I. Course Overview  

The photovoltaic field is evolving very rapidly. Yet formal education and training have concentrated efforts mostly at both ends of the spectrum – basic science, and systems designers and installers training. There seems to be a void in formal undergraduate engineering-technology courses at the systems level. This course presents the fundamental but a comprehensive engineering basis for photovoltaic (PV) systems design to prepare the student for making sound engineering judgment in the design of PV systems. To achieve this purpose the course discusses the what, why and how – giving the student a clear understanding of the parameters for PV systems design. In this sense, the course is remarkably different from the various workshops on PV system design, installation, operation and maintenance, and other technician training courses.

The course discusses the solar spectrum, determination of the sun’s location relative to a point on the earth, insolation optimization, as well as the various components of the PV system. Also touched on are PV systems design philosophies as well as the design process implementation. Economic and environmental considerations are also covered. Although the primary emphasis of this course is on the electrical components of PV systems, the course is comprehensive enough to give the student a strong foundation in the mechanical and other aspects of PV systems engineering.

II. Expected Learning Outcome  

The goal of this course is to educate the student in the fundamentals of photovoltaic systems so that the student will understand the engineering basis for the electrical, mechanical, economic and aesthetic aspects of PV system design. The student who successfully completes this course will therefore be expected to have gained certain competences. These competencies include a mixture of abilities to explain certain theoretical concepts in PV systems. Behavioral changes from participating in this course include ability to:

- Locate the sun from any point on earth at any time
- calculate and maximize the amount of irradiation on a collector
- Describe the PV building blocks
- Describe the physics of PV cell – the photovoltaic effect
- Prepare I-V characteristic curves to determine the maximum power point on a PV cell operating characteristic curve
- Choose the various components of the balance of system (BOS)
- Compare various energy storage devices/systems
- Compare various types of battery systems
- Compare the various PV cell technologies
- Draw a block diagram of a PV electric system
- Determine the mechanical forces acting on an installed PV array
- Cost a PV system
- Evaluate system environmental impact.

Specific learning objectives for each instructional unit are discussed in the unit/module syllabus.
III. General Information for Students

Textbook The primary textbook for this course is “Photovoltaic Systems Engineering” by Roger Messenger and Jerry Ventre, CRC Press, latest edition. This is a required test book.

Reference materials are listed in the pertinent module syllabi. Students are advised to see the department’s student handbook and the university catalogue for applicable rules and regulations as the classes for this course will be conducted strictly according to those rules and regulations. Other rules of conduct may be announced by the instructor.

Prerequisites Proficiency in calculus and electric circuit analyses is required. Knowledge of electronic principles will be advantageous. Accordingly, the prerequisites for this course are MATH 2110 and ECET 2200.

IV. Instructional Units/Modules This course is designed to develop the cognitive skills of the learner. No extensive laboratory exercises are involved. A full description of each of the following units of instruction covered in the course is given in the module syllabus:

- Unit 1. – Solar Radiation and Insolation
- Unit 2. – Introduction to PV Systems
- Unit 3. – Mechanical Considerations
- Unit 4. – PV Systems Economy
- Unit 5. – Externalities and Photovoltaics
- Unit 6. – The Physics of Photovoltaic Cells
- Unit 7 – Present and Proposed PV Cells

V. Evaluation of Learning Outcome A variety of instruments and methods will be used to assess the pertinent task analyses or competencies the student has acquired. These include a test at the completion of each instructional module; a final comprehensive examination to measure the ability of the student to retain and synthesize information from the various modules for an integrated body of knowledge; and a term paper to evaluate the student’s ability to derive ideas from what was learnt and to formulate concepts based on knowledge gained from the course. Specific instruments for evaluating the effectiveness of the instructional activities and strategies for each unit are listed in the module syllabi.
## VI. Course Specifications

### Table 1. Course Specifications Matrix

<table>
<thead>
<tr>
<th>#</th>
<th>Section of Task Analysis</th>
<th>Instruction Unit</th>
<th>Level of Training/priority</th>
<th>% Course time</th>
<th>Allotted Time (Weeks)</th>
<th>Location and/or Facilities</th>
<th>Materials and Supplies</th>
<th>Resources/ references</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>System wind loading analysis and design</td>
<td>Mechanical Considerations</td>
<td>High</td>
<td>08</td>
<td>1</td>
<td>Lecture room, Field</td>
<td>Cartesian graph paper</td>
<td><em>Minimum Design Loads for Building and Other Structures</em>, ASCE Standard, ANSI/ASCE 7-95,</td>
</tr>
<tr>
<td>4</td>
<td>System cost analysis; PV System design</td>
<td>PV Systems Economy</td>
<td>Very High</td>
<td>14</td>
<td>2</td>
<td>Lecture room</td>
<td>Electronic calculator</td>
<td><em>Engineering Economy</em></td>
</tr>
<tr>
<td>5</td>
<td>Compliance with regulations and codes</td>
<td>Externalities and Photovoltaics</td>
<td>High</td>
<td>07</td>
<td>1</td>
<td>Lecture room</td>
<td></td>
<td>Fthenakis, V. M. and Moskowitz, P. D., <em>Emerging Photovoltaic Technologies: Environmental and Health Issues Update</em>, NREL/NSL Photovoltaic Programs Review, AIP Press, New York; Other</td>
</tr>
<tr>
<td>6</td>
<td>The Physics of Photovoltaic Cells</td>
<td>High</td>
<td>14</td>
<td>2</td>
<td>Lecture room</td>
<td></td>
<td></td>
<td><em>Silberberg, M., Chemistry: The Molecular Nature of Matter and Charge</em>, Mosby, St Louis MO</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td></td>
<td>100</td>
<td>14</td>
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<td></td>
</tr>
</tbody>
</table>
Instruction Unit – One  Solar Radiation and Insolation

Introduction  Knowledge of the properties of sunlight and the sun’s relationship to the earth is essential for optimizing the performance of photovoltaic and other devices and systems that convert solar energy to other useful forms. Important solar phenomena, including the solar spectrum, atmospheric effects, solar radiation components, determination of sun position, measurement of solar parameters, and orientation of solar collector are discussed in this unit of instruction.

Required Entry Behavior  Students are expected to be familiar with the solar system, the globe. A strong background in Euclidian geometry and trigonometry will be advantageous.

Behavioral Objectives  At the completion of this unit, the student will be able to:
  • Describe the sun and solar spectrum
  • Determine irradiance and irradiation on a collector
  • Measure global radiation using pyranometer
  • Maximize irradiation on a collector

Equipment and Supplies  Pyranometer, Globe and Worldwide Irradiation Charts (supplied by the department); Geometric set, graph papers (supplied by student)

Learning Activities and Strategies  This unit consists of classroom and field activities. The classroom presentations will be punctuated with demonstrations both inside and outside the classroom. The following is a tentative plan for covering the instructional materials for achieving unit objectives:
  • The solar spectrum  30 minutes
  • The effect of atmosphere on sunlight  30 minutes
  • Introduction to insolation specifics  30 minutes
  • The orbit and rotation of the earth  60 minutes
  • Tracking the sun  60 minutes
  • Measuring the sun  60 minutes
  • Capturing the sun  30 minutes
  • Hour Test  60 minutes
Total time  360 minutes (2 weeks)

Field Activities  Measurement of radiation using pyranometer; Maximizing irradiation on a collector (collector orientation)

Unit Evaluation  Group/team field projects, hour test

Hubbert, M. K., The Energy Resources of the Earth, Scientific America, Vol 225, No 3, Sept 1971, 60 - 70
Instruction Unit Two – Introduction to PV Systems

Introduction
The building blocks of the PV system (from cell to array) and the various components that make up the balance of system (BOS) are discussed in this unit. System configurations and design considerations are discussed in detail.

Required Entry Behavior
A strong background in electric circuit analysis is required. Proficiency in differential and integral calculus is required.

Behavioral Objectives
At the completion of this unit, the student will be able to:
- Describe the PV building blocks
- Describe the physics of PV cell
- Prepare I-V characteristic curves to determine the maximum power point on a PV cell operating characteristic curve
- Choose the various components of the balance of system (BOS)
- Compare various energy storage devices/systems
- Compare various types of battery systems
- Draw a block diagram of a PV electric system

Equipment and Supplies
PV cells, cell model, modules and models of modules, BOS components (charge controllers, inverters and other electronic parts) and electric load.

Learning Activities and Strategies
This unit consists of classroom and laboratory exercises. Classroom presentations will be followed with laboratory demonstrations and exercises. The following is a tentative plan for covering the instructional materials for achieving unit objectives:
- The PV cell 30 minutes
- PV cell I-V curve 60 minutes
- The PV module and Array 30 minutes
- Operating Characteristic of PV module 60 minutes
- The chemistry and Properties of lead-acid storage battery 45 minutes
- The chemistry and Properties of nickel-cadmium storage battery 45 minutes
- Other battery systems 30 minutes
- Overview of hydrogen storage and fuel cell 60 minutes
- Other storage systems and devices 30 minutes
- Charge controllers 30 minutes
- PV system Inverters 60 minutes
- System Load 30 minutes
- System configuration from generation to Load 60 minutes
- Hour Test 90 minutes

Laboratory Exercises
- PV cell I-V curve 60 minutes
- Determination of composite operating characteristic for a PV module 60 minutes
- PV system configuration 120 minutes

Total Time 900 minutes (5 weeks)

Unit Evaluation
Laboratory reports, hour test
Reference Materials
Hancock, Jr., O. G., Hydrogen Storage, the hydrogen alternative, Photovoltaics International, March, 1996.
Instruction Unit Three – Mechanical Considerations

Introduction The mechanical design of photovoltaic systems requires a multidisciplinary approach, involving civil and mechanical engineering, material science, aerospace engineering and architecture to some extent. This unit is an overview of design considerations involving the determination of the mechanical forces acting on the system, selecting, sizing and configuring the members to balance these forces and the choice of materials that would provide system longevity and integrity.

Required Entry Behavior Students are expected to be familiar with laws of static and dynamic equilibrium. A background in strength of materials will be advantageous.

Behavioral Objectives At the completion of this unit, the student will be able to:

- Describe the forces acting on an installed PV array
- Calculate wind loads, snow loads, dead loads, live loads, and other loads
- Determine the mechanical properties of a member
- Discuss other properties of material that affect array structural support

Equipment and Supplies Wooden and metallic members, other construction materials (supplied by the department); Geometric set, graph papers (supplied by student).

Learning Activities and Strategies This unit consists of classroom and field activities. The classroom presentations will be punctuated with demonstrations both inside and outside the classroom. The following is a tentative plan for covering the instructional materials for achieving unit objectives:

- Important properties of matter 90 minutes
- Computing mechanical forces 90 minutes

Total time 180 minutes (1 week)

Field Activities Field trip to observe installed arrays;

Unit Evaluation Group/team field projects, Take home test

Instruction Unit 4 – PV Systems Economy

Introduction The costs to be considered when choosing PV system as an energy source include acquisition costs, operating costs, and maintenance and replacement costs. A reliable means of determining cost competitiveness of a PV system is the method of life cycle costing, which accounts for all costs associated with the system over its useful lifetime. This method of analysis will take into account the time value of money. Also, an economic analyses which considers ‘latent’ opportunity costs such as the inevitability of the use of this technology will be considered.

Required Entry Behavior Students are expected to be familiar with accounting economics. A background in engineering economic analysis will be advantageous.

Behavioral Objectives At the completion of this unit, the student will be able to:

- Discuss time value of money
- Perform life cycle cost analysis
- Determine annual payments on borrowed money
- Evaluate the economic merit of using PV system versus other energy sources

Equipment and Supplies Electronic calculator.

Learning Activities and Strategies This unit consists of classroom instructions only. The following is a tentative plan for covering the instructional materials for achieving unit objectives:

- The time value of money 90 minutes
- Life cycle cost analysis 90 minutes
- The effect of borrowing on life cycle cost 30 Minutes
- Unit electric cost 30 minutes
- Cost of photovoltaic externalities 60 minutes
- Hour test 60 minutes

Total time 360 minutes (2 weeks)

Unit Evaluation Hour test

Reference Materials Donald G Norman, Engineering Economic Analysis, Oxford University Press
Instruction Unit 5 – Externalities and Photovoltaics

Introduction
Externalities are factors resulting from energy use that are often, if ever, incorporated into the cost of energy. This unit will explore externalities such as environmental effects, health and safety issues, subsidies, access, sustainability and impact on rural development.

Required Entry Behavior
Students are expected to be familiar with everyday – common knowledge environmental issues and have heard of some of the infrastructural problems in the developing world.

Behavioral Objectives
At the completion of this unit, the student will be able to:
• Discuss the impact of various forms of energy use on the environment
• Discuss the impact of various forms of energy on human health
• Classify energy systems as clean or pollutant
• Quantify the cost of externalities
• Evaluate the merit of using PV system versus other energy sources

Equipment and Supplies
None

Learning Activities and Strategies
This unit consists of classroom instructions only. The following is a tentative plan for covering the instructional materials to achieve unit objectives:
• Environmental effects of energy sources 30 minutes
• Quantifying the cost of externalities 60 minutes
• Health and safety as externalities 30 Minutes
• Externalities associated with PV systems 30 minutes
• Energy issues in developing countries 30 minutes
Total time 360 minutes (2 weeks)

Unit Evaluation
Take Home Test

Reference Materials
Selected Publications from UN and UN agencies (TBA)
Instruction Unit 6 – The Physics of Photovoltaic Cells

Introduction
This unit presents the basics of PV system energy conversion. Present limitations on cell production and some of the emerging methods for overcoming these limitations are discussed.

Required Entry Behavior
Students are expected to be familiar with electronics principles, and the theory of operation of the pn junction in particular.

Behavioral Objectives
At the completion of this unit, the student will be able to:
• Describe the process of energy conversion in a PV cell
• Discuss the fundamental principles of PV cell design
• Discuss PV system performance and factors affecting performance

Equipment and Supplies
None

Learning Activities and Strategies
This unit consists of classroom instructions only. The following is a tentative plan for covering the instructional materials to achieve unit objectives:
• Overview of semiconductor materials  60 minutes
• The pn junction  60 minutes
• Optical absorption and photoconductors  60 minutes
• Maximizing PV cell performance  120 minutes
• Hour test  60 minutes
Total time  360 minutes (2 weeks)

Unit Evaluation
Hour Test

Reference Materials
Silberberg, M., Chemistry: The Molecular Nature of Matter and Charge, Mosby, St Louis MO
Instruction Unit 7 – Present and Proposed PV Cells

Introduction
This unit covers some of the present technologies in PV cell fabrication as well as the operation of a variety of cells. A discussion of emerging technologies is also presented in this unit.

Required Entry Behavior
Students are expected to be familiar with electronics principles and the theory of operation of the pn junction in particular.

Behavioral Objectives
At the completion of this unit, the student will be able to:

• Describe various types of PV cell
• Describe how a wafer is fabricated
• Describe the essential features of a cell
• Compare various types of cells based on their performance and cost.
• Discuss some emerging technologies for cell production.

Equipment and Supplies
None

Learning Activities and Strategies
This unit consists of classroom instructions only. The following is a tentative plan for covering the instructional materials to achieve unit objectives:

• Silicon PV cells 40 minutes
• Gallium arsenide cells 40 minutes
• Copper indium (Gallium) diselenide cells 40 minutes
• Cadmium telluride cells 40 minutes
• Emerging technologies 20 minutes

Total time 180 minutes (1 weeks)

Unit Evaluation
Take Home Test

Reference Materials
Hu, C., and White, R., Solar Cells, From Basics to Advanced systems, McGraw-Hill