

First Name: \_\_\_\_\_ Last Name: \_\_\_\_\_ Sciper: \_\_\_\_\_

## Solar Energy Conversion Devices and Plants: Exam

Date: 29<sup>th</sup> January, 2024; Duration: 3 hours

Personal summary, calculator only. Answers on these sheets only.

Total: [90 points]

---

### Section I: Multiple choice questions [72 points]

- Each question carries 4 points and has **one or more correct** option(s).
  - Full points are awarded only when all correct options are marked.
  - Partial points: Each correct option gives +1 point, each wrong option gives -1 point.
- 

1. Which of the following statement(s) is/are correct for a normally illuminated pn junction at equilibrium with no external bias?
  - In the quasi-neutral region, no current is carried by majority charge carriers
  - In quasi-neutral region, only diffusion current is carried by minority charge carriers
  - In the space charge region, the overall cell current is spatially constant
  - The electrostatic potential inside the space charge region is non-linear
2. Choose the correct statement(s) on the kinetics of an electrochemical reaction.
  - Changing  $j_o$  changes the minimum potential required to obtain a net current
  - The value of  $j_o$  is zero for an ideal reference electrode
  - If  $j_o$  is greater than the limiting current, the reaction is kinetically limited
  - The kinetic rate parameters ( $j_o$  and  $\alpha$ ) for a particular half cell reaction only depends on the type of electrode on which the reaction is taking place
3. Which statement(s) is/are correct? Assume: solar altitude angle is  $60^\circ$ , diffuse fraction of the atmosphere is 0.2, transmittance of the atmosphere is 0.6,  $q_{solar}=1360 W/m^2$ 
  - Solar radiation corresponds to AM2 spectrum
  - DNI is equal to  $816 W/m^2$
  - GHI is equal to  $883 W/m^2$
  - Daily equivalent sun hours (ESH) in Lausanne doubles on summer solstice as compared to winter solstice as the number of daylight hours doubles  
(**Hint:** Daily ESH is a convenient way to express solar irradiance per day and is defined as the equivalent number of hours of  $1 kW/m^2$  illumination per day)

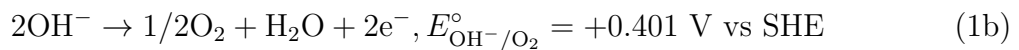
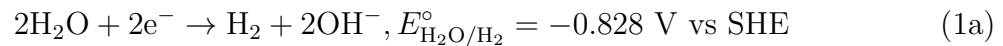
First Name: \_\_\_\_\_ Last Name: \_\_\_\_\_ Sciper: \_\_\_\_\_

4. Choose the correct statement(s) with regard to effect of temperature and doping on the properties of a c-Si semiconductor (for material properties see Table 1)
- Fermi level of an intrinsic semiconductor is not exactly at the middle of the band gap
  - Increasing the temperature to two times the room temperature moves the fermi level towards the conduction band by 3.77%
  - Doping concentration of n-doped semiconductor to keep the fermi level at the middle of the band gap is  $N_D = 1.92 \times 10^9 \text{ cm}^{-3}$
  - Intrinsic concentration varies as  $T^{3/2}$  with temperature
5. An isolated system of enclosed black body radiation undergoes an adiabatic free expansion from an initial state  $P_1, V_1, T_1$  to a final state  $P_2, V_2, T_2$ . The temperature of the surrounding is  $T_0$ .
- The system follows a process given by the relationship  $PV = \text{constant}$
  - The final temperature  $T_2$  is given by  $T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{\frac{3}{4}}$
  - Entropy change of the process is zero
  - Exergy destruction is given by  $\frac{4}{3}aT_1^3V_1T_0\left(\frac{T_1}{T_2} - 1\right)$
6. Which statement(s) with respect to the Fermi level in a semiconductor is/are true?
- The Fermi level always represents a real energy level
  - Temperature has no effect on the position of the Fermi level
  - The Fermi level can be directly measured
  - n-doping of a semiconductor will move the Fermi level towards the valence band
7. Consider a c-Si PV cell with surface area  $A$  at temperature  $T_c$  generating electrical power  $E$ .  $q_s$  is the solar energy absorbed by the cell,  $q_c$  the useful heat released by it,  $q_o$  the energy radiated by it.  $T_s$  and  $T_o$  are the temperature of the sun and the surrounding. Neglect convective and reflective losses. The solar correction constant is  $C' (= \frac{R_{sun}^2}{S_{sun-earth}^2})$ .
- Energy efficiency of the cell is given by  $\frac{E}{C'\sigma T_s^4}$
  - Useful heat flux is given by  $C'\sigma T_s^4 - \sigma T_c^4 - \frac{E}{A}$
  - Exergy associated with useful heat is given by  $q_c\left(1 - \frac{T_o}{T_c}\right)$
  - Exergy associated with radiation energy is given by  $q_o\left(1 - \frac{T_o}{T_c}\right)$

First Name: \_\_\_\_\_ Last Name: \_\_\_\_\_ Sciper: \_\_\_\_\_

**Questions 8-9 concern the following problem statement.**

A photoelectrode made of c-Si is in contact with an alkaline electrolyte (pH = 14). Use eq. (2) to determine the energy levels of the two half reactions (for material properties see Table 1):



$$E = -4.4 \text{ eV} - qE_{\text{half-react}}^\circ - 2.303 \frac{k_{\text{B}}T}{q} p\text{OH} \quad (2)$$

$$1\text{eV} = 1.602\text{e-}19 \text{ J.}$$

8. How would you use the photoelectrode under illumination?

- It can be used as both photoanode and photocathode
- It can be used only as a photocathode
- It can be used only as a photoanode
- Another semiconductor should be used

9. Choose the correct wavelength range(s) of the incident light on the photoelectrode for the photoelectrochemical reaction to happen (if it were to happen)

- $\lambda \leq 1300 \text{ nm}$
- $\lambda \leq 1200 \text{ nm}$
- $\lambda \leq 1100 \text{ nm}$
- $\lambda \leq 1000 \text{ nm}$

First Name: \_\_\_\_\_ Last Name: \_\_\_\_\_ Sciper: \_\_\_\_\_

**Questions 10-13 concern the following problem statement.**

Consider a setup of a solar thermolysis reaction. A solar reactor operating at a constant temperature of 1200 K, exposed to solar irradiation of  $1 \text{ kW/m}^2$  with a concentration factor of 200, receiving water at a rate of 0.59 mol/s and dissociates it stoichiometrically into  $H_2$  and  $O_2$ . The enthalpy change ( $\Delta H_{\text{react}}$ ) for this reaction is 285.8 kJ/mol, and the entropy change ( $\Delta S$ ) is 163.3 J/mol/K at 298 K. The products,  $H_2$  and  $O_2$ , are used in an ideal fuel cell to generate water vapor at the reactor temperature. Assume that  $\Delta H$  and  $\Delta S$  values are independent of temperature for both the splitting of liquid water and the dissociation of water vapor into  $H_2$  and  $O_2$ . Consider the phase change of liquid water to water vapor at  $100^\circ\text{C}$  and atmospheric pressure with a  $\Delta H_{\text{vapourization}}$  of 42 kJ/mol and  $\Delta S_{\text{vapourization}}$  of 112.6 J/mol/K.

10. What is the amount of solar heat utilized by the reactor under these conditions?

- $Q_{\text{solar}} = 349.05 \text{ kW}$
- $Q_{\text{solar}} = 339.31 \text{ kW}$
- $Q_{\text{solar}} = 409.182 \text{ kW}$
- $Q_{\text{solar}} = 285.80 \text{ kW}$

11. How much heat is re-radiated by the reactor, assuming it operates at 1200 K?

- $Q_{\text{rerad}} = 199.48 \text{ kW}$
- $Q_{\text{rerad}} = 205.21 \text{ kW}$
- $Q_{\text{rerad}} = 142.25 \text{ kW}$
- $Q_{\text{rerad}} = 240.59 \text{ kW}$

12. Compute the process efficiency of the given setup.

- $\eta = 21.3\%$
- $\eta = 12.6\%$
- $\eta = 34.2\%$
- $\eta = 57.9\%$

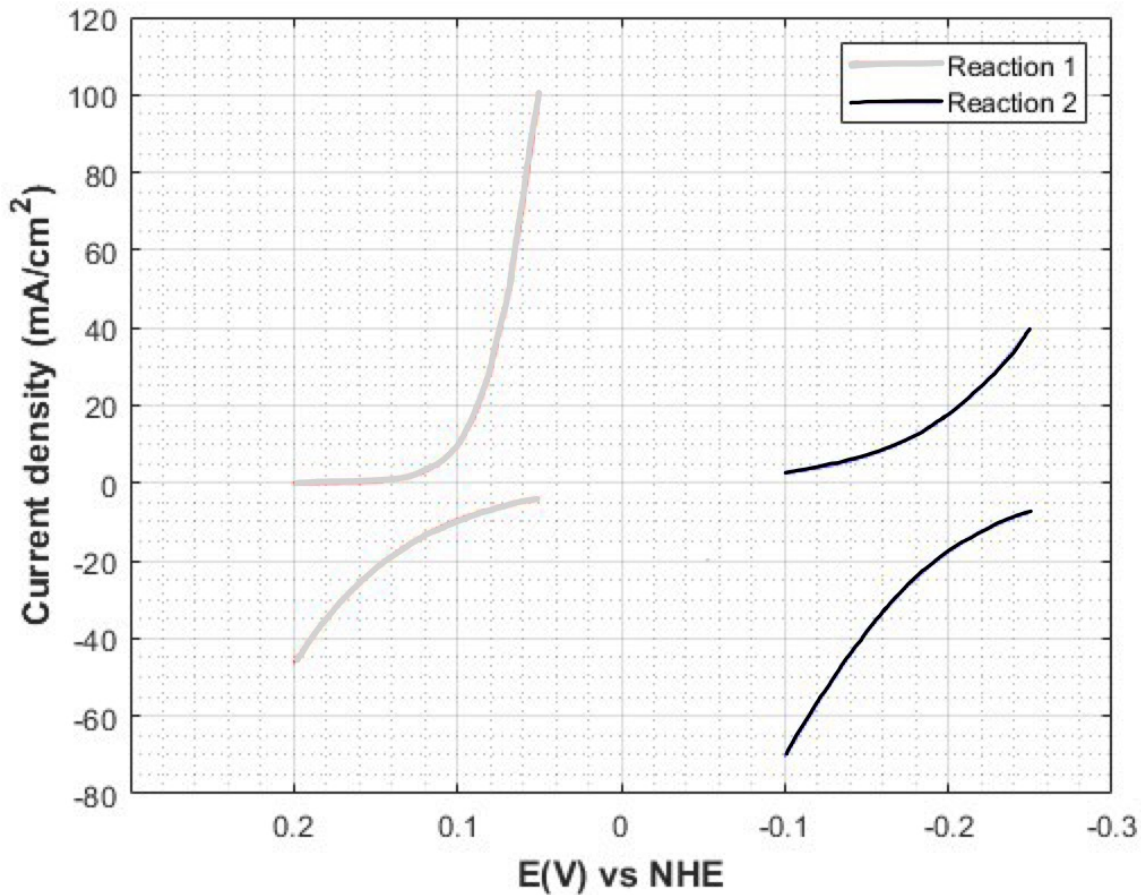
13. What is the theoretical maximum efficiency of the process?

- $\eta_{\text{max}} = 75.17\%$
- $\eta_{\text{max}} = 25.67\%$
- $\eta_{\text{max}} = 31.00\%$
- $\eta_{\text{max}} = 41.21\%$

First Name: \_\_\_\_\_ Last Name: \_\_\_\_\_ Sciper: \_\_\_\_\_

Questions 14-15 concern the following problem statement.

Consider two electrochemical reactions ( $O + ne^- \leftrightarrow R$ ) occurring at standard temperature and pressure whose current-potential characteristics are given by the following graphs.



**Figure 1:** Current-potential characteristic of the two electrochemical reactions. The two curves corresponding to a single reaction denote the anodic and the cathodic branch of the reaction, with positive current being the cathodic branch and the negative current being the anodic branch.

The electrode surface area is 1 cm<sup>2</sup>. The charge transfer resistance and the bulk concentration of the electroactive species for the two reactions are given in this table:

First Name: \_\_\_\_\_ Last Name: \_\_\_\_\_ Sciper: \_\_\_\_\_

	Charge transfer resistance ( $\Omega$ )	Oxidizing species concentration ( $M$ )	Reducing species concentration ( $M$ )
Reaction 1	1.28	0.1	0.5
Reaction 2	1.47	0.5	1

14. Choose the correct statement(s) corresponding to the equilibrium potential of the two reactions

- $E_{eq1} = 0.1$  V
- $E_{eq1} = 0.2$  V
- $E_{eq2} = -0.1$  V
- $E_{eq2} = -0.2$  V

15. Choose the correct statement(s) with regard to the two reactions

- Exchange current density of reaction 1 is  $10 \text{ mA/cm}^2$  and reaction 2 is  $17.5 \text{ mA/cm}^2$ .
- Standard reduction potential of reaction 1 is  $0.12$  V vs (NHE) and reaction 2 is  $-0.18$  V vs (NHE).
- Reaction 2 would be occurring at the anode if a fuel cell is constructed using the given two half cell reactions.
- Number of electrons exchanged in both the reactions is 1.

16. We consider a concentrated solar power (CSP) system based on a solar tower. Choose the correct statement(s)

- A typical CSP power plant efficiency is 35% to 45%
- A typical heat transfer fluid is synthetic oil
- The biggest losses in the heliostat field are the cosine losses
- Thermal storage allows for 24h operation and is typically sensible heat storage

First Name: \_\_\_\_\_ Last Name: \_\_\_\_\_ Sciper: \_\_\_\_\_

**Questions 17-18 concern the following problem statement**

We want to design a combined parabolic dish and 3D CPC solar concentrating system, with CPC concentration ratio equal to 2.42 and the length of the CPC equal to 11.37 cm. The axis of the parabolic dish and the CPC are aligned with the CPC kept at the focal plane of the dish, whose focal length is 4.5 m.

17. Choose the correct statement(s) corresponding to CPC-dish system design

- The acceptance angle of the CPC is 40 degrees
- The Inlet radius of the CPC is 5.81 cm
- The Outlet radius of the CPC is 3.73 cm
- Half acceptance angle of the dish is 8.73 mrad

18. Choose the correct statement(s) corresponding to the parabolic dish design

- The mean concentration ratio of the dish is 3183.90
- The Aperture area of the dish is 33.71  $m^2$
- Minimum possible half acceptance angle for a parabolic dish is 4.65 mrad
- Theoretical maximum mean concentration ratio of any parabolic dish, in general, is 46248.44

First Name: \_\_\_\_\_ Last Name: \_\_\_\_\_ Sciper: \_\_\_\_\_

## Section II: Solar cell analysis [18 points]

A pn junction solar cell is constructed using n-type (100 nm) and p-type crystalline silicon (c-Si) (100 microns) layers of identical doping concentrations  $10^{17} \text{ cm}^{-3}$ , and subjected to normal incident irradiance of  $1 \text{ kW/m}^2$  on the n-side. It is connected to a load whose current density varies exponentially with the voltage according to the relation  $i_{\text{load}}(\text{mA/cm}^2) = 3.19 \times 10^{-5} \cdot e^{38.64 \times V_{\text{load}}}$ .

Consider the following assumptions and the data for the analysis of the solar cell

- (i) Hole and electron current densities at the edges of the depletion regions in the n and p layers are identical and equal to  $25 \text{ mA/cm}^2$ .
- (ii) Incident light is monochromatic with a wavelength of 500 nm, and the refractive index (n) and extinction coefficient (k) of c-Si at this wavelength are 4 and 0.05, respectively.
- (iii) Temperature of the solar cell is 300 K
- (iv) Neglect the recombination of charge carriers in the depletion region
- (v) Reflectivity of the n-type layer is zero.
- (vi) the solar cell is operating at a temperature of 300 K
- (vii) the dark saturation current for the np junction diode is given  $10^{-10} \text{ mA/cm}^2$

Compute the following

1. The short-circuit current density in the solar cell [12 points]
2. The efficiency of the solar cell [6 points]

First Name: \_\_\_\_\_ Last Name: \_\_\_\_\_ Sciper: \_\_\_\_\_

**Table 1:** Property Values for c-Si at 300 K

Property	Value
Work function ( $\chi$ )	4.05 eV
Energy Band Gap ( $E_g$ )	1.12 eV
$\epsilon_r$	11.7
$N_C$	$4.91 \times 10^{18} \text{ cm}^{-3}$
$N_V$	$2.7 \times 10^{19} \text{ cm}^{-3}$

**Table 2:** Physical constants.

Name	Value
Charge constant, $q$ (Coulomb)	1.602e-19
Boltzmann constant, $k_B$ (J/K)	1.381e-23
Faraday's constant, $F$ (Cmol <sup>-1</sup> )	96485.332
Planck's constant, $h$ (Js)	6.626e-34
Free electron mass, $m_0$ (kg)	9.11e-31
Stefan-Boltzmann constant, $\sigma$ (Wm <sup>-2</sup> K <sup>-4</sup> )	5.670e-8
Ideal gas constant, $R$ (Jmol <sup>-1</sup> K <sup>-1</sup> )	8.314
Radius of the Sun, $R_s$ (m)	6.96e8
Distance Earth-Sun, 1 AU (m)	1.496e11

**SCHOOL OF ENGINEERING**  
**MECHANICAL ENGINEERING**  
LRESE - Laboratory of Renewable Energy Sciences and Engineering



First Name: \_\_\_\_\_ Last Name: \_\_\_\_\_ Sciper: \_\_\_\_\_

**SCHOOL OF ENGINEERING**  
**MECHANICAL ENGINEERING**  
LRESE - Laboratory of Renewable Energy Sciences and Engineering



First Name: \_\_\_\_\_ Last Name: \_\_\_\_\_ Sciper: \_\_\_\_\_

**SCHOOL OF ENGINEERING**  
**MECHANICAL ENGINEERING**  
LRESE - Laboratory of Renewable Energy Sciences and Engineering



First Name: \_\_\_\_\_ Last Name: \_\_\_\_\_ Sciper: \_\_\_\_\_

**SCHOOL OF ENGINEERING**  
**MECHANICAL ENGINEERING**  
LRESE - Laboratory of Renewable Energy Sciences and Engineering



First Name: \_\_\_\_\_ Last Name: \_\_\_\_\_ Sciper: \_\_\_\_\_

**SCHOOL OF ENGINEERING**  
**MECHANICAL ENGINEERING**  
LRESE - Laboratory of Renewable Energy Sciences and Engineering



First Name: \_\_\_\_\_ Last Name: \_\_\_\_\_ Sciper: \_\_\_\_\_

**SCHOOL OF ENGINEERING**  
**MECHANICAL ENGINEERING**  
LRESE - Laboratory of Renewable Energy Sciences and Engineering



First Name: \_\_\_\_\_ Last Name: \_\_\_\_\_ Sciper: \_\_\_\_\_

**SCHOOL OF ENGINEERING**  
**MECHANICAL ENGINEERING**  
LRESE - Laboratory of Renewable Energy Sciences and Engineering



First Name: \_\_\_\_\_ Last Name: \_\_\_\_\_ Sciper: \_\_\_\_\_

**SCHOOL OF ENGINEERING**  
**MECHANICAL ENGINEERING**  
LRESE - Laboratory of Renewable Energy Sciences and Engineering



First Name: \_\_\_\_\_ Last Name: \_\_\_\_\_ Sciper: \_\_\_\_\_

**SCHOOL OF ENGINEERING**  
**MECHANICAL ENGINEERING**  
LRESE - Laboratory of Renewable Energy Sciences and Engineering



First Name: \_\_\_\_\_ Last Name: \_\_\_\_\_ Sciper: \_\_\_\_\_