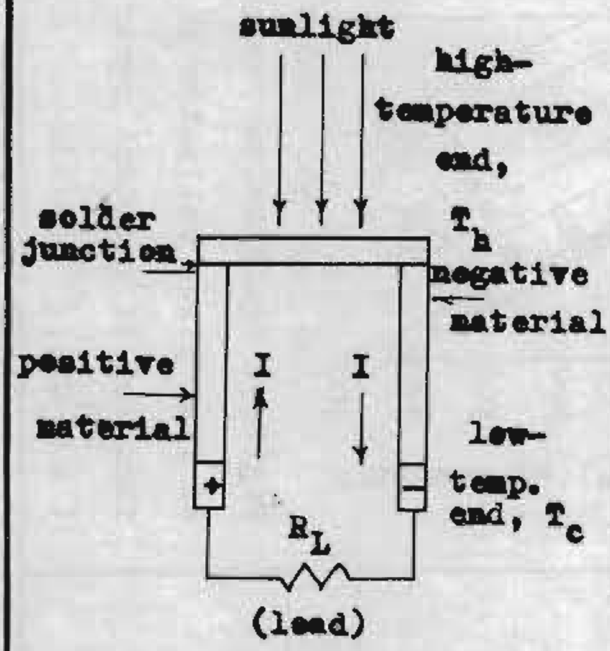
Fig(2): Equivalent circuit of illuminated solar cell.



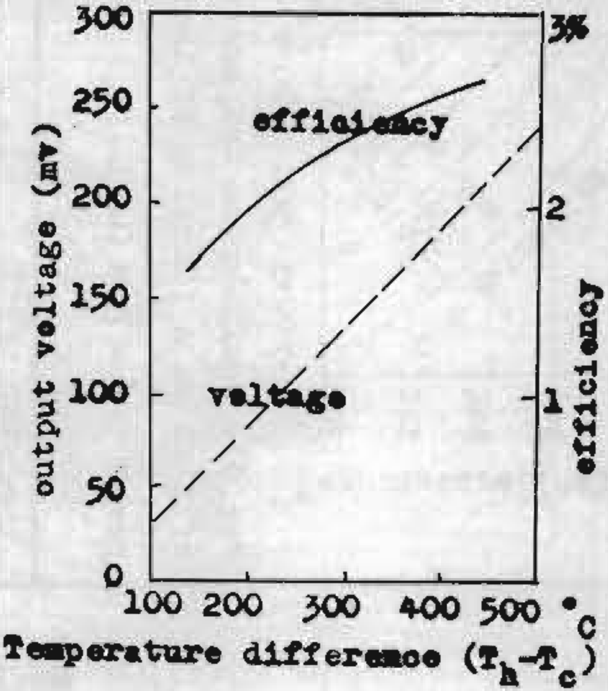
Fig(4): Various configurations of photoemissive cell.



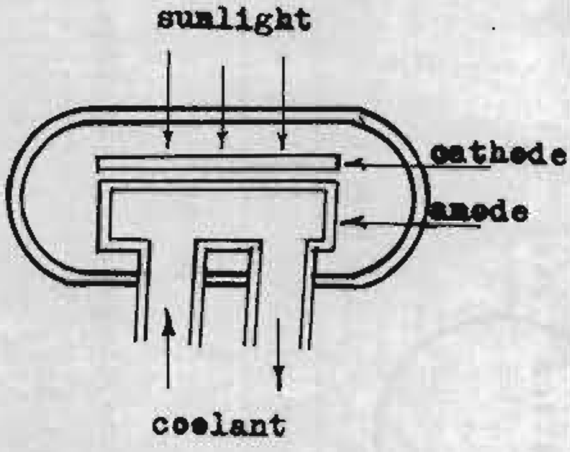
Fig(3): I-V characteristic of solar cell.



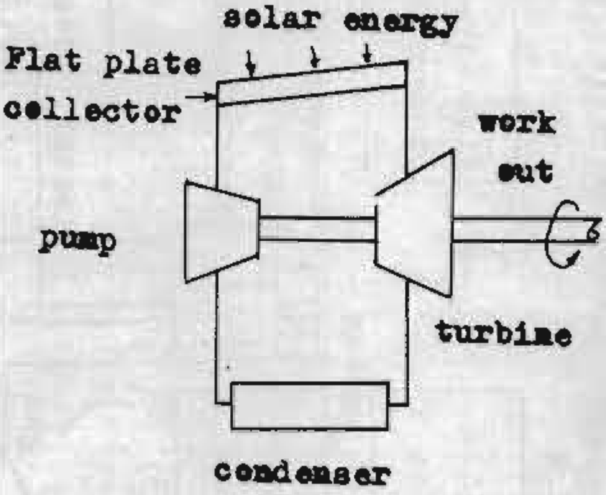
Fig(5): Thermojunction device.



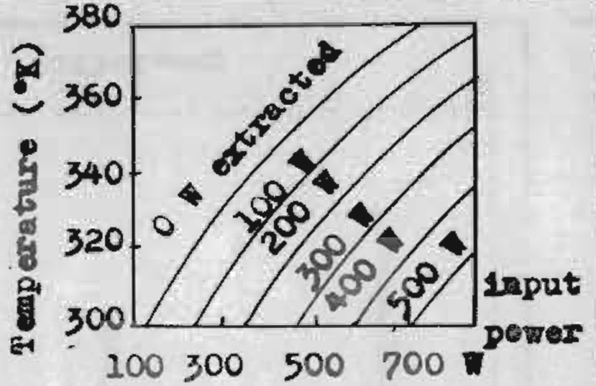
Fig(6): The output voltage and the conversion efficiency for actual thermojunction (lead - selenium).



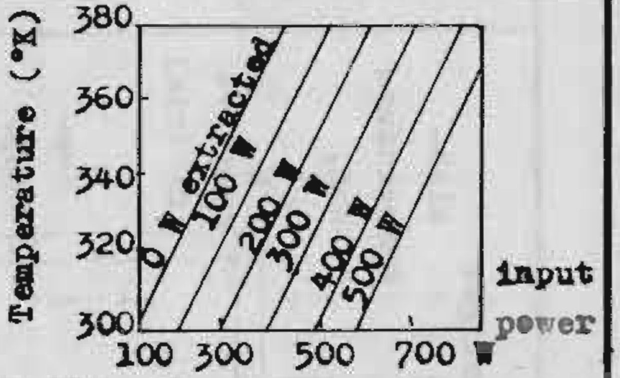
Fig(7): Schematic diagram of a thermionic defice.



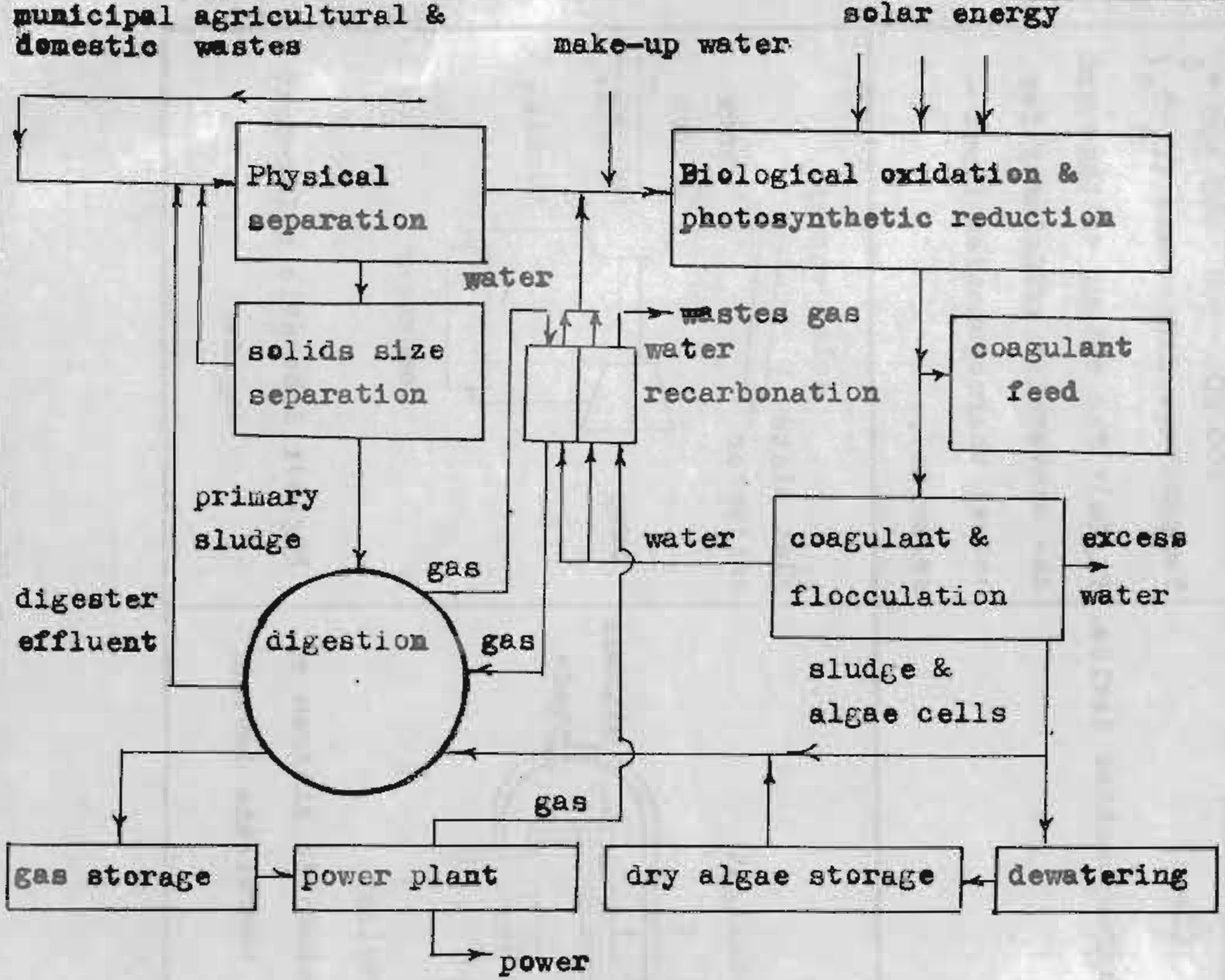
Fig(8): Schematic solar-heat engine.



Fig(9): Equilibrium temperature of flat as a function of incident power (a = $\mathcal{E}$ = 0.9).



Fig(10): Equilibrium temperature of flat plate collector as a function of incident power (a = 0.9, $\mathcal{E}$ = 0.1).



Fig(11): Single line diagram of principal elements of algae-methane plant.

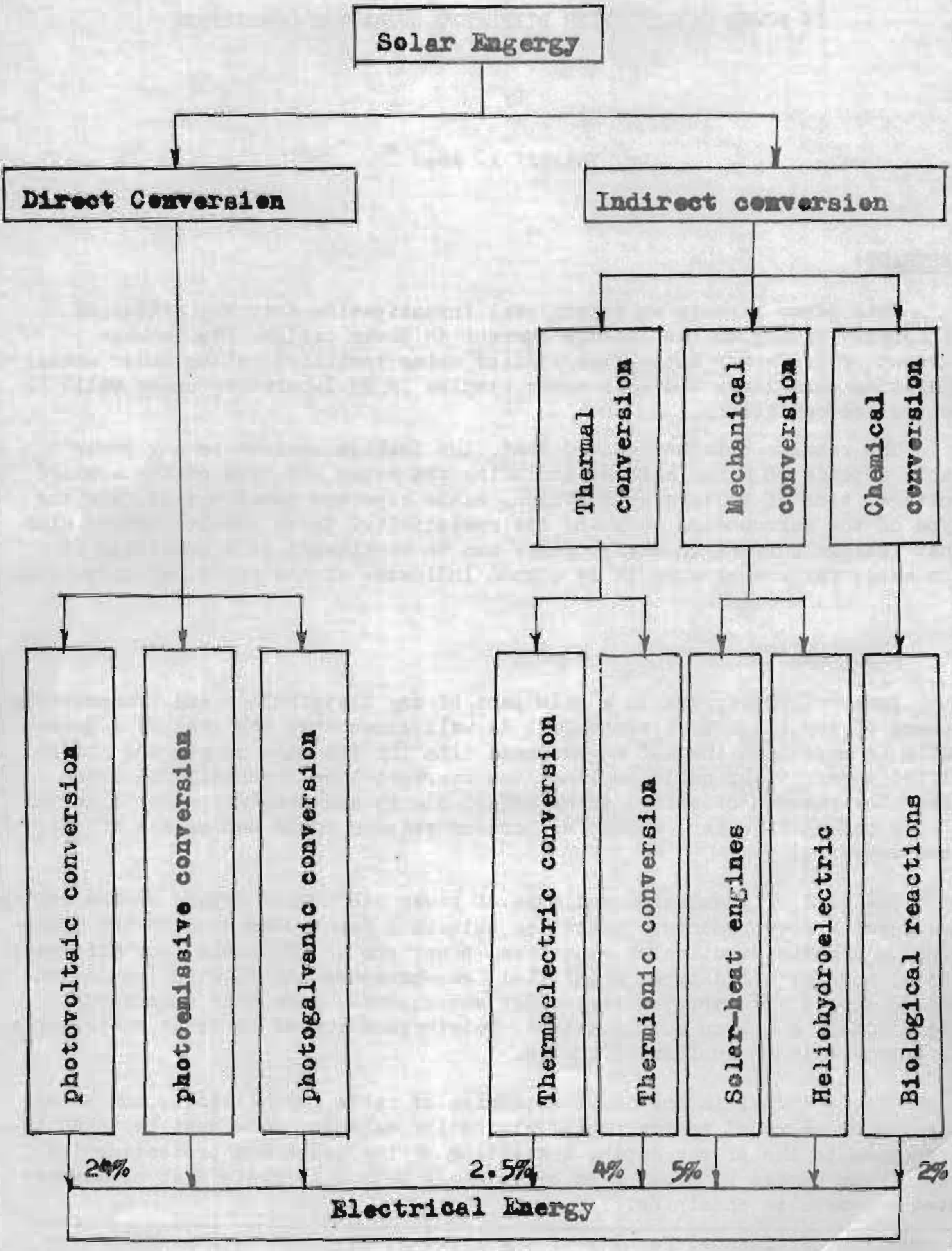


Fig (12): Differrent methods of solar energy conversion.