

## Renewable Energy: Solar Electricity Solution

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### 1. First estimations

- (a) By using equations  $I = 1.1 \cdot I_0 \cdot \left( (1 - h/15) 0.7^{AM^{0.678}} + h/15 \right)$  and  $AM = \frac{1}{\cos(z) + 0.50572 \cdot (96.07995 - z)^{-1.6364}}$ , the solar intensity can be estimated at an altitude of 12 km and at latitude 30 °N each 10min using [sunearthtools.com](http://sunearthtools.com). The daily intensity is the sum of the intensity over each 10min and is 16.70 kWh/m<sup>2</sup>/day for a plane oriented in the sun direction. For an horizontal plane as the PV panels on Solar Impulse, the intensity is given by:  $I^* = I \cdot \cos(z)$  and therefore the maximum daily electrical energy that can be harvested falls down to 9.35 kWh/m<sup>2</sup>/day.
- (b) For both Solar Impulse 1 and 2:
- i.  $I_{solar\ input} = I_{max} \cdot albedo = 1.399\text{kW/m}^2 \cdot 0.9 = 1.259\text{kW/m}^2$   
 Solar Impulse 1:  $P_{solar} = I_{solar} \cdot A = 1.259 \cdot 200 = 252\text{ kWp} \Rightarrow \eta_{PV} = \frac{P_{SI1}}{P_{solar}} = \frac{45}{252} = 17.86\%$   
 Solar Impulse 2:  $P_{solar} = 340\text{ kWp} \Rightarrow \eta_{PV} = 19.41\%$
  - ii.  $\eta_{PV\ to\ propulsion} = \frac{P_{propulsion}}{P_{PV}}$   
 Solar Impulse 1:  $\eta_{PV\ to\ propulsion} = \frac{4 \cdot 10 \cdot 0.7457}{45} = 66.28\%$   
 Solar Impulse 2:  $\eta_{PV\ to\ propulsion} = \frac{4 \cdot 17.4 \cdot 0.7457}{66} = 78.64\%$
- (c) Record flight of SI1 of 1541 km in 18h20min gives an average flight speed of 84 km/h, which was probably achieved with a lot of tail wind. Note it is less than a day's length (24h) and only half the announced expected endurance of 36h. At the best, the solar input on the 29.03 at 30°N is 9.35 kWh/m<sup>2</sup> for 200 m<sup>2</sup> = 1870 kWh. With a PV efficiency of 17.86%, it gives 1870 · 0.1786 = 334 kWh<sub>e</sub>. With fully charged batteries and a complete day of sun, 84 kWh from batteries + 334 kWh<sub>e</sub> · 0.85 from PV to batteries = 368 kWh available for a single flight. With the PV to engine efficiency, this is 244 kWh<sub>e</sub>. With an optimum engine power use of 6 kW, it should be possible to fly during 244/6 = 40h 40min on a perfect sunny day, on the 29.03 at 30°N. Ideally this should suffice for the 12.24h day flight, and charge the battery fully for the night flight. At full power, the engines consume 29.83 kW and therefore can fly only during 2h 49min on fully charged batteries without solar energy. It is clear that, for sustained flight including "bridging" the night, power consumption must be kept as low as possible. In addition, it also appears that the propulsion efficiency could be increased (from 66%). This is achieved in SI-2, which also is equipped with more PV, more power, and more storage.
- (d) With 12 intended stops around the globe, an average flight distance of 40'000 km / 12 = 3'333 km should be performed and even 5'000 km non-stop trips to cross Pacific.

Assuming average flight speed of 70 km/h, a 3333 km stretch would take  $3333/70 = 48$  h, or 1.98 days (2 full days). It is challenging to realise this by a single-manned plane, the pilot having to sleep at some stage. The power consumption assuming continuous optimal motor use of 6 kW of an average trip is 286 kWh. The PV energy brought to the battery during these two days of flight is given by:

$E_{PV \text{ to battery}} = I^* \cdot \eta_{PV} \cdot A \cdot 0.85 \cdot t_{flight} = 9.35 \cdot 0.1941 \cdot 270 \cdot 0.85 \cdot 1.98 = 825 \text{ kWh}$ . The electrical energy from the PV panels should be definitely sufficient to cover the entire flight at optimal motor use. Even if the battery must be charged during the day for the night flight,  $847 - 4 \times 41 = 683$  kWh is left for the flight. Nevertheless, if the motors are not at optimal use and more power is needed, it might not be sufficient. In case of using continuously maximum power, the power consumption for the trip becomes 2471 kWh and the power brought by PV is not sufficient.

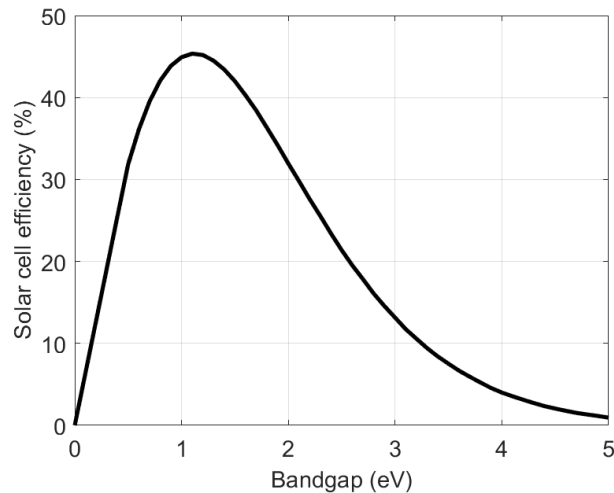
The same calculation can be performed for a flight of 5'000km and the electrical energy consumption is 429 kWh for 3 full days. The PV + batteries gives a total engine energy of 1077 kWh. There is around 700 kWh of energy unused but the big unknown is the weather condition for consecutive days of flight which can limit the PV production during daytime and might make the flight infeasible.

- (e) The specific consumption is given by:  $P/v_{av}$  where  $P$  is the optimal power of the engines and  $v_{av}$  the average speed. For Solar Impulse 1, the specific consumption is 0.12 kWh/km assuming an average speed of 50 km/h which is already less than an electric car and for Solar Impulse 2 assuming an average speed of 70 km/h it is 0.09 kWh/km.

2. Theoretical efficiency of a solar cell based on its bandgap is determined using the formula

$$\eta = \frac{\int_0^{\lambda_{gap}} \frac{E_{gap}}{E_{\lambda}} e_{\lambda b} d\lambda}{\int_0^{\infty} e_{\lambda b} d\lambda}$$

with the black power emissive power  $e_{\lambda b}(\lambda, T)$  given by  $e_{\lambda b}(\lambda, T) = \frac{2hc_0^2}{\lambda^5 (e^{hc_0/(k\lambda T)} - 1)}$ . The solar cell efficiency depicted in figure 1 has been solved with Matlab (file provided on Moodle).



**Figure 1:** Solar cell efficiency depending on the bandgap of its semiconductor material

3. With an efficiency of 20% at 950 W/m<sup>2</sup>, a normal solar cell delivers 190 W/m<sup>2</sup>, or 19 mW/cm<sup>2</sup>. If this particular cell delivers 200 mW/cm<sup>2</sup>, or 10.5 times more, it can only be a concentrating solar cell (with an effective concentration factor of 10.5).
4. A solar cell has a short circuit current density of 33 mA/cm<sup>2</sup> and a open circuit voltage of 0.55. Its fill factor is 0.7.

(a) The fill factor, FF, is given by:  $FF = \frac{I_{P_{max}} \cdot V_{P_{max}}}{I_{sc} \cdot V_{oc}}$  where  $I_{P_{max}} \cdot V_{P_{max}}$  is the maximum power,  $P_{max}$ .

Hence, the maximum power is 12.705 mW/cm<sup>2</sup>.

(b) The diode equation with series resistance (ohmic contact),  $R_s$ , and shunt resistance (defects),  $R_{sh}$ , is given by:

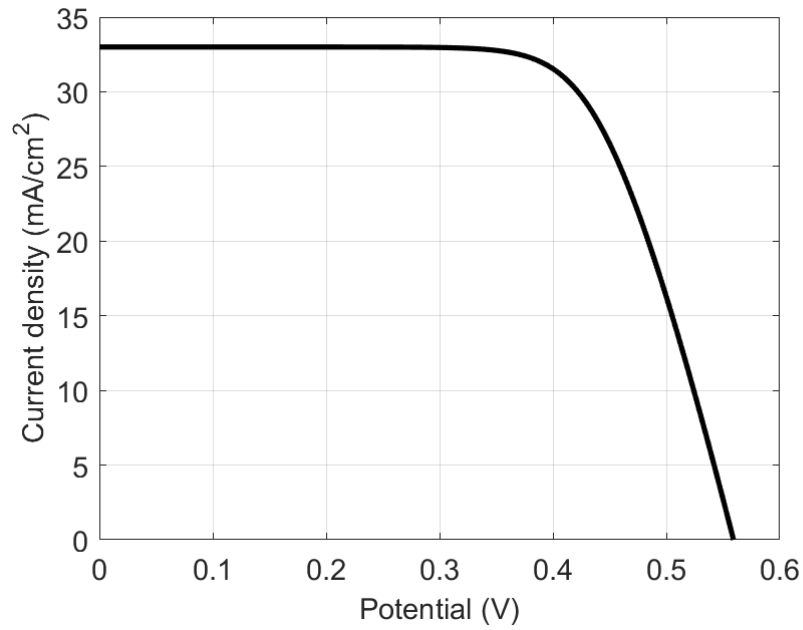
$$I = I_L - I_0 \cdot \left( e^{\frac{qV + qIR_s}{k_B T}} - 1 \right) - \frac{V + IR_s}{R_{sh}}$$

Assuming an infinite shunt resistance (no defects) leads to the following equation:

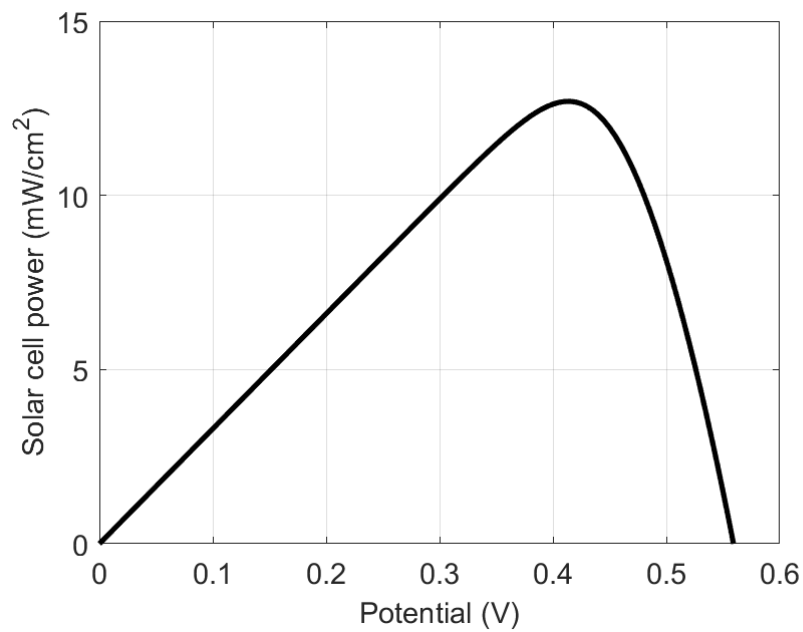
$$I = I_L - I_0 \cdot \left( e^{\frac{qV + qIR_s}{k_B T}} - 1 \right)$$

This equation is solved iteratively on Matlab (given in the solution) with a potential varying from 0 V to 0.6 V with a first guess on the series resistance of 2 Ω·cm<sup>2</sup>. Then, the maximum of the power I·V is found. If the maximum power is higher than the given maximum power of 12.705 mW/cm<sup>2</sup> (question (a)) the resistance is increased until it gives the maximum power of this solar cell.

The series resistance is 2.634 Ω·cm<sup>2</sup>. The I-V curve and the power curve are depicted in figure 2 and 3.



**Figure 2:** Solar cell photocurrent density versus potential



**Figure 3:** Solar cell power density versus potential

5. Consider average annual solar irradiance in Switzerland,  $1'250 \text{ kWh/yr/m}^2$ , on a horizontal surface.
- (a) The  $10 \text{ m}^2$  PV module recovers  $1'250$  (horizontal surface)  $\times$   $1.1$  (tilted roof)  $\times$   $0.12$  (efficiency)  $\times$   $10 \text{ m}^2 = 1'650 \text{ kWh}_{\text{el}}$  and so provides 30% of the yearly electricity consumption of the house (assuming storage when needed).
  - (b) The  $6 \text{ m}^2$  solar thermal module would capture  $1'250$  (horizontal surface)  $\times$   $1.1$  (tilted roof)  $\times$   $0.3$  (efficiency)  $\times$   $6 \text{ m}^2 = 2'475 \text{ kWh}_{\text{th}}$  and so provide only 12% of the heating needs. With ca.  $5/6$  ( $16'700 \text{ kWh}_{\text{th}}$ ) for low temperature space heating, and ca.  $1/6$  ( $3'300 \text{ kWh}_{\text{th}}$ ) for sanitary hot water preparation, the  $6 \text{ m}^2$  thermal solar panel would then cover  $2'475/16'700 = 15\%$  of the annual space heating needs and  $2'475/3'300 = 75\%$  of the annual hot water needs.