Answer all 5 questions. (Max. points from each question is 6; total 30).

1. Question

Answer the questions. 1 point each.

a) What is doping? What is the most common N- and P-type dopants in silicon? Why and how do affect the conductivity of silicon?
b) What are the minority carriers in N-type silicon? What determines their concentration at room temperature i) in the dark, ii) under illumination?
c) If the bandgap of a pn-junction solar cell is decreased (conceptually), how does it affect the short circuit current and open circuit voltage of the cell (according to theory)?
d) What is Fermi energy? How does it relate to the solar cell voltage?
e) If the donor atom density in silicon is increased, how does it affect the Fermi energy of electrons (in the dark, at equilibrium)?
f) Why do all well-performing solar cells exhibit diode-like current-voltage characteristics, even if they are not necessarily based on pn-junctions?

2. Question

Answer the questions. 1 point each.

a) Consider a solar module made of 72 identical solar cells that each have maximum power point (MPP) voltage V_{MPP} = 0.5 V and current I_{MPP} = 5 A. If the solar module has six parallel-connected strings of cells, each string consisting of 12 series-connected cells, what is the V_{MPP} and I_{MPP} of the solar module?
b) What does the nominal power rating of a photovoltaic module, also called "watt-peak" or "peak-watt" (Wp) mean? At which conditions is it determined?
c) A solar module has rated power of 285 W and its dimensions are 166 cm x 100 cm. What is its energy conversion efficiency?
d) What are the two main challenges that development of perovskite solar cells need to overcome before they can become competitive with crystalline silicon solar cells?
e) Why do multi-junction solar cells reach higher efficiency than single junction cells?
f) When is the electricity produced by residential photovoltaic systems expected to become economically competitive with grid electricity for typical homeowners in Southern Finland? What factors affect the timeline?

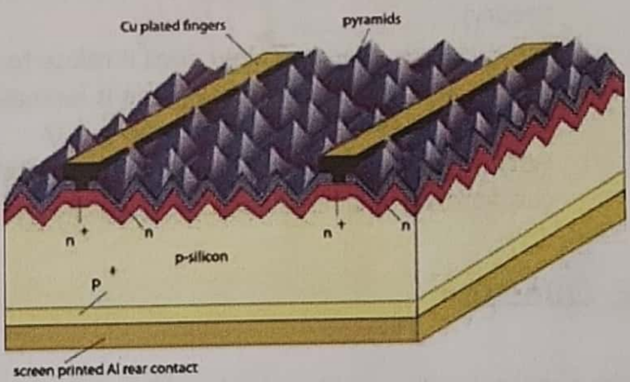
3. Question

The figures below show a photo and a schematic cross section of a crystalline silicon solar cell.

What are the main factors – related to the physical properties of the materials or structural properties of the solar cell or design – that determine the short-circuit current of the cell produced at 1000 W/m² AM1.5G solar illumination?

List the main factors, both gains or losses, of both optical and electrical by nature, and explain how and why they affect the current output of the cell. Try to be as thorough as you can but include only factors that you understand and can briefly (in few words) explain – mere long list of unexplained guesses does not count as valid answer.

Tip: Think about the sequence of processes in which light (flux of photons) is converted to electricity (current). (6 points total)



4. Question

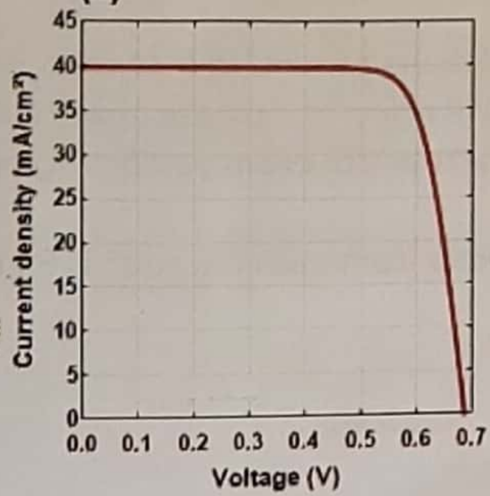
The figures (ii)-(vi) below show current–voltage (IV) curves of solar cells measured at the standard test conditions (STC). The IV curves can be represented with an equivalent circuit model which has five parameters: light-collected current J_L, saturation current density J_0, ideality factor m, shunt resistance R_{sh}, and series resistance R_s.

a) Draw the equivalent circuit corresponding to the IV curve and name its components. (0.5 p)
b) Using the five parameters, give the corresponding mathematical expression of the IV curve. (0.5 p)
c) Figure (ii) is the reference case, with the parameter values of the table in figure (i). Estimate approximately from figure (ii) the open circuit voltage (V_{OC}), short circuit current density (I_{SC}), fill factor (FF), and energy conversion efficiency (h). (0.5 p)
d) d) Figures (iii)-(vi) represent each variation of one of the parameters: J_L, J_0, R_{sh}, and R_s vs. the reference value. Which figure corresponds to variation of which parameter? (0.5 p)
e) Estimate the range of variation (lowest and highest value) of the parameter values corresponding to the curves. (2 p)
f) Explain which material or structural property could cause these variations in
   a. R_{sh} (0.5 p)
   b. R_s (0.5 p)
   c. J_0 (1 p)

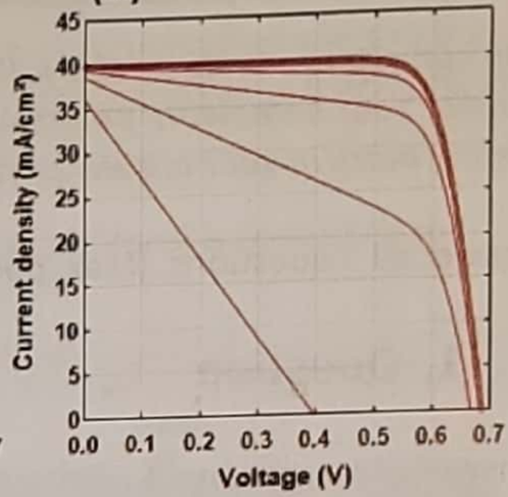
(i)

INPUTS			
Light-collected current	J_L	40	mA/cm²
Saturation current	J_0	1E-13	A/cm²
Ideality factor	m	1	
Shunt resistance	R_{sh}	10000	Ω·cm²
Series resistance	R_s	1	Ω·cm²

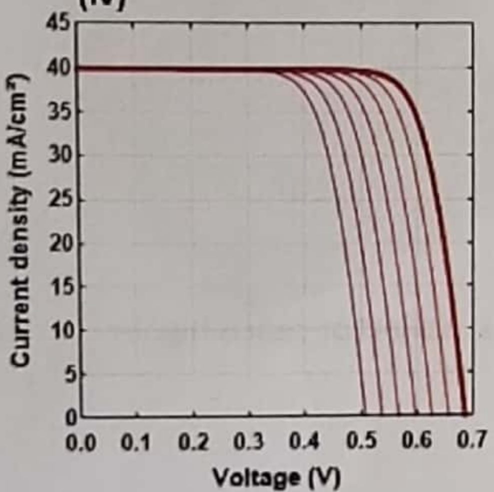
(ii)



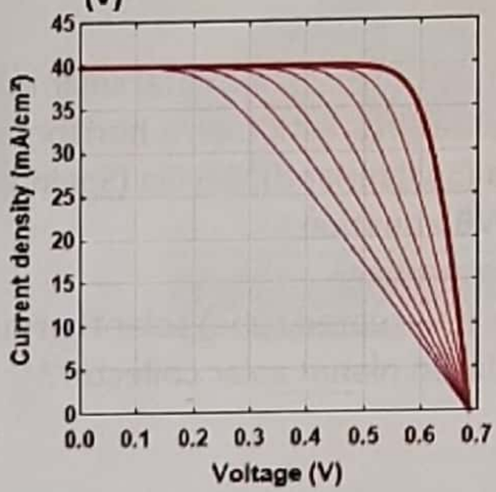
(iii)



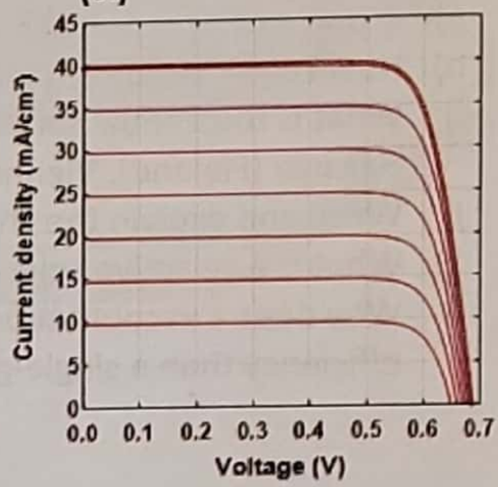
(iv)



(v)



(vi)



5. Question

Let's consider a grid-connected PV system installed on the roof of a single-family house in Southern Finland, where the average total cost of grid electricity is 0.10 €/kWh. The yearly total solar irradiation on the module surface has been estimated to be 900 kWh/m² per year. The overall efficiency of the PV system is 15 % and its expected operational lifetime is 25 years. The household consumes 7300 kWh electricity per year (120 m² floor area, four persons, no electric heating). Assuming that the household can sell their surplus PV electricity at the same price as they buy electricity from the grid (which is equivalent to 100 % self-consumption),

a) How low should the investment costs (€/m² of module area) of the PV system be, to make the generated PV electricity competitive with the grid electricity? (1 p)
b) What are the investment costs of this system per rated power (€/Wp)? (1 p)
c) How large roof area must be covered with the PV modules to generate as much PV electricity as the household consumes per year? (1 p)
d) What is the investment cost of this system (€)? (1 p)
e) What other factors should a more realistic economic assessment consider, which are omitted here? (2 p)