

Solar electricity: Exercise solution

1. First estimations (excel file provided on Moodle)

- (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. The daily intensity is the sum of the intensity over each 10min and is 16.66 kWh/m²/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 9.58 kWh/m²/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: $P_{solar} = I_{solar} \cdot A = 1.259 \cdot 200 = 252\text{ kWp} \Rightarrow \eta_{PV} = \frac{P_{SI1}}{P_{solar}} = \frac{45}{241} = 17.87\%$

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 9.58 kWh/m² for 200 m² = 1915 kWh. With a PV efficiency of 17.87%, it gives 1915 · 0.1787 = 342 kWh_e. With fully charged batteries and a complete day of sun, 84kWh from batteries + 342 kWh_e · 0.85 from PV to batteries = 375 kWh available for a single flight. With the PV to engine efficiency, this is 249 kWh_e. With an optimum engine power use of 6 kW, it should be possible to fly during 249/6=41h25min on a perfect sunny day the 29.03 at 30°N. Ideally this should suffice for the 12.28h 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 2h49min 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:

$$E_{PV \text{ to battery}} = I^* \cdot \eta_{PV} \cdot A \cdot 0.85 \cdot t_{flight} = 9.58 \cdot 0.1941 \cdot 270 \cdot 0.85 \cdot 1.98 = 847 \text{ kWh.}$$

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, 521 kWh is left for the flight. Nevertheless, if the the motor 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 than 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 1128 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).

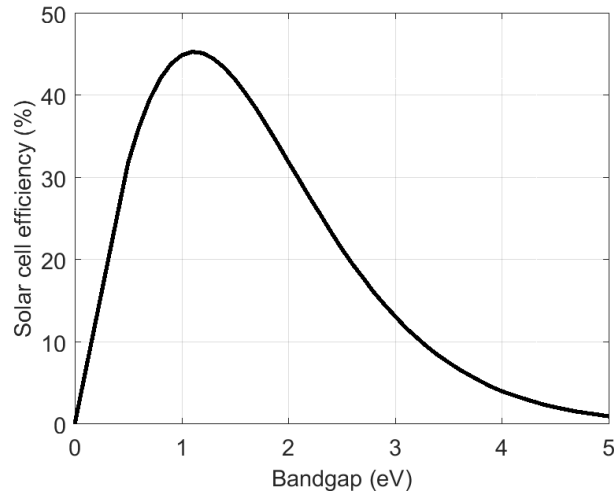


Figure 1: Solar cell efficiency depending on the bandgap of its semiconductor material

3. With an efficiency of 20% at 950 W/m², a normal solar cell delivers 190 W/m², or 19 mW/cm². If this particular cell delivers 200 mW/cm², 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/cm² 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/cm².

(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 0V to 0.55V with a first guess on the series resistance of 1 Ω·cm². 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/cm² (question (a)) the resistance is increased until it gives the maximum power of this solar cell. The series resistance is 2.64 Ω·cm².

The I-V curve and the power curve are depicted in figure 2 and 3.

5. Consider average annual solar irradiance in Switzerland, 1'250 kWh/yr/m², on a horizontal surface.

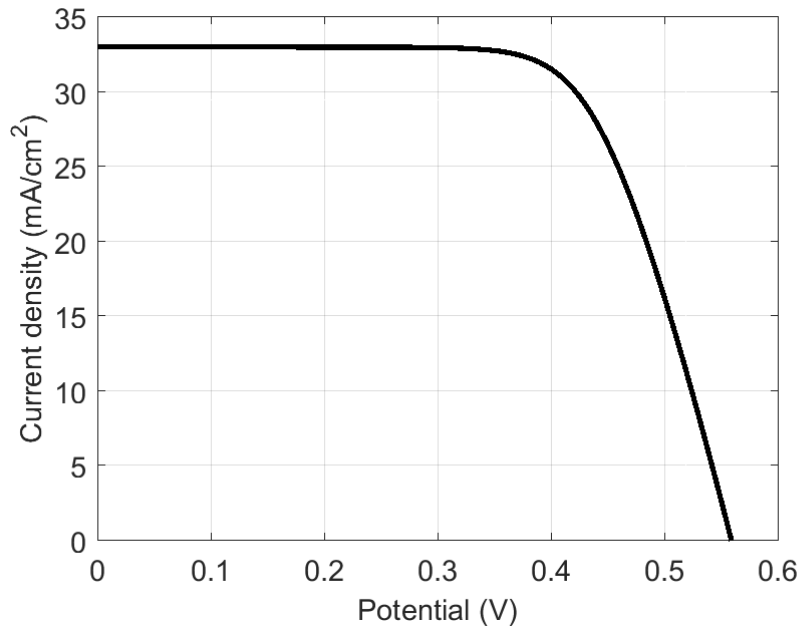


Figure 2: Solar cell photocurrent density versus potential

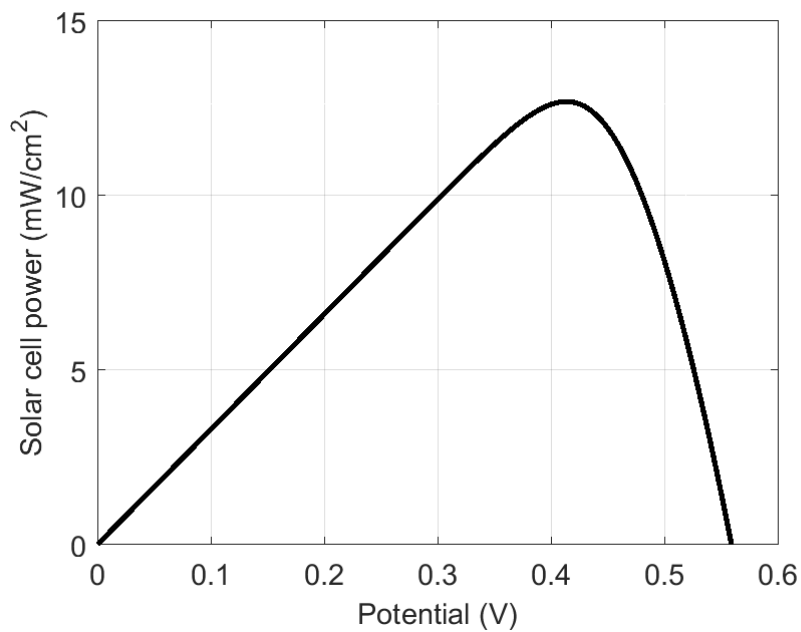


Figure 3: Solar cell power density versus potential

- (a) The 10 m^2 PV module, when on a horizontal plane (i.e. if the roof were flat), recovers $1'250$ (horizontal surface) \times 1.1 (tilted roof) \times 0.12 (efficiency) \times $10 \text{ m}^2 = 1'650 \text{ kWh}_e$ and so provides 30% of the yearly electricity consumption of the house (assuming storage when needed). One should bear in mind that household electricity needs account for only ca. 25% of the total electricity consumption in the country, hence the PV contribution, while substantial, would then deliver $30\% \times 25\% = 7.5\%$ of the total electricity.
- (b) The 6 m^2 solar thermal module would capture $1'250$ (horizontal surface) \times 1.1 (tilted roof) \times 0.3 (efficiency) \times $6 \text{ m}^2 = 2'475 \text{ kWh}_{th}$ and so provide only 12% of the heating needs. With ca. $5/6$ ($16'700 \text{ kWh}_{th}$) for low temperature space heating, and ca. $1/6$ ($3'300 \text{ kWh}_{th}$) for sanitary hot water preparation, which in fact is the best and most adapted application of solar thermal absorbers, the 6 m^2 thermal solar panel would then cover $2'475/3'300 = 75\%$ of the annual hot water needs. Households in fact consume $2/3$ of the space heating + hot water heating for the whole country, so the total contribution to heating needs would be $75\% \times 66\% = 50\%$ of all sanitary hot water.