ECET 3801 Fundamentals of Photovoltaic Systems Engineering (3 Semester Hours)

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 hand book 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 students ability to derive ideas from what was learnt and to formulate concept 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

#	Section of Task Analysis	Instruction Unit	Level of Training/ priority	% Course time	Allotted Time (Weeks)	Location and/or Facilities	Materials and Supplies	Resources/ references
1	Site selection and preparation	Solar Radiation and Insolation	Very High	14	2	Lecture room, Field	Globe model, Geometry set, pyranometer	Markvat, T., Ed., *Solar Electricity*, John Wiley and Sons.
2	PV System analysis and design	Introduction to PV Systems	Very High	36	5	Lecture room, Laboratory	PV cells, modules and BOS components	Markvat, T., Ed., *Solar Electricity*, John Wiley and Sons; Linden D., Ed., *A Handbook of Batteries, 2nd Ed.*, McGraw-Hill; other
3	System wind loading analysis and design	Mechanical Considerations	High	08	1	Lecture room, Field	Cartesian graph paper	*Minimum Design Loads for Building and Other Structures*, ASCE Standard, ANSI/ASCE 7-95,
4	System cost analysis; PV System design	PV Systems Economy	Very High	14	2	Lecture room	Electronic calculator	*Engineering Economy*
5	Compliance with regulations and codes	Externalities and Photovoltaics	High	07	1	Lecture room		Fthenakis, V. M. and Moskowwitz, P. D., *Emerging Photovoltaic Technologies: Environmental and Health Issues Update, NREL/SNL Photovoltaic Programs Review*, AIP Press, New York; Other
6		The Physics of Photovoltaic Cells	High	14	2	Lecture room		Silberberg, M., *Chemistry: The Molecular Nature of Matter and Charge*, Mosby, St Louis MO
7		Present and Proposed PV Cells	Moderate	07	1	Lecture room		Hu, C., and White, R., *Solar Cells, From Basics to Advanced systems*, McGraw-Hill
	Total			100	14			

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

Reference Materials

Markvart, T., Ed., *Solar Electricity*, John Weliy & Sons, Chichester, U. K., 1994;

McCluney, W. R., *Sun Position in Florida*, *Design notes*, Florida Energy Center, Cocoa, FL., (FSEC-DN-4-83), 1985

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-cadmiun 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

Hu, C. and White, R., *Solar Cells, from Basics to Advanced Systems*, McGraw-Hill, New York, 1983.

Markvart, T., Ed., *Solar Electricity*, John Weliy & Sons, Chichester, U. K. 1994

Linden, D., Ed., *Handbook of Batteries, 2nd Edition*, McGraw Hill, New York, 1994

Hancock, Jr., O. G., *Hydrogen Storage, the hydrogen alternative*, *Photovolaics International*, March, 1996.

Roland, B., Nitsch, J. and Wendt, H., *Hydrogen and Fuel Cells - the Clean Energy System*, Elsevier Sequoia, Oxford UK., 1992

UL 1741, *Standard for static inverters and charge controllers for use in photovoltaic power systems*, Underwriters Laboratories, Inc. Northbrook, IL, May 1999.

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

Reference Materials

Clauser, H. R., Editor inChief, *The Encyclopedia of Engineering Materials and Processes*, Reinhold Publishing, New York,

Minimum Design Loads for Building and Other Structures, ASCE Standard, ANSI/ASCE 7-95,

SSU Statics text book

SSU Strength of materials test book

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
Markvart, T, Ed., *Solar Electricity*, John Wiley & Sons, Chichester, U. K., 1994

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 Paterson, M., *Global warming and Global Politics*, Routledge, London, 1996

Markvart, T, Ed., *Solar Electricity*, John Wiley & Sons, Chichester, U. K., 1994.

Fthenakis, V. M. and Moskowwitz, P. D., *Emerging Photovoltaic Technologies: Environmental and Health Issues Update, NREL/SNL Photovoltaic Programs Review*, AIP Press, New York.

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	60minutes
• Maximizing PV cell performance	120 minutes
• Hour test	60 minutes
Total time	360 minutes (2 weeks)

Unit Evaluation Hour Test

Reference Materials

R. L. Boylestad, *Introductory Circuit Analyses*, Prentice Hall, Englewood Cliffs, New Jersey.

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	40minutes
• Gallium arsenide cells	40 minutes
• Copper indium (Gallium) diselenide cells	40minutes
• Cadmium telluride cells	40minutes
• Emerging technologies	20 minutes
Total time	180 minutes (1weeks)

Unit Evaluation Take Home Test

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