Fall 2017
Prof. George Gross
Room 4052 ECEB

ECE 333 Green Electric Energy – Midterm 2

***Monday, December* 4, 2017.**

6:00 – 7:30 *p.m.*

***ECEB* Room 1015.**

Closed book, closed notes.

Cell phones are not allowed.

Three doubles-sided cheat sheets on A4-size paper and simple calculators are allowed.

Name: ____ last 4 digits of your UIN:_______

The exam consists of 4 problems. **Read** each problem carefully. In the solution, **state** clearly each assumption and its justification in every problem and **show** all your work.

problem	**type**	**points**	**grade**
1	*PV performance estimation*	45	
2	*internal rate of return*	45	
3	*PV system sizing and configuration*	45	
4	*brief questions*	65	
total		**200**	

Problem 1: [45 points] *PV* Performance Estimation

We consider a 505 m^2 *PV* system consisting of 420 modules. Each module capacity under *stc* is 86 W_p.

a. [12 points] Given that the *PV* system *AC* output under *stc* is 27.8 kW, **calculate** the non-temperature related *PV* power derate factor χ.

$p_{DC,stc} = (86)(420) = 36.12 kW_p$ (4 points)

$p_{AC,stc} = (\chi)(p_{DC,stc})$

$\chi = \frac{p_{AC,stc}}{p_{DC,stc}} = \frac{27.8}{36.12} = 0.77$

b. [33 points] Assume an average daily insolation of 5 *suns* with the temperature-related derate factor χ' = 0.7. **Answer** the questions below making use of the application of the peak-hours approach.

i. **[11 points] Determine** the expected annual energy production of the *PV* system.

$$Annual\ energy = (p_{DC,stc})(\chi')\left(\frac{daily\ insolation}{1\frac{kW}{m^2}}\right)(365)$$

$$Annual\ energy = (36.12)(0.7)(5)(365) = 46{,}143.3\ kWh/y$$

ii. **[11 points] Determine** the *PV* system capacity factor $c.f._{DC}$.

$$c.f._{DC} = (\chi')\left(\frac{daily\ insolation}{1\frac{kW}{m^2}}\right)\left(\frac{1}{24\frac{h}{\mathrm{d}}}\right)$$

$$c.f._{DC} = (0.7)(5)\left(\frac{1}{24}\right) = 0.1458$$

iii. **[11 points] Determine** the overall *PV* system efficiency $\bar{\eta}$.

$$\bar{\eta} = \frac{(\text{Annual energy})}{\left(\frac{daily\ insolation}{1\frac{kW}{m^2}}\right)(Area)(365)}$$

$$\bar{\eta} = \frac{(46143.3)}{(5)(505)(365)} = 5\%$$

Problem 2: [45 points] ***Internal Rate of Return***

Suppose you are hired as a consultant to advise your client on an investment in a *PV* project. Your client asks you to evaluate two *PV* projects with the characteristics tabulated below.

PV **Project 1:**

feature	***value***
capacity	20 *kW*
lifetime	15 *years*
investment costs	*$* 130,500
annual load consumption reduction	200 *MWh*
monthly peak demand reduction	35 *kW*

PV **Project 2:**

feature	***value***
capacity	20 *kW*
lifetime	15 *years*
investment costs	*$* 93,200
annual load consumption reduction	180 *MWh*
monthly peak demand reduction	26 *kW*

The table below provides the cost data:

charges	***value***
electricity	80 *$/MWh*
demand	10 *$/kW–month*

You will need to use the *IRR* table provided at the last page to answer the questions below.

a. **[35 points]** Your client requests that you provide the *IRR*s of the two projects. **Determine** their values and **explain** the appropriateness of *IRR* to measure the performance of each project. Is a higher *IRR* better or worse for a project? Please **explain** your rationale in the response to the question. **Show** all your work. **State** all the assumptions you use and why they are reasonable.

- The IRR is a measure of how quickly we recover an investment, the speed or rate at which the returns recover an investment
- Hence, IRR is an appropriate metric to decide between the projects as assessing which project will return an investment faster.
- Higher IRR is better as it return an investment faster.

Project 1:

The annual savings of Project 1:

- energy savings: (200 *MWh*)(80 *\$/MWh*) = *\$* 16,000
- peak demand savings : (35 *kW*)(10 *\$/kW-month*) (12 *months*) = *\$* 4,200

Total savings = *\$* 16,000 + *\$* 4200 = *\$* 20,200

The *IRR* is the value of d' that results in

$$0 = -130{,}500 + 20{,}200\,\frac{1-(\beta')^{15}}{d'}$$

$$\frac{1-(\beta')^{15}}{d'} = 6.46$$

The table look-up produces $d' = 13\ \%$.

Project 2:

The annual savings of Project 2:

- energy savings: (180 *MWh*)(80 *\$/MWh*) = *\$* 14,400
- peak demand savings : (26 *kW*)(10 *\$/kW-month*) (12 *months*) = *\$* 3,120

Total savings = *\$* 14,400 + *\$* 3,120 = *\$* 17,520

The *IRR* is the value of d' that results in

$$0 = -93{,}200 + 17{,}520 \frac{1-(\beta')^{15}}{d'}$$

$$\frac{1-(\beta')^{15}}{d'} = 5.32$$

The table look-up produces $d' = 17\ \%$.

b. **[10 points] Select** your recommended choice between the 2 projects. You must **justify** your selection.

PV Project 2 should be selected because its IRR value is higher than the IRR value of PV Project 1.

Problem 3: [45 points] *PV* System Sizing and Configuration

As the lead engineer on a project to install a *PV* system to supply 4,088 *kWh/y,* you are asked to quantify the specific results for the project based on the tabulated data below. Assume that the average daily insolation is 5 $kWh/m^2 - d$ and the temperature-related derate factor χ' = 0.7.

PV Module Data:

parameter/variable	***symbol***	***value***	***units***
maximum power	p_m	200	*W* (*DC*)
MPP voltage	v_{MPP}	50	*V* (*DC*)
MPP current	i_{MPP}	3	*A* (*DC*)
open-circuit voltage	v_{oc}	60	*V* (*DC*)
short-circuit current	i_{sc}	5	*A* (*DC*)

PCU specifications:

parameter/variable	***symbol***	***value***	***units***
maximum voltage input	v_{PCU}^{M}	730	*V* (*DC*)
maximum current input	i_{PCU}^{M}	23	*A* (*DC*)
maximum MPTT voltage input	v_{MPTT}^{M}	620	*V* (DC)
minimum MPTT voltage input	v_{MPTT}^{m}	330	*V* (DC)

a. **[12 points] Determine** the required *DC* output of the system $p_{DC,stc}$ under *stc*.

$$(p_{DC,stc}) = \frac{annual\ energy}{(\chi')\left(\dfrac{daily\ insolation}{1\,\dfrac{kW}{m^2}}\right)(365)}$$

$$(p_{DC,stc}) = \frac{4{,}088}{(0.7)(5)(365)} = 3.2\ kW_p$$

b. **[12 points] Estimate** the total number of *PV* modules that **must** be purchased to design the *PV* system.

$$Total\ number\ of\ modules = \frac{(p_{DC,stc})}{Maximum\ power\ of\ the\ PV\ module} = \frac{3200}{200} = 16$$

c. **[21 points] Present** a feasible configuration of the *PV* modules, so that every module operates at its *MPP* value. **Indicate** how the *MPP* requirement is met.

$$N_s \leq \min\left\{\frac{v^M_{PCU}}{v_{MPP}}, \frac{v^M_{MPTT}}{v_{MPP}}\right\} = \min\left\{\frac{730}{50}, \frac{620}{50}\right\} = 12.4$$

$$N_s \geq \frac{v^m_{MPTT}}{v_{MPP}} = \frac{330}{50} = 6.6$$

$$N_p \leq \frac{i^M_{PCU}}{i_{MPP}} = \frac{23}{4} = 5.75$$

Since 16 modules must be installed, $N_s = 8$, and $N_p = 2$.

The configuration is in accordance with the PV Module and PCU specifications, hence every module is operating at its MPP.

Problem 4: [65 points] Brief Questions

a. **[15 points] State** the specific services that a *CSP* plant with a thermal energy storage (*TES*) provides, that cannot be provided by a *CSP* plant without a *TES*.

- A TES provides flexibility in CSP energy production
- TES enables a CSP plant to produce electricity outside the sunrise–sunset periods and also provides smoothing of the CSP power output in cases of cloud cover occurrences
- The storage of energy during the lower demand periods and its use for generation for delivery in higher–demand periods increase the economic value of the CSP–TES–produced energy and may offset the additional TES investment costs

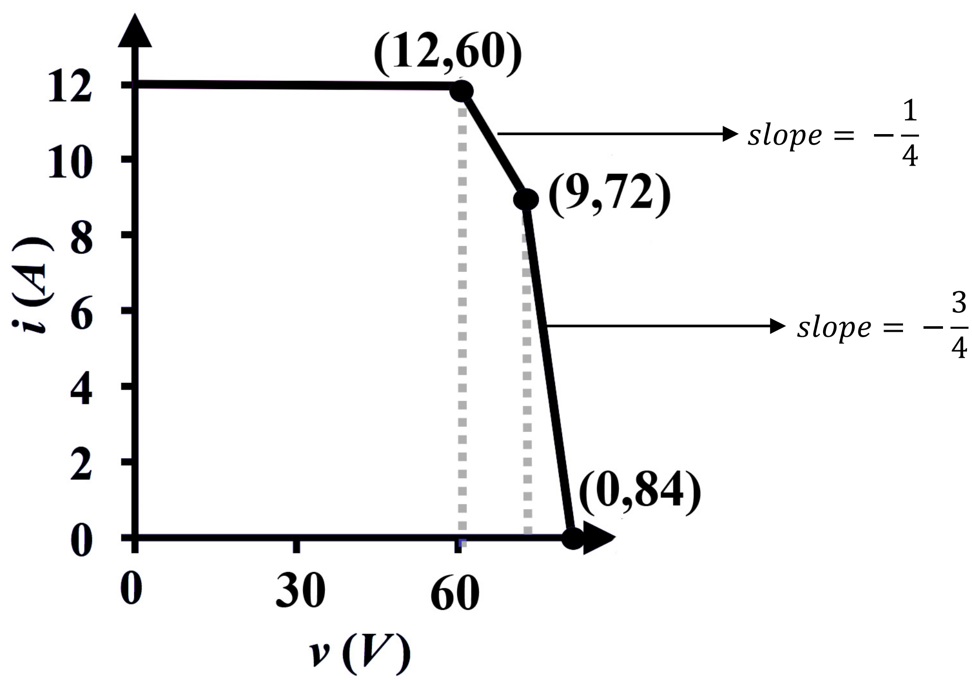
b. **[15 points] State** the key benefits of the installation of tracking systems for *PV* panels. **Discuss** the two tracking system types and **enumerate** their individual characteristics.

The solar panels are equipped with tracking systems to allow the panels to track the movement of the sun across the sky and change panel positions to better use the insolation the panels receive

Tracking systems are categorized as

- two–axis trackers, which can adjust the two panel angles – tilt and azimuth – to orient the panels to be perpendicular to the sun rays
- single–axis trackers, which can change only one of the solar panel angles – either tilt or azimuth

c. **[15 points]** The piece-wise linear $i - v$ curve of a *PV* module is provided as below:



Determine by inspection the *current* and *voltage* values of the maximum power operating point.

The maximum power operating point of the curve will be in one of the corners of the polytope, hence it is sufficient to check the corners.

The power delivered at (12, 0) is 0 W.
The power delivered at (12,60) is 720 W.
The power delivered at (9, 72) is 648 W.
The power delivered at (0, 84) is 0 W.

(12, 60) delivers the highest power. Hence the current of the maximum power operating point is 12 A and the voltage of the maximum power operating point is 60 V.

d. **[10 points]** Which of the following statements is (are) **not correct**?

a) An input-output curve of a conventional unit is characterized by its monotonically non–decreasing shape.
b) Approximately 33 % of the world's total *PV* capacity makes Europe the world's leading region in terms of cumulative installed capacity at the end of 2016.
c) Spain is the leading country in the world in terms of total installed *CSP* capacity.
d) The application of the time–of–use (*TOU*) rates always decreases the monthly electricity bill of the customers.
e) One of the key drivers for *US PV* growth is rebate programs, which are enacted to reduce the total investment costs of *PV* systems, especially for residential/commercial *PV* installations.

e. **[10 points]** Which of the following statements is (are) **not correct**?

a) The difference at a specified location on the earth surface between the solar time and the civil time arises from the earth's uneven movement along its orbit of the annual revolution around the sun and the deviation of the local time meridian from the location longitude.
b) Germany, Korea and Spain were the top three nations in terms of *PV* capacity additions in 2016.
c) Fixed costs are those costs incurred that are independent of the operation of a resource and are incurred even if the resource is not operating.

d) The approximation used for the clear–sky direct beam radiation explicitly accounts for the time-varying intensity of the sun and distance between the earth and the sun.

e) The payment foregone by the net metered solar owners are pushing the distribution utilities to shift the collection of the electricity infrastructure to the non-solar-owner customers.

The *IRR* Table:

Life (years)	9%	11%	13%	15%	17%	19%	21%	23%	25%	27%	29%	31%	33%	35%	37%	39%
1	0.92	0.90	0.88	0.87	0.85	0.84	0.83	0.81	0.80	0.79	0.78	0.76	0.75	0.74	0.73	0.72
2	1.76	1.71	1.67	1.63	1.59	1.55	1.51	1.47	1.44	1.41	1.38	1.35	1.32	1.29	1.26	1.24
3	2.53	2.44	2.36	2.28	2.21	2.14	2.07	2.01	1.95	1.90	1.84	1.79	1.74	1.70	1.65	1.61
4	3.24	3.10	2.97	2.85	2.74	2.64	2.54	2.45	2.36	2.28	2.20	2.13	2.06	2.00	1.94	1.88
5	3.89	3.70	3.52	3.35	3.20	3.06	2.93	2.80	2.69	2.58	2.48	2.39	2.30	2.22	2.14	2.07
6	4.49	4.23	4.00	3.78	3.59	3.41	3.24	3.09	2.95	2.82	2.70	2.59	2.48	2.39	2.29	2.21
7	5.03	4.71	4.42	4.16	3.92	3.71	3.51	3.33	3.16	3.01	2.87	2.74	2.62	2.51	2.40	2.31
8	5.53	5.15	4.80	4.49	4.21	3.95	3.73	3.52	3.33	3.16	3.00	2.85	2.72	2.60	2.48	2.38
9	6.00	5.54	5.13	4.77	4.45	4.16	3.91	3.67	3.46	3.27	3.10	2.94	2.80	2.67	2.54	2.43
10	6.42	5.89	5.43	5.02	4.66	4.34	4.05	3.80	3.57	3.36	3.18	3.01	2.86	2.72	2.59	2.47
15	8.06	7.19	6.46	5.85	5.32	4.88	4.49	4.15	3.86	3.60	3.37	3.17	2.99	2.83	2.68	2.55
20	9.13	7.96	7.02	6.26	5.63	5.10	4.66	4.28	3.95	3.67	3.43	3.21	3.02	2.85	2.70	2.56
25	9.82	8.42	7.33	6.46	5.77	5.20	4.72	4.32	3.98	3.69	3.44	3.22	3.03	2.86	2.70	2.56
30	10.27	8.69	7.50	6.57	5.83	5.23	4.75	4.34	4.00	3.70	3.45	3.22	3.03	2.86	2.70	2.56