Lakehead University
Department of Mechanical & Mechatronics Engineering
EMEC-5671: RENEWABLE Energy FOR Mechanical Engineering Systems
Course Prof.: Dr. Basel Ismail, P.Eng

Project I:

Maximization of Solar PV & Wind Turbines Power Output using Modeling and Numerical Simulations – *A Case Study of a Hypothetical Canadian Site*

General Requirements:

1. The term project mark constitutes 25% of the course mark (see the course outline). The project has two main components**: part (A)** Solar PV system, and **part (B)** Wind power system.
2. Solar & wind energy data (the datasheet) were provided for each group (of 2 students) pertaining to the assigned potential Canadian site location;
3. Each group is assigned a potential site coordinates (case study) for which a PV system would be designed and installed and for which the optimum tilt angle for this system need be analyzed and determined for best efficiency;
4. **Each group is required to work independently from other groups in the project;**
5. The project should be delivered by the deadline (see the deadline section of this handout);
6. The required format and specifications of the project to be submitted as a final product – more details are provided here;
7. The final mark for the project depends on several factors (see the heading project format and submission in this handout).
8. The project report must include a section detailing the tasks of the two students in their project work (who did what?).

PART (A):

Optimizing the tilt angle of a solar PV panel for optimal design to maximize the utilizable solar energy & electrical power output for a potential site coordinates (case study)

Introduction:

The inclination (tilt) angle at which a solar PV module is sloped from the horizontal is one of the most influencing system parameters that affect the output of the PV system. This is due to the fact that the variation in the tilt angle affects the amount of incident solar radiation received on a PV system and utilized by the load once installed at a certain site. To maximize the overall power production of a given PV system throughout the year, the tilt angle has to be optimized for a given site. In addition, positioning the PV system at an optimum tilt angle leads to lesser PV array area required to match a fixed load, thus reducing the cost of the system.

Objective for Part (A): In this part, it is required to determine the unique optimum tilt angle $\boldsymbol{\beta_{opt}}$ of a solar PV panel that corresponds to the maximum incident solar radiation on the collector surface for each month in the year for a given site coordinates (hypothetical case study).

The following parameters are fixed:

1. The solar PV system will be Equator-pointed (i.e. facing south with azimuth angle equal zero) at all times of the modeling process and energy conversion analysis;
2. The tilt angle will be varied from 0-90° in an increment of 3° for every month in the year (i.e. from Jan-Dec).

Mathematical Modeling and General Calculation Procedure for Part (A):

As stated earlier, the main objective is to vary the PV surface tilt angle by an increment of 3° from 0-90° and estimate the corresponding monthly average daily solar radiation values ($\bar{H}_T$) received on this tilted PV surface for the average (mean) day in every month in the year. $\bar{H}_T$ is to be estimated using the Isotropic-Sky Model (use Dr. Ismail's Class Notes) according to the following general numerical calculation procedure:

For a fixed tilt angle, β (starting with 3°) and month of the year (starting with Jan):

1. Calculate the solar angles: sunset hour angle, declination angle based on the average/mean day of the month in the year "$\bar{n}$" (use Table, class notes);
2. Calculate $\bar{H}_o$ using Eq. (6-3)a and convert units to MJ/m^2;
3. Estimate the monthly average daily clearness index using Eq. (6-5)a and the data provided ($\bar{H}$) for the given latitude site;
4. Estimate the fraction of monthly average daily diffuse to total radiation on a horizontal surface ($\frac{\bar{H}_d}{\bar{H}}$) using the appropriate empirical relationship of either Eq. (6-9) or (6-10) depending on the applicable criterion;
5. Calculate the monthly average daily geometric factor of beam radiation ($\bar{R}_b$) using Eqs. (6-13) & (6-14);
6. Estimate the monthly average daily radiation incident on the tilted PV surface ($\bar{H}_T$) using Eq. (6-8) for the given site;
7. Calculate the monthly average daily contributions for beam, sky diffuse, and ground reflectance for each month considering the optimum tilt angle. Compare your results of these three terms with $\bar{H}_T$ (use % fractions) in Table form;
8. Calculate $(\bar{R})_{max} = \frac{(\bar{H}_T)_{max}}{\bar{H}}$ corresponding to optimal tilt angle for each month. Present your results in a Table form.

Repeat the calculation procedure using MS Excel program by fixing another β with an increment of 3° till 90° is reached. Repeat whole procedure for February through December (i.e. complete year).

By plotting the results in a graph where x-axis is the tilt angle and y-axis is $\bar{H}_T$, the optimum tilt angle $\boldsymbol{\beta_{opt}}$ can be determined for each month in the year. This optimum angle corresponds to the maximum value $(\bar{H}_T)_{max}$ for that particular month. It would be useful to split the graph into four each takes three months (i.e. four seasons in the year). Calculate the average optimum tilt angle for each season; present your results in Tables. Compare your respective results with those values on horizontal surface ($\boldsymbol{\beta = 0^o}$) for all months – by showing % increase or decrease.

9. Calculate the yearly averaged tilt angle using:

$$\left(\bar{\beta}_{opt}\right)_{year} = \frac{\sum_{Jan}^{Dec} \beta_{opt}}{12} \quad \text{.........Eq. (1)}$$

10. Calculate the monthly average hourly solar radiation $(\bar{I}_T)_{opt}$ for all hour-pairs in the daylight (first determine the number of sunshine or daylight hours, *N,* to know how many hour-pairs before noon, etc) for the mean day for each month (from Jan to Dec). In case the calculated value *N* came to be with a fraction then round off the figure to the nearest even integer (for example, if N=9.3 then consider N=8, if N=10.3 then consider N=10, if N=7.8 => N=8). This will help to have symmetrical integers around noon and also to avoid getting negative values for the hourly radiation. For the calculation of $(\bar{I}_T)_{opt}$, use the optimum tilt angle for different months obtained from previous calculations. Consider symmetrical conditions around noontime. Also, obtain the yearly average $\left(\bar{I}_T\right)_{year}$ for each hour-pair.

<u>Project I - PART (B):</u>

Estimation of available and output wind energy for the given site coordinates and presenting a commercial wind turbine application case study.

<u>Objective of Part (B):</u>

In this part, it is required to estimate the available wind energy to examine the feasibility of installing a horizontal-axis two-blade, high speed turbine at the given site coordinates. Also, it is required to research and select a commercial wind turbine for a given case study to be discussed in detail. <u>The turbine blade diameter is fixed to be 10 m</u>.

<u>Mathematical Modeling and General Calculation Procedure - Part (B): Compare your results graphically and in Table form:</u>

1. Calculate the available wind energy density (kWh/m^2) for each month in the year (assuming the wind average speed is the same for all days of the month), and annual wind energy density (kWh/m^2) for the given site;
2. Calculate the available wind energy (kWh) received by the turbine for each month in the year and the total annual wind energy;

3. Calculate the ideal (Betz limit) producible wind energy by the wind turbine for each month;
4. Calculate the monthly average maximum axial thrust (kN) acting on the turbine bearings;
5. The actual producible wind energy for each month, and annual. Use the performance curve (Figure k-1, class notes) to determine the power coefficient for the whole range of λ (or Ω) in the figure. Hint: a mathematical expression for λ versus C_p could be initially determined (using best curve fitting by Excel program) and then used in the calculation procedure, instead of manually locating the points.
6. Calculate the monthly average actual operational speed (RPM) and Torque for each month at the best actual operating conditions for the turbine.
7. (Important item) Research to find a commercial wind turbine that can fit this application. Present a case study (load requirement and application) related to your given location. Present specifications and discuss in detail your selection of the wind turbine. Show the related design diagram of the wind turbine.

Project format & submission:

The project report is expected to be prepared using a compatible MS Word processor and the graphs, simulations & calculations to be performed using a compatible MS Excel spreadsheet program. The final report electronic document (as a single file in PDF format) should be submitted by the following deadline:

Deadline for submitting the project final report (electronic as single PDF file by 11:59pm, Tuesday, May 21, 2024.

Method of submission:
The groups are required to submit their final and complete project reports (as a single PDF file) by uploading their submissions to the CourseLink (D2L) course site. First, one student from each group (the group has to decide who will submit the project) login his/her myCourseLink for EMEC-5671-SB course site. Under the "***Assignment***" tab there is a folder named "**EMEC-5671-Term Project I-Report Submissions**). The assigned student (responsible from the group) should upload and submit into this folder. Any other methods of submissions (e.g. email) are not accepted. It should be noted that right after the submission deadline the assignment folder will be closed and the student will not be able to submit.
Before submission, the student should name his/her report in this format:
"*EMEC-5671-Term Project I-the group (2 Students) Last names-Students Seat #s..*"
NOTE:
Students can ONLY make one project report submission through uploading their project report PDF file to the submission course folder. The system will NOT allow any multiple submissions by the student. Therefore, the student should check the completeness of his/her final report before uploading and submitting by the deadline. Also, before

submission, it's the student full responsibility the student (assigned by the group) to make sure that the final report (PDF file) has no errors and not corrupt. Failure to open the doc by the professor will result in a zero mark for the report! Also, violating this submission method will result in losing marks.

Clarification Note: All Groups are required to submit their final report (as PDF only) as instructed here above (Method of Submission). The groups should NOT submit their final report in MS word and they should NOT submit their Excel doc. However, some groups may be required to submit their Excel worksheets (in digital file) upon Dr. Ismail's request via email (NOT via the D2L site).

Report Formats:

In typing your report using MS W

ord, use 1.5 line spacing,12 pt font size, Times New Roman fount type. The number of pages in the final report should not exceed 80 pages (including the project handout). In the last pages of the report, the student should include copy of the project handouts (this doc). It is highly recommended to optimize the total number of pages in order to present complete quality work (the report quality is normally judged based on quality and conciseness of contents while satisfying the amount of work as per requirements). The final mark for the project depends on a number of factors, for example:

1- Quality of introduction for the case study
2- Organization of results and Quality of generated graphs
3- Depth of discussion of results
4- Thoroughness of analysis (or modeling)
5- Clarity of presentation of results
6- Sample of calculations
7- Consistency of the work done
8- Reliability of references used in the report
9- Overall quality of the submitted final report in PDF format.

The final report should include standard report elements, such as:

1. cover page (should include: University name, Department name, Course code and name, project title, Group # and students names with their seat numbers (in a box), Professor's name, and date of submission)
2. Table of contents
3. acknowledgement (indicating the project-related experience gained form Dr. Ismail's course and project, etc.)
4. A statement related to the Student Code of Academic Integrity should be signed. This statement should be included in the project report (right after the Acknowledgement section) and signed by the student:

Statement of Student Code of Conduct – Academic Integrity (must be signed by the student):

As per the Lakehead University Student Code of Conduct – Academic Integrity, students are required to act ethically and with integrity in academic matters and demonstrate behaviours that support the university's academic values. ***In submitting this completed exam, I am therefore affirming the following statements to be true:***

- I have completed this project without the assistance of anyone;
- With the exceptions of the course textbook, and Dr. Ismail's Class notes (EMEC-5671 course), and Google maps, I have NOT accessed any sources or materials (print, online, or otherwise) in the completion of this project;
- This project is protected by copyright. Reproduction or dissemination of this document or the contents or format of this document in any manner whatsoever (e.g., sharing the content with other students) is strictly prohibited. and;
- And, in accordance with Section III: Violations of this Academic Integrity Code, I understand that providing any false or misleading information, or by accessing any outside assistance, constitutes a breach of academic integrity as outlined in Lakehead University's Academic Integrity and Policies.

Student's Signature:

5. Abstract or summary
6. List of figures
7. List of tables
8. Nomenclature (notations used in the report arranged in alphabetical order)
9. Introduction. Introduce and describe the project theme and show a Google Map for the assigned location. Also, introduce the location and case study in detail.
10. Objective(s) of the project & application requirements.
11. A section detailing the tasks of the group members (the two students) - who did what?
12. Step-by-step simulations procedure and parametric study.
13. Detailed sample of calculations (to be typed using MS Word Equation editor).
14. Discussion of results. Discuss your results based on graphical and numerical outputs.
15. Conclusion (highlighting main findings of the numerical simulations, analysis and comparison of results).
16. Recommendations, if any, relevant to the project final results.
17. References used (i.e. cite professor name, course #, and year for class notes, and any other Ref used),

Appendix (see next pages) ➔

Appendix I

Mathematical Modeling and Methodology:

$\overline{H}_T$ and $\overline{I}_T$ are to be modeled for the assigned site location using the Isotropic model (class notes) according to the following equations:

(I) Computation of $\overline{H}_T$:

$$\overline{H}_T = \overline{H}\left(1 - \frac{\overline{H}_d}{\overline{H}}\right)\overline{R}_b + \overline{H}_d\left(\frac{1+\cos\beta}{2}\right) + \overline{H}\,\overline{\rho}_g\left(\frac{1-\cos\beta}{2}\right) \qquad \text{.............(1)}$$

Note: Obtain the units for $\overline{H}$, $\overline{H}_d$, and $\overline{H}_T$ in MJ/m^2 . Note the values of $\overline{H}$ given for your assigned site in the data sheet was given in kWh/m^2 . You should convert it to MJ/m^2 (as stated in the data sheet given).

For computation of $\frac{\overline{H}_d}{\overline{H}}$:

For $\omega_s \le 81.4^o$ and $0.3 \le \overline{K}_T \le 0.8$

$$\left(\frac{\overline{H}_d}{\overline{H}}\right) = 1.391 - 3.560\,\overline{K}_T + 4.189\left(\overline{K}_T\right)^2 - 2.137\left(\overline{K}_T\right)^3 \qquad \text{..........................(2)}$$

And for $\omega_s > 81.4^o$ and $0.3 \le \overline{K}_T \le 0.8$

$$\left(\frac{\overline{H}_d}{\overline{H}}\right) = 1.311 - 3.022\,\overline{K}_T + 3.427\left(\overline{K}_T\right)^2 - 1.821\left(\overline{K}_T\right)^3 \qquad \text{........................(3)}$$

$$\omega_s = \cos^{-1}\left(-\tan\phi\tan\delta\right) \qquad \text{.........................(4)}$$

$$\delta = 23.45\sin\left[360\,\frac{(284+n)}{365}\right] \qquad \text{................(5)}$$

Where, *n* is the day of the year based on $\overline{n}$ the mean day of the month (see Table in class notes or your solar data sheet).

$$\overline{H}_o = \frac{24*3600*1367}{\pi}\left(1 + 0.033\cos\frac{360*n}{365}\right)*\left(\cos\phi\cos\delta\sin\omega_s + \frac{\pi\omega_s}{180}\sin\phi\sin\delta\right) \qquad \text{......(6)}$$

(Note: The resulting unit for this equation is J/m^2 . You should convert the unit for $\overline{H}_o$ in MJ/m^2 .)

$$\overline{R}_b = \frac{\cos(\phi-\beta)\cos\delta\sin\omega_s' + (\pi/180)\,\omega_s'\sin(\phi-\beta)\sin\delta}{\cos\phi\cos\delta\sin\omega_s + (\pi/180)\,\omega_s\sin\phi\sin\delta} \qquad \text{.............(7)}$$

$$\omega_s' = \min\begin{bmatrix}\cos^{-1}(-\tan\phi\tan\delta) \\ \cos^{-1}(-\tan(\phi-\beta)\tan\delta)\end{bmatrix} \quad \text{.................(8)}$$

$$\overline{R} = \frac{\overline{H}_T}{\overline{H}} \quad \text{.....................(9)}$$

(II) Computation of $\bar{I}_T$:

Note: In computing $\bar{I}_T$, ω is calculated at the mid-point hour of the hour-pair

$$\bar{I}_T = \overline{K}_T \overline{H}_o\left[\left(r_t - \frac{\overline{H}_d}{\overline{H}} r_d\right)R_b + \frac{\overline{H}_d}{\overline{H}} r_d\left(\frac{1+\cos\beta}{2}\right) + \bar{\rho}_g r_t\left(\frac{1-\cos\beta}{2}\right)\right] \quad \text{........(10)}$$

$$r_d = \left(\frac{\pi}{24}\right)\left[\frac{(\cos\omega - \cos\omega_s)}{\left(\sin\omega_s - \frac{\pi\omega_s}{180}\cos\omega_s\right)}\right] \quad \text{...........................(11)}$$

Equations for ω_s and δ are given previously.

$$r_t = \left(\frac{\pi}{24}\right)(a + b\cos\omega)\left[\frac{(\cos\omega - \cos\omega_s)}{\left(\sin\omega_s - \frac{\pi\omega_s}{180}\cos\omega_s\right)}\right] \quad \text{...........................(12-a)}$$

$$a = 0.409 + 0.5016\sin(\omega_s - 60) \quad \text{....................(12-b)}$$

$$b = 0.6609 - 0.4767\sin(\omega_s - 60) \quad \text{.....................(12-c)}$$

$$\omega = 15(ST - 12) \quad \text{.............................(13)}$$

$$N = \frac{2}{15}\cos^{-1}(-\tan\phi\tan\delta) \quad \text{................(14)}$$

$$R_b = \frac{\cos(\phi-\beta)\cos\delta\cos\omega + \sin(\phi-\beta)\sin\delta}{\cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta} \quad \text{.................(15)}$$

Appendix II

Results Format:

Tables (Part A):

Table 1: Results of the estimated values of $\left(\overline{H}_T\right)_{\max}$ at corresponding monthly values of β_{opt}

Month	$\left(\beta_{opt}\right)_{month}$	$\overline{H}_o$ $\left(MJ/m^2\right)$	$\overline{H}$ $\left(MJ/m^2\right)$	$\overline{K}_T$	N (Hrs)	$\frac{\overline{H}_d}{\overline{H}}$	$\overline{R}_b$	$\overline{H}_d$ $\left(MJ/m^2\right)$	$\left(\overline{H}_T\right)_{\max}$ $\left(MJ/m^2\right)$	$\overline{R}$
JAN										
FEB										
...										
...										
DEC										

Table 2: Computed results of $\left(\bar{I}_T\right)_{\max}$ (MJ/m^2) at $\left(\beta_{opt}\right)_{month}$

Month	Hour-pair of the mean day in the month (solar time)						
	....	6-7 am (5-6 pm)	7-8 am (4-5 pm)	8-9 am (3-4 pm)	9-10 am (2-3 pm)	10-11 am (1-2 pm)	11-12 am (12-1 pm)
JAN							
FRE							
...							
DEC							
Yearly average hourly $\left(\bar{I}_T\right)_{year}$							

$\left(\beta_{opt}\right)_{year} =$

Figures (Part A-Solar PV):

Figure 1-A: Comparison of monthly average daily solar radiation.
Plot $\overline{H}_o$ and $\overline{H}$ (in MJ/m^2) vs. Month

Figure 2-A: Comparison of $\overline{H}_T$ for each month (Dec-Feb) representing winter season
Plot ($\overline{H}_T$) vs. β (also indicate on the figure the max and min values corresponds to which month)

Figure 3-A: Comparison of $\overline{H}_T$ for each month (Mar-May) representing spring season
Plot ($\overline{H}_T$) vs. β (also indicate on the figure the max and min values corresponds to which month)

Figure 4-A: Comparison of $\overline{H}_T$ for each month (Jun-Aug) representing summer season
Plot ($\overline{H}_T$) vs. β (also indicate on the figure the max and min values corresponds to which month)

Figure 5-A: Comparison of $\overline{H}_T$ for each month (Sep-Nov) representing fall season
Plot ($\overline{H}_T$) vs. β (also indicate on the figure the max and min values corresponds to which month)

Figure 6-A: Comparison of the maximum monthly average daily solar radiation.
Plot $\overline{H}$, $(\overline{H}_T)_{max}$ (in MJ/m^2) vs. Month (total two curves in this figure)

Figure 7-A: Comparison of $\left(\bar{I}_T\right)_{year}$ for each hour-pair in the year
Plot ($\left(\bar{I}_T\right)_{year}$ vs. Time (hour)

Figures (Part B- Wind power):

Figure 1-B: Comparison of the available wind energy (kWh) received by the turbine for each month in the year
Figure 2-B: Comparison of the ideal (Betz limit) producible wind energy by the wind turbine for each month
Figure 3-B: Comparison of the actual producible wind energy for each month
Figure 4-B: Comparison of the monthly average maximum axial thrust (kN) acting on the turbine bearings.
Figure 5-B: Design drawing of the selected commercial wind turbine with tabulated details related to its technical specifications, etc.

Methodology, Discussion & Results:

The project report should start with Part A and after that present Part B. Effectively, discuss your results based on your results in the Tables and Figures. In your discussion highlight interesting findings. Make appropriate discussion immediately after a Table or figure. Make final overall discussion & comments based on your useful project-related insights.