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

Renewable Energy

First Name: ________________

Last Name : ________________

Sciper : ___________________

RENEWABLE ENERGY: EXAM PART HAUSSENER

Date: June 30, 2017; 16:15-19:15; CO1, Duration: 3 hours
Allowed material: Calculator, personal summary (10 single pages A4), and formula memento.
Three exercises – 50% of total points

Exercise 1. (8% of total points) Geothermal energy conversion

a) What is the typical temperature gradient in the earth shell? Assuming the geothermal reservoir is at 3 km and is exploited in a thermodynamic cycle, what is the maximum theoretical efficiency (cold reservoir at room temperature)?

b) A small geothermal heat pump system is used to heat a private house. The geothermal well head exit has a temperature of 100°C and is used to heat the air of the house before being reinjected to the soil at a temperature of 30°C. The geothermal fluid is a glycol-water mixture and has a flow rate of 100mL/s. The heat capacity of the geothermal fluid is 4.18kJ/kg/K and the density is 1000kg/m^3. The air from outside at 5°C needs to be heated to 25°C in the house within 20 minutes. The air density is 1.29kg/m^3 and the heat capacity 1kJ/kg/K. The exchanger efficiency between the geothermal fluid and the heated air is 0.7. The ceiling of the house is at a height of 2.5m. Consider the complete volume of air in the house is to be heated to 25°C. Assume the cold source at 15 °C.

   i. What is the living surface of this house?
   ii. What is the exergy efficiency of this system? Comment on the result.

Exercise 2. (16% of total points) Energy storage approaches

We want to store energy to enable night electricity production of a concentrated solar power plant. The averaged incoming light power of this power plant is 100MW. The mirror reflectance is 0.9, the absorptance of the receiver is 0.9. The heated working fluid can be converted to electrical energy with a steam cycle with an efficiency of 40%, a gearbox's efficiency of 0.98, and a generator's efficiency of 0.98. We want to store 1 hour of electricity produced during the day for night production. You need to choose between three energy storage options: 1) flywheels, 2) thermal storage, and 3) compressed air energy storage.

a) What characteristics would you use to compare the three options? Which storage option would you choose and why?

b) **Option flywheel**:

   i. What is the amount of energy that needs to be stored during 1 hour?
   ii. The ultimate strength of the flywheel is 1000N/mm^2, the density of the material used is 800 kg/m^3, the shape factor is 0.5. The flywheel is based on a hollow cylinder with an inner radius, R_i, of 48cm, an outer radius, R_o, of 50cm, a height of 100cm, and a moment of inertia given by $I=mR_o^2$. What is the minimum number of flywheels that is needed to store the energy?
   iii. What is the maximum rotational speed of these flywheels?

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c) **Option thermal storage**: We will store now this energy in thermal heat with a molten salt mixture composed of $NaNO_3$ and KNO_3. The heat of this molten salt will be used to run the turbine.
   i. What is the amount of thermal energy that needs to be stored to produce 1 hour of electrical power?
   ii. We use a counter flow heat exchanger with an efficiency of 80%. Liquid water at 40°C is heated up to 500°C to be used in the steam cycle, the molten salt is at 580°C and is cooled down to 250°C. The molten salt has a heat capacity of 1.5kJ/kg/K and a density of 1500kg/m^3. Draw a scheme of the temperature along the heat exchanger for the molten salt and the water. What is the volume of the molten salt that must be used to store this heat energy?

d) **Option compressed air energy storage**:
   i. We will use now the electrical energy produced and store it in a compressed air energy storage system. The air at 40°C is adiabatically compressed from 1bar to 70bar. Draw a scheme of the P-V diagram of this adiabatic compression along with an isothermal compression for the same pressure.
   ii. What is the temperature after the adiabatic compression? The heat capacity ratio of air is 1.4.
   iii. Consider that we want to store 30MWh. What is the volume of the cavity using this adiabatic compression assuming that only 85% of this energy can be recovered? You must derive the expression for the work needed for adiabatic compression and then use this expression to find the volume.

Exercise 3. (26% of total points) Solar power production

We have a PV plant where the absorbing area is of the size as EPFL's Rolex Learning Center (20'000 m^2). The typical irradiation in Lausanne is given in table 1. For simplicity, assume GHI = DNI + DHI.

a) The PV panel is made of triple-junction Si cells, having bandgaps of 1.9 eV, 1.4 eV and 1.6 eV (1 eV = $1.60218 \cdot 10^{-19}$ J).
   i. Which one of the cells will be on top, in the middle, and on the bottom? Why?
   ii. What is the maximum amount of solar radiation that can be absorbed by each cell if used as single junctions? What is the fraction of each cell absorbed when used in the triple junction configuration? Use table 2 for the fractional factorial functions.
   iii. Calculate the theoretical possible efficiency of the triple junction cell. Use one band per cell only for the calculation. How does this efficiency compare to a typical silicon cell module you can buy today?
   iv. Why is this efficiency lower than the maximum possible fraction that can be absorbed by the triple junction cell?
   v. What is the annual electricity production of this plant? What is the annual power of this plant?

vi. Assume this DC power is provided to the EPFL campus using a cable with a cross-section area of 50cm^2, 200 m lengths, a resistivity of $1.6 \cdot 10^{-8}$ Ωm, and a voltage of 700 kV. Then the power is converted in a DC-AC converter with an efficiency of 95%. How much power can actually be supplied to EPFL?

b) We now use PV panels made of III-V materials, having bandgaps of 1.8 eV, 0.7 eV, and 1.42 eV. The Rolex Center is covered with dish concentrators (assume the concentrator collection area equals 20’000 m^2), concentrating 1000 times. Each dish has a PV cell in its focal area.
   i. What is the total active PV area?
   ii. What is the total output power? Assume the dish optical efficiency is 85%. Use table 2 for the fractional factorial functions.
   iii. Compare the III-V PV case with the triple junction Si PV case in terms of electricity cost. The Si cells are CHF 200/m^2, the III-V cells are CHF 40’000/m^2, and the concentrator is CHF 150/m^2.

Table 1: Typical hourly irradiation in Lausanne (DNI and DHI given in W/m^2).

Hour	DNI	DHI
0.5	0	0
1.5	0	0
2.5	0	0
3.5	0	0
4.5	0	0
5.5	0	0
6.5	0	19
7.5	208	99
8.5	481	125
9.5	575	153
10.5	665	178
11.5	778	150
12.5	841	124
13.5	807	131
14.5	710	155
15.5	569	165
16.5	333	161
17.5	93	102
18.5	0	15
19.5	0	0
20.5	0	0
21.5	0	0
22.5	0	0
23.5	0	0

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Table 2: Fractional black body function.

λT [10^{-6} m K]	$F_{0-\lambda T}$	λT [10^{-6} m K]	$F_{0-\lambda T}$	λT [10^{-6} m K]	$F_{0-\lambda T}$	λT [10^{-6} m K]	$F_{0-\lambda T}$	λT [10^{-6} m K]	$F_{0-\lambda T}$	λT [10^{-6} m K]	$F_{0-\lambda T}$
500	1.299E-09	3150	0.307	5800	0.720	8450	0.873	11100	0.933	13750	0.961
550	1.349E-08	3200	0.318	5850	0.725	8500	0.875	11150	0.934	13800	0.961
600	9.294E-08	3250	0.329	5900	0.729	8550	0.876	11200	0.935	13850	0.962
650	4.674E-07	3300	0.340	5950	0.734	8600	0.878	11250	0.936	13900	0.962
700	1.839E-06	3350	0.351	6000	0.738	8650	0.879	11300	0.936	13950	0.963
750	5.949E-06	3400	0.362	6050	0.742	8700	0.881	11350	0.937	14000	0.963
800	1.644E-05	3450	0.372	6100	0.746	8750	0.883	11400	0.938	14050	0.963
850	3.990E-05	3500	0.383	6150	0.750	8800	0.884	11450	0.938	14100	0.964
900	8.703E-05	3550	0.393	6200	0.754	8850	0.886	11500	0.939	14150	0.964
950	1.735E-04	3600	0.404	6250	0.758	8900	0.887	11550	0.940	14200	0.964
1000	3.208E-04	3650	0.414	6300	0.762	8950	0.889	11600	0.940	14250	0.965
1050	5.559E-04	3700	0.424	6350	0.766	9000	0.890	11650	0.941	14300	0.965
1100	9.113E-04	3750	0.434	6400	0.769	9050	0.891	11700	0.941	14350	0.965
1150	0.001	3800	0.443	6450	0.773	9100	0.893	11750	0.942	14400	0.965
1200	0.002	3850	0.453	6500	0.776	9150	0.894	11800	0.943	14450	0.966
1250	0.003	3900	0.462	6550	0.780	9200	0.895	11850	0.943	14500	0.966
1300	0.004	3950	0.472	6600	0.783	9250	0.897	11900	0.944	14550	0.966
1350	0.006	4000	0.481	6650	0.786	9300	0.898	11950	0.944	14600	0.967
1400	0.008	4050	0.490	6700	0.790	9350	0.899	12000	0.945	14650	0.967
1450	0.010	4100	0.499	6750	0.793	9400	0.901	12050	0.946	14700	0.967
1500	0.013	4150	0.507	6800	0.796	9450	0.902	12100	0.946	14750	0.968
1550	0.016	4200	0.516	6850	0.799	9500	0.903	12150	0.947	14800	0.968
1600	0.020	4250	0.524	6900	0.802	9550	0.904	12200	0.947	14850	0.968
1650	0.024	4300	0.533	6950	0.805	9600	0.905	12250	0.948	14900	0.968
1700	0.029	4350	0.541	7000	0.808	9650	0.907	12300	0.948	14950	0.969
1750	0.034	4400	0.549	7050	0.811	9700	0.908	12350	0.949	15000	0.969
1800	0.039	4450	0.557	7100	0.814	9750	0.909	12400	0.949	15050	0.969
1850	0.045	4500	0.564	7150	0.816	9800	0.910	12450	0.950	15100	0.969
1900	0.052	4550	0.572	7200	0.819	9850	0.911	12500	0.950	15150	0.970
1950	0.059	4600	0.579	7250	0.822	9900	0.912	12550	0.951	15200	0.970
2000	0.067	4650	0.587	7300	0.824	9950	0.913	12600	0.951	15250	0.970
2050	0.075	4700	0.594	7350	0.827	10000	0.914	12650	0.952	15300	0.971
2100	0.083	4750	0.601	7400	0.829	10050	0.915	12700	0.952	15350	0.971
2150	0.092	4800	0.608	7450	0.832	10100	0.916	12750	0.953	15400	0.971
2200	0.101	4850	0.614	7500	0.834	10150	0.917	12800	0.953	15450	0.971
2250	0.110	4900	0.621	7550	0.837	10200	0.918	12850	0.954	15500	0.971
2300	0.120	4950	0.627	7600	0.839	10250	0.919	12900	0.954	15550	0.972
2350	0.130	5000	0.634	7650	0.841	10300	0.920	12950	0.955	15600	0.972
2400	0.140	5050	0.640	7700	0.844	10350	0.921	13000	0.955	15650	0.972
2450	0.151	5100	0.646	7750	0.846	10400	0.922	13050	0.956	15700	0.972
2500	0.161	5150	0.652	7800	0.848	10450	0.923	13100	0.956	15750	0.973
2550	0.172	5200	0.658	7850	0.850	10500	0.924	13150	0.956	15800	0.973
2600	0.183	5250	0.664	7900	0.852	10550	0.925	13200	0.957	15850	0.973
2650	0.194	5300	0.669	7950	0.854	10600	0.925	13250	0.957	15900	0.973
2700	0.205	5350	0.675	8000	0.856	10650	0.926	13300	0.958	15950	0.974
2750	0.217	5400	0.680	8050	0.858	10700	0.927	13350	0.958	16000	0.974
2800	0.228	5450	0.686	8100	0.860	10750	0.928	13400	0.958	16050	0.974
2850	0.239	5500	0.691	8150	0.862	10800	0.929	13450	0.959	16100	0.974
2900	0.251	5550	0.696	8200	0.864	10850	0.930	13500	0.959	16150	0.974
2950	0.262	5600	0.701	8250	0.866	10900	0.930	13550	0.960	16200	0.975
3000	0.273	5650	0.706	8300	0.868	10950	0.931	13600	0.960	16250	0.975
3050	0.285	5700	0.711	8350	0.869	11000	0.932	13650	0.960	16300	0.975
3100	0.296	5750	0.715	8400	0.871	11050	0.933	13700	0.961	16350	0.975

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ÉCOLE POLYTECHNIQUE
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RENEWABLE ENERGY: EXAM PART HAUSSENER

Date: June 30, 2017; 16:15-19:15; CO1, Duration: 3 hours
Allowed material: Calculator, personal summary (10 single pages A4), and formula memento.
Three exercises – 50% of total points (total 106 points)

Exercise 1. (8% of total points, 16.5 p) Geothermal energy conversion

a) What is the typical temperature gradient in the earth's shell? Assuming the geothermal reservoir at this temperature (at a certain depth) can be exploited in a thermodynamic cycle, what is the maximum theoretical efficiency (cold reservoir at room temperature)?
Solution: ~30K/km **(1p)**
Carnot efficiency (1p) = 1- Tc/Th **(1p)** = (at 3 km depth the temperature is 25+363K) = 1-298/388 = 23% **(0.5p)**

b) A small geothermal heat pump system is used to heat a private house. The geothermal well head exit has a temperature of 100°C and is used to heat the air of the house before being reinjected to the soil at a temperature of 30°C. The geothermal fluid is a glycol-water mixture and has a flow rate of 100mL/s. The heat capacity of the geothermal fluid is 4.18 kJ/kg/K and the density is 1000kg/m^3. The air from outside at 5°C needs to be heated to 25°C in the house within 20 minutes. The air density is 1.29kg/m^3 and the heat capacity 1 kJ/kg/K. The exchanger efficiency between the geothermal fluid and the heated air is 0.7. The ceiling of the house is at a height of 2.5m. Consider the complete volume of air in the house is to be heated to 25°C.

   i. What is the living surface of this house?

Solution: i- $Q_{air}=\rho_{air}*cp_{air}*H\_{Ceiling}*A/\Delta t\Delta T_{air}$**(1p)**$=Q_{geo}*\eta_{exchanger}$**(1p)**
$Q_{geo}=\rho_{geo}*cp_{geo}*V'\Delta T_{geo}$**(1p)**
$m_{air}=\rho_{air}*H\_{Ceiling}*A$
A = $Q_{geo}*\eta_{exchanger}/(c_{air}\Delta T_{air}\,\rho_{air}\,H\_{Ceiling}/\Delta t)$**(1p)**
A = 381.06 m^2**(0.5p)**

   ii. What is the exergy efficiency of this system? Comment on the result.

Solution: ii- $Ex_{log,source}= Q_{geo}*(1- T_{amb}/ T_{log,source})$ **(1p)** =4.24 kW **(0.5p)**
$T_{log,source}=(T_{h,geo}-T_{c,geo})/\ln(T_{h,geo}/T_{c,geo})$ **(1p)**=63.789°C (337 K) **(0.5p)**
$Ex_{log,air}= Q_{air}*(1- T_{amb}/ T_{log,air})$**(1p)**=0 or -8.2286 W **(0.5p)**
$T_{log,air}=(T_{h,air}-T_{c,air})/\ln(T_{h,air}/T_{c,air})$**(1p)**=14.88°C (288 K) **(0.5p)**
$\eta_{ex}=Ex_{log,air}/Ex_{log,source}$**(1p)**=0% or -0.19% **(0.5p)**
The exergy efficiency is very low because the heated temperature of air is only 25°C.**(1p)**

Exercise 2. (16% of total points, 32.5p) Energy storage approaches

We want to store energy to enable night electricity production from a concentrated solar power plant. The averaged incoming light power of this power plant is 100MW. The mirror reflectance is 0.9, the absorptance of the receiver is 0.9. The heated working fluid can be converted to electrical energy with a steam cycle with an efficiency of 40%, a gearbox's efficiency of 0.98, and a generator's efficiency of 0.98. We want to store 1 hour of electricity produced during the day for night production. You need to choose between three energy storage options: 1) flywheels, 2) thermal storage, and 3) compressed air energy storage.

a) Based on your knowledge, which storage option would you choose and why? Explain your choice by comparing the specific characteristics of each storage option.

Solution a): Relevant characteristics are energy density**(1p)**, power density**(1p)**, and storage time**(1p)**.

Thermal heat is the best option for this case because flywheel is too short for one hour during the night and compressed air storage is an overkill as it is more complex and long term storage option compared to thermal heat.**(1p)**

b) **Option flywheel**:

i. What is the amount of energy that needs to be stored during 1 hour?

Solution i: $P_{stored}=Irr*Ref*Abs*\eta_{steam}*\eta_{gear}*\eta_{gen}*\Delta t$**(1p)** =31.12MWh .**(0.5p)** = 1.12e11J

ii. The ultimate strength of the flywheels are 1000N/mm^2, the density of the material used is 800 kg/m^3, the shape factor is 0.5. The flywheels are based on a hollow cylinder with an inner radius, R_i, of 48cm, an outer radius, R_o, of 50cm, a height of 100cm, and a moment of inertia given by $I=mR_o^2$. What is the minimum number of flywheels that are needed to store this energy?

Solution ii: $m=\pi H(R_o^2- R_i^2)\rho$ **(1p)** =49.26 kg

$E_{max}=Km\sigma_{max}/\rho$.**(1p)** =8.55 kWh

No. flywheels= E_{stored}/ E_{max}.**(1p)** =3'639.**(0.5p)**

iii. What is the maximum rotational speed of these flywheels?

Solution iii: $E_{max}=Km\sigma_{max}/\rho$.**(1p)** $=1/2mR_o^2\omega_{max}^2$.**(1p)**

$\omega_{max}=1/R_o(2\sigma_{max} K/\rho)^{0.5}$.**(1p)** =2236 rad/s or 21'353rpm .**(0.5p)**

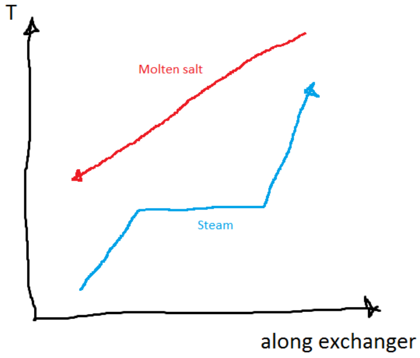
c) **Option thermal storage**: We will store now this energy in thermal heat with a molten salt mixture composed of $NaNO_3$ and KNO_3. The heat of this molten salt will be used to run the turbine.

i. What is the amount of thermal energy that needs to be stored to produce 1 hour of electrical power?

Solution i: $P_{heat}=P_{stored}/(\eta_{steam}*\eta_{gear}*\eta_{gen})$.**(1p)** $E=P*\Delta t$.**(1p)** = 81MW * 1h = 81 MWh .**(0.5p)** = 2.91e11 J

ii. We use a counter flow heat exchanger with an efficiency of 80%. Liquid water at 40°C is heated up to 500°C to be used in the steam cycle, the molten salt is at 580°C and is cooled down to 250°C. The molten salt has a heat capacity of 1.5 J/kg/K and a density of 1500 kg/m^3. Draw a scheme of the temperature along the heat exchanger for the molten salt and the water. What is the volume of the molten salt that must be used to store this heat energy?

Solution ii:



(1p) for molten salt, .**(1p)** for steam (with constant part)

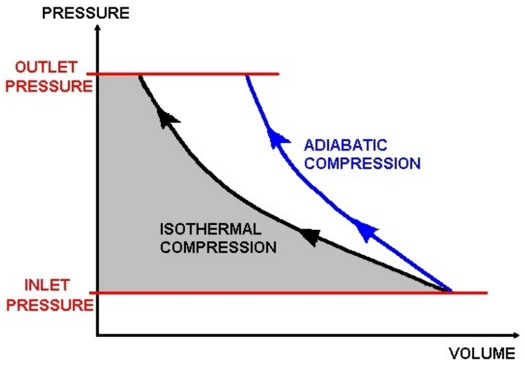
$E_{heat}/\eta_{exchanger}$ **(1p)** $=V\ \rho\ c_{p,molten\ salt}\ \Delta T_{molten\ salt}$ **(1p)**

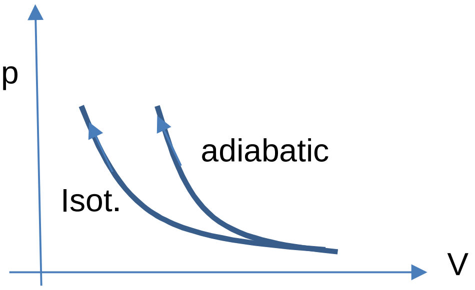
$V=E_{heat}/\eta_{exchanger}/(\rho c_{p,molten\ salt}\ \Delta T_{molten\ salt})$ **(1p)** $=490.1\ m^3$**(0.5p)**

d) **Option compressed air energy storage**:

i. We will use now the electrical energy produced and store it in a compressed air energy storage system. The air at 40°C is adiabatically compressed from 1bar to 70bar. Draw a scheme of the P-V diagram of this adiabatic compression along with an isothermal compression for the same pressure.

Solution i:





Adiabatic line **(0.5p)** and isothermal line **(0.5p)**, in correct relation to each other **(1p)**

Either case is ok, depends if they do Vdp or pdV

ii. What is the temperature after the adiabatic compression? The heat capacity ratio of air is 1.4.

Solution ii: PV^k=constant for adiabatic compression **(1p)** incorporate ideal gas law: $pv=RT/M$ **(1p)**

$P_0(nRT_0/P_0)^k=P_0^{1-k}T_0^k$ which would be $=P_1^{1-k}T_1^k$
$T_1=(P_0/P_1)^{(1-k)/k}T_0$ **(1p)**=781°C (1054.2 K) **(0.5p)**

iii. Consider that we want to store 30MWh. What is the volume of the cavity using this adiabatic compression assuming that only 85% of this energy can be recovered? You must derive the expression for the work needed for adiabatic compression and then use this expression to find the volume.

Solution iii: $W=-\int_{V1}^{V2} PdV$ **(1p)**

For adiabatic $PV^k = C$ (constant)

$W=-\int_{V1}^{V2} CV^{-k}dV$ **(1p)** $=\frac{-C}{1-k}(V2^{1-k}-V1^{1-k})$ **(1p)**

$P_1V_1^k = C$

$W=\frac{P_1V_1}{k-1}\left(\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}-1\right)$ **(1p)**

W/η **(1p)** $=P_1V_1/(k-1)\cdot((P_2/P_1)^{(k-1)/k}-1)$
$V_1=(W/\eta)\cdot\{(k-1)/P_1\}\cdot 1/((P_2/P_1)^{(k-1)/k}-1)$ **(1p)** $=2.15e5\ m^3$ **(0.5p)**

Same marking approach if they did it with Vdp

Exercise 3. (26% of total points, 56p) Solar power production

We have a PV plant where the absorbing area is of the size as EPFL's Rolex Learning Center (20'000 m^2). The typical irradiation in Lausanne is given in table 1. For simplicity, assume GHI = DNI + DHI.

a) The PV panel is made of triple-junction Si cells, having bandgaps of 1.9 eV, 1.4 eV and 1.6 eV (1 eV = $1.60218\cdot10^{-19}$ J).

i. Which one of the cells will be on top, in the middle, and on the bottom? Why?
Arrangement must be in decreasing order of bandgaps. Top: 1.9 eV, Middle: 1.6 eV, Bottom: 1.4 eV **(1p)**. If the photon has higher energy than the bandgap, the excess energy is absorbed and lost as heat. So, absorbing the higher energy photons first makes it more efficient. **(1p)**

ii. What is the maximum amount of solar radiation that can be absorbed by each cell if used as single junctions? What is the fraction of each cell absorbed when used in the triple junction configuration? Use table 2 for the fractional factorial functions.

$$\lambda=\frac{hc}{E}\mathbf{(1p)}\rightarrow\lambda_{1.9eV}=654.2763\,nm\mathbf{(0.5p)};\ \lambda_{1.6eV}=776.9531\,nm\mathbf{(0.5p)};\ \lambda_{1.4eV}=887.9464\,nm\mathbf{(0.5p)}$$

Assuming each bandgap single cell has max possible absorbed light fraction (T=6000K; also ok if 5800K):
Single junction:
1.9 eV cell: $F_{0-654.27}=0.4671$ **(1p)**
1.6 eV cell: $F_{0-776.95}=0.5886$ **(1p)**
1.4 eV cell: $F_{0-887.94}=0.6723$ **(1p)**
Triple junction: understand that it is F0-λ2 – F0-λ1 **(1p)**
1.9 eV cell: $F_{0-654.27}=0.4671$ **(1p)**

1.6 eV cell: $F_{654.27-776.95} = 0.1215$ **(1p)**
1.4 eV cell: $F_{776.95-887.94} = 0.0837$ **(1p)**

iii. Calculate the theoretical possible efficiency of the triple junction cell. Use one band per cell only for the calculation. How does this efficiency compare to a typical silicon cell module you can buy today?

$$\eta_{max} = \sum_{i=1}^{N} \frac{E_g}{E_{\lambda_{m,i}}} F_{\lambda_i-\lambda_{i+1}} \,\mathbf{(1p)} = \sum_{i=1}^{N} \frac{\lambda_{m,i}}{\lambda_g} F_{\lambda_i-\lambda_{i+1}} \,\mathbf{(1p)}$$

$$\lambda_{m,1.9eV} = 327.1382\,nm\,\mathbf{(1p)};\ \lambda_{m,1.6eV} = 715.6147\,nm\,\mathbf{(1p)};\ \lambda_{m,1.4eV} = 832.4498\,nm\,\mathbf{(1p)}$$

$$\begin{aligned}\eta_{max} &= \frac{327.1382}{654.2763}0.4671 + \frac{715.6147}{776.9531}0.1215 \\ &\quad + \frac{832.4498}{887.9464}0.0837\,\mathbf{(1p\ for\ the\ sum, not\ numerical\ values)} \\ &= 0.4239 = 42.39\%\,\mathbf{(0.5p)}\end{aligned}$$

A typical silicon cell module has efficiency of 20% (anything between 15%-25%). **(1p)**

iv. Why is this efficiency lower than the maximum possible fraction that can be absorbed by the triple junction cell?

Because one photon can only generate one electron-hole pair **(1p)**, and so all energy of the photon larger than the band gap energy will not contribute to this **(1p)**

v. What is the annual electricity production of this plant? What is the annual power of this plant?

$$GHI(integrated\ for\ 24\ hr) = 7637\ Wh/m^2\ \mathbf{(2p)}$$

$$\begin{aligned}\text{Annual electricity output} &= \eta_{max} * GHI * A_{abs}\ \mathbf{(1p)} \\ &= 0.423 * 7637 * 20000 \\ &= 23.582\ \text{GWh}\,\mathbf{(0.5p)}\end{aligned}$$

$$Output\ Power = \frac{annaul\ electricity}{24 * 365}\,\mathbf{(1p)} = 2.6920\ MW\,\mathbf{(0.5p)}$$

Same points if they go via daily averaged input power

vi. Assume this DC power is provided to the EPFL campus using a cable with a cross-section area of 50cm², 200 m lengths, a resistivity of 1.6·10⁻⁸ Ωm, and a voltage of 700 kV. Then the power is converted in a DC-AC converter with an efficiency of 95%. How much power can actually be supplied to EPFL?

$$Resistance = \frac{\rho l}{A}\,\mathbf{(1p)} = \frac{1.6 * 10^{-8} * 200}{50 * 10^{-4}} = 6.4 * 10^{-4}\ \Omega\,\mathbf{(0.5p)}$$

$$Current\ through\ wire = I = \frac{Power}{V}\,\mathbf{(1p)} = \frac{2.6920 * 10^6}{700 * 10^3} = 3.8457\ A\,\mathbf{(0.5p)}$$

$$Power\ loss\ due\ to\ cable\ transmission = I^2R\,\mathbf{(1p)} = 5.11^2 * 6.4 * 10^{-4} = 0.0095\ W\,\mathbf{(0.5p)}$$

Power loss due to cable transmission is negligible because of ultra high voltage transmission.

$$Power\ after\ AC - DC\ conversion = \eta_{AC-DC} * Daily\ Power\ Output\,\mathbf{(1p)} = 3.4\ MW\,\mathbf{(0.5p)}$$

b) We now use PV panels made of III-V materials, having bandgaps of 1.8 eV, 0.7 eV, and 1.42 eV. The Rolex Center is covered with dish concentrators (assume the concentrator collection area equals 20’000 m^2), concentrating 1000 times. Each dish has a PV cell in its focal area.

i. What is the total active PV area?

$$Active\ PV\ area = \frac{20000}{1000}\mathbf{(1p)} = 20m^2\mathbf{(0.5p)}$$

ii. What is the total output power? Assume the dish optical efficiency is 85%. Use table 2 for the fractional factorial functions.

Realization to only use DNI **(1p);** $DNI_{mean} = 252.5\ W/m^2$ **(2p)**

$$To\ calculate\ max.theoretical\ efficiency:\ \ \eta_{max} = \sum_{i=1}^{N}\frac{E_g}{E_{\lambda_{m,i}}}F_{\lambda_i-\lambda_{i+1}} = \sum_{i=1}^{N}\frac{\lambda_{m,i}}{\lambda_g}F_{\lambda_i-\lambda_{i+1}}\mathbf{(1p)}$$

$$\lambda = \frac{hc}{E}\mathbf{(1p)} \rightarrow \lambda_{1.8eV} = 690.6250\,nm\mathbf{(1p)};\ \lambda_{1.42eV} = 875.4401\,nm\mathbf{(1p)};\ \lambda_{0.7eV} = 1775.893\,nm\mathbf{(1p)}$$

Triple junction (in case they didn’t do it in the first part, you would give them the point here for the understanding on how to do it for layered junctions):

1.80 eV cell: $F_{0-690.63} = 0.5060$**(1p)**

1.42 eV cell: $F_{690.63-875.44}$ = 0.6643 – 0.5060 = 0.1583**(1p)**

0.70 eV cell: $F_{875.44-1775.89}$ = 0.9261 – 0.6643 = 0.2618**(1p)**

$$\lambda_{m,1.9eV} = 345.3150\,nm\mathbf{(1p)};\ \lambda_{m,1.6eV} = 783.0326\,nm\mathbf{(1p)};\ \lambda_{m,1.4eV} = 1325.7\,nm\mathbf{(1p)}$$

$$\eta_{max} = \frac{345.3150}{690.6250}0.5060 + \frac{783.0326}{875.4401}0.1583 + \frac{1325.7}{1775.893}0.2618\mathbf{(1p\ for\ sum, not\ numerical\ values)} = 0.5900 = 59\%\mathbf{(1p)}$$

$$Output\ Power = \eta_{dish} * \eta_{max} * DNI_{mean} *\ A_{abs}\mathbf{(1p)} = 0.85 * 0.5900 * 252.5 * 20 * 1000 = 2.53MW\ \mathbf{(0.5p)}$$

iii. Compare the III-V PV case with the triple junction Si PV case in terms of cost per electricity productoin. The Si cells are CHF 200/m^2, the III-V cells are CHF 40’000/m^2, and the concentrator is CHF 150/m^2.

$$Cost_{Si-PV} = (200 * 20000\mathbf{(1p)})/electricity = \mathbf{(1p)}4{,}000{,}000\ CHF/(2.69*365*24)\mathbf{(0.5p)}$$

$$Cost_{III-V-PV} = (40000 * 20\ + 150 * 20000\mathbf{(1p)})/electricity = \mathbf{(1p)}3{,}800{,}000\ CHF/(2.53 * 365 * 24)\mathbf{(0.5p)}$$

It is cheaper to use III-V PV than Si PV**(1p)**