Principles and Performance of

Solar Energy Thermal Systems

(A Web Course)

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Preface

Attention of scientists and engineers all over the world has been drawn to develop alternative energy technologies, since the oil crisis in 1973. See, http://en.wikipedia.org/wiki/1973_oil_crisis. Attempts have been many, efforts have been plenty, resulting in some success stories and some not so successful. Adapting the successful routes, viable and reliable systems and their wide spread implementation are evolving. See, http://www.seia.org/research-resources/major-solar-projects-list

Considerable effort in research, development and field testing of solar energy systems has been put in. Many methodologies and rational (against *rule of thumb*) principles have evolved over the past three decades for designing and operating the solar energy systems. Continual updating of knowledge in emerging technologies is imperative. In retrospect, some of the lacunae that have been identified world over can be summarized as following. While reasonable design strategies, methodologies, and even software packages {e.g., TRNSYS, see at http://www.trnsys.com/} are available, widespread implementation and knowledgeable evaluation are due. Feed back on the operational difficulties has not been fruitfully forwarded for second-generation implementation. Perhaps, the initial systems installed had the sole objective of proving the technology. Also, financing, design, production, installation and monitoring are often done by different groups or organization and the coordination has been inadequate.

The choice of some what science based approach has been made mainly keeping the students of undergraduate and postgraduate programs in mind and is prepared at two levels, though, they are interwoven. For the, not so technical minded, it is informative and presents enough information to understand the technical jargon, so that a meaningful communication is ensured between the designer, administrator and the implementers. For the technically oriented, sufficient details are included, with which detailed calculations can be made to arrive at rational conclusions regarding the application, size, implementation and economics of the commonly recommended solar energy systems. Some open ended questions have been included, with the hope, that the serious minded students and researchers address these issues.

It is RECOMMENDED that the, students, learners, practitioners and design engineers from manufacturing industries to go through my VIDEO course on "SOLAR ENERGY TECHNOLOGY"; these two complement each other.

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Acknowledgements

I express my gratitude to,

Prof. J. A. Duffie, of Solar Energy Laboratory, University of Wisconsin, Madison, USA, who introduced this subject to me.

Prof. W. A. Beckman of Solar Energy Laboratory, University of Wisconsin, Madison, USA who had been my research advisor when I had been working as a UNESCO fellow. I learnt many approaches from Prof. Beckman which enabled me to approach difficult problems in the area of solar energy.

Prof. S. A. Klein of Solar Energy Laboratory, University of Wisconsin, Madison, USA, for asking difficult questions; also for answering them for me many times.

Further,

I must make a particular mention of the authoritative text book "Solar Engineering of Thermal Processes" by J. A. Duffie and W. A. Beckman [1], without which I would not have, been able to teach this subject over thirty times during my career at IIT, Kharagpur, India, and, now ventured into this exercise.

My Contribution essentially lies in noting the difference in the scope and applications for tropical climates and at lower latitudes, say less than 23^{o}. Partly the credit goes to some of my excellent students (at undergraduate, Master's and Doctoral levels) who did the calculations, which proved or disproved my hunches!

The information used from the web sites is gratefully acknowledged and find recorded along with* REFERENCES*, under* URLs [59]*. These have been listed also as under.

a) http://www.ucsusa.org/clean_energy/our-energy-choices/renewable-energy/how-solar-energy-works.html

b) http://en.wikipedia.org/wiki/Horsepower

c) http://en.wikipedia.org/wiki/Bow_and_arrow

d) http://www.culturequest.us/aboriginal_tools/boomerang.htm

e) http://www.bp.com/assets/bp_internet/globalbp/globalbp_uk_english/reports_and_publications/statistical_energy_review_2011/STAGING/local_assets/pdf/statistical_review_of_world_energy_full_report_2012.pdf.

f) http://en.wikipedia.org/wiki/Visvesvaraya_Iron_and_Steel_Plant

g) http://www.nal.usda.gov/awic/pubs/HumanAnimalBond/HumanAnimalBond.htm

h) http://archaeology.about.com/od/ancientdailylife/qt/fire_control.htm

i) http://en.wikipedia.org/wiki/File:AxialTiltObliquity.png

j) http://en.wikipedia.org/wiki/Hubbert_peak_theory

k) http://www.indiaenvironmentportal.org.in/files/srd-sec.pdf

l) http://repository.ias.ac.in/31225/1/31225.pdf

m) http://www.mapsofindia.com/lat_long/#

n) www.**india**environmentportal.org.in/files/srd-sec.pdf

o) http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data3.cfm/region=2_asia_wmo_region_2/country=IND/cname=India

p) http://www.timegenie.com/latitude_and_longitude/state_coordinates/intn

q) http://www.indiasolar.com/cal-value.htm

r) http://www.eai.in/club/users/dheen/blogs/665

s) http://en.wikipedia.org/wiki/Solar_energy

t) http://en.wikipedia.org/wiki/Solar_tracker

Exercises are given in Appendix A2. If you could not solve, send a scanned copy of your attempt; an answer shall be provided and your solution procedure shall be checked.

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In addition, a solution manual under preparation with additional problems will be sent on request.

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Contents

MODULE 1
Energy and Need for Dependence on External Sources

Lecture No: 1

In this Module 1, Lecture No. 1 deals with

Lecture 1

1.1 INTRODUCTION

Attention of scientists and engineers all over the world has been drawn to develop alternative energy technologies, since the oil crisis in 1973. The commonly referred oil crisis is more of a crisis of prices; in addition to, of course,

a) quick dwindling of fossil fuel reserves and
b) increase in demand at an alarming rate.

Realization of these two aspects led scientists and engineers look for alternatives. Many options have been found and examined. Prominent among the options are as following.

a) Solar thermal
b) Solar photovoltaic
c) Wind energy
d) Geothermal
e) Tidal and wave energies.

Among these, solar energy is relatively more uniformly available. Also according to one estimate, **the energy that reaches the Earth from 20 days of sunshine is equal to the energy stored in all of Earth's reserves of fossil fuels like, coal, petroleum, and natural gas.**

See, http://www.ucsusa.org/clean_energy/our-energy-choices/renewable-energy/how-solar-energy-works.html [a].

In additions to the 'fuels' (commonly referred to as fossil fuels) referred above, two prominent, existing and fairly widely used, energy sources are the hydro-electric and the nuclear. though the potential of hydro-electric route is enormous, may not be available at a chosen location in addition to the other problems of huge land getting submerged and relocation of the people and other life forms in the area. Similarly, nuclear energy (particularly the breeder reactors) option holds a promise, though mired by safety issues and spread of pollutants.

In this course on solar thermal energy, we shall not devote our attention to examining the merits and demerits of all possible future energy sources.

Before we examine the solar option in detail, it is worthwhile to examine if there is any intrinsic reason for dependence on external energy resources to meet the needs of human beings, viz., food, shelter and clothing. Of course, the provision to fulfill the needs of other live forms also has to be made.

1.2 POWER RATING OF HUMAN BEINGS

Typical power rating of human being (an athlete in 100 m sprint) is ≈ 1200 W = 1.7 h.p. This is almost the peak power the human being can produce for a few seconds. Typically, an average human being can sustain working for a longer duration at about 300-500W. A quick estimate of the energy required to produce or make available the material needs (food, shelter and clothing) of a human being exceeds the energy he can provide for himself to meet his requirements. **This imbalance perhaps led to the dependence on external energy sources. The problem is compounded by increasing population.**

A person of mass m (kg) runs up a height h (m) in time t (sec), then power {(mgh)/t} Watts. A person of mass 55 kg runs up a height of 7 m in 2 sec., the power rating corresponds to (55x9.8x7)/2 = 1717 W. Horse Power = 1717/747 = 2.17 hp. The maximum horsepower developed by a human being over a few seconds time can be measured by timing a volunteer

Exercise: The student can do this by actual timing of the volunteer to climb say, 20 steps, 20 cm high each, running up the stairs in the lecture hall OR the stairs leading to the lecture hall !

A healthy person

develops up to two hp, 1 hp = 746 W, for a short duration. Also, see, http://en.wikipedia.org/wiki/Horsepower [b]

1.3 THE NEEDS

It has already been mentioned that the man needs food, shelter and clothing for survival and in order to increase comfort and convenience level additional requirements (add-ons) to the above three have come to be widely used. E.g., heating or cooling the shelter, faster vehicles to commute from one place to another, warm clothing, processed food for ready use, nutritious, less volume food etc. The reader can easily identify among these examples those that fall under convenience or comfort/ luxury category.

1.4 TOOLS, MECHANICAL ADVANTAGE, MACHINES

One of the earliest discoveries by the man was fire. He started using the fire in a controlled manner. Fire served a wide variety of purposes. Lighting, cooking, and the 'heat treatment' (in present day terminology) of stone tools and making burnt clay objects. Fire is used to even provide comfort when the climate is cold.

In order that the intended tasks are carried out conveniently, the man invented tools that aid application of force at the intended point or target. The tools ranged from stones, sharp, pointed or of suitable shape to the present day tools including weapons of mass destruction. Also simultaneously, taking 'mechanical advantage' has come to vogue, e.g., lifting water or heavy weights. Man, made pointed weapons of wood, bone, and ivory to defend himself. Spear (made by sharpening the heavy end of wooden poles), bow and arrow, and boomerang.

See,

http://en.wikipedia.org/wiki/Bow_and_arrow [c]

http://www.culturequest.us/aboriginal_tools/boomerang.htm [d]

Human population started increasing considerably with the advent of controlled use of fire, learning of making tools, and use of animal power. Thus, the man's needs and the desire to be more comfortable led to employing animal power for agriculture, transport etc. which in turn led to dependence on 'external sources' for energy started to grow.

1.5 DEPENDENCE ON EXTERNAL FUELS

With increase in population at an increasing rate and limited natural resources (to meet the food, shelter and clothing), dependence on a finite land to meet the needs, a variety of innovations have been made. All these were energy intensive. From power tilling to mechanized farms and post harvest operations, storage and transport in agriculture sector and similar operations on animal stock became heavily dependent on energy produced from external sources. The main sources have been coal and oil. Considerable support followed from hydro electric power and in more recent times from nuclear power. The fossil fuels reserves are finite and last a relatively short time at the present rate of consumption. Latest Statistical Review of World Energy (June, 2012) is available at bp.com/statisticalreview.

URL:
http://www.bp.com/assets/bp_internet/globalbp/globalbp_uk_english/reports_and_publications/statistical_energy_review_2011/STAGING/local_assets/pdf/statistical_review_of_world_energy_full_report_2012.pdf
[e]. As per this report, the oil consumption for India from 2001 to 2011 has been, 107.0 111.3 113.1 120.2 119.7 120.4 133.4 144.1 153.7 157.2 172.3, million tonnes respectively. Oil Prices per barrel varied approximately from $10 (1974) to $110 (2011), most of the time monotonically. It may be noted that the price in 1974 is splurge in the price due to the "oil crisis".

Note, the units of measure of oil used frequently, in books/ technical journals by different authors. For ease of understanding,

1 Barrel oil =158.98 liters = 42 US Gallons

1 Barrel oil of crude oil $= 5.8 \times 10^7$ **BTU**

$= 7.12 \times 10^9$ **J**

Realization that the existing reserves of fossil fuels do not last long and the increase in prices led the scientists and engineers to look for alternatives, re-evaluate the technologically available solutions for economic viability in view of the change in prices. It has become necessary to reexamine various options since some of the fossil fuels (e.g., coal) not only provide the energy needed for the endothermic reactions, but also participate in the chemical reaction, e.g., reduction of iron ore to iron in a blast furnace. Such Technologies are many, require long period to find an alternative that does not call for use of fossil fuel reserves. The example is given to emphasize, that reduction in dependence on fossil fuels for energy generation prolongs the availability of the fuels for technologies involved in making say, iron and steel. Thus it is established that concentrated effort be made to develop technologies that reduce the dependence on fossil fuels.

In order that the energy availability is not limited and also the use of fossil fuels is put on a decreasing trend, one path is to make the processes and machines more efficient, and reduce the losses of energy. This aspect may broadly be termed as energy conservation, which also involves energy management, waste heat recovery etc.

The student may appreciate the efforts made in this direction resulting in two wheelers giving now 100 km/l of petrol from about 40 km/l in the 1980's. Similarly many house hold appliances are given "star" rating depending on the energy used by the machine for a given task. Practically, incandescent lamps are getting replaced by compact fluorescent and sodium vapor lamps for lighting. The efforts also have resulted in better insulation materials. There are many, methods and devices for energy conservation. Energy conservation, itself is a broad area.

ALTERNATE (RENEWABLE, NON-CONVENTIONAL) ENERGY AND THE SOLAR OPTION

The terminology commonly heard, alternate energy sources, renewable energy sources, or non-conventional energy sources is somewhat misleading and certainly confusing. Strictly speaking, what is conventional today might have been non-conventional a hundred years back. Similarly, the alternate energy source leads to the question, 'alternate', to what? Renewable energy source gives the impression, that the source is perennial. Even, "solar energy" (and hence its manifestations) lasts a finite time, no matter how long this finite time is! Though we use these terms synonymously, we should understand the implication and distinction which is, many times, missed by the readers, speakers, as well as listeners.

Commonly talked about alternate energy sources are, solar energy, wind energy, bio-mass, wave and tidal energy, and geothermal sources etc. Among these, solar energy appears to be the most promising.

The justification comes from the following considerations.

(i) Nearly perennial

(ii) Well distributed over the world (we may say, there is no bias for developed, developing or underdeveloped countries), predictable (though one may not be able to predict the solar radiation, say, on August 27th , 2012 at a location during 9.30 AM to 11.30 AM, one can work with likely averages for design purposes). By these features, one can guess the limitations of the other sources.

(iii) For example, wind energy, a manifestation of the solar, is about only 2% of the solar energy and is restricted to certain high wind velocity zones for harnessing. Of course, we do note, wind energy is a high grade energy source.

(iv) Wave and tidal energy are restricted by location as well as low efficiency.

(v) Similarly, geothermal energy is not uniformly distributed and is limited like fossil fuels.

Given that a promising (with already some proven success) option is the solar energy, we attempt to study the principles, applications and methods to predict the performance of the solar energy systems. We note at this stage that a solar energy system performance though depends on the 'solar collector' performance, also highly depends on the system configuration. This is where this course as presented here has a broader scope, than many books that are available with the notable exception of Duffie and Beckman [1].

Thus, solar energy is virtually an inexhaustible source. It is a clean energy source and does not pollute the atmosphere like the fossil fuels. Given the perennial nature of solar energy, this resource is envisaged to play a prominent role in meeting our energy requirements.

1.7 SOLAR ENERGY UTILIZATION: DIFFERENT ROUTES

Solar energy can be utilized to produce thermal energy or mechanical form of energy which eventually can be used to produce electricity; convenient for transmission and distribution. The technological routes involve production of thermal energy and subsequent conversion to mechanical and electrical forms of energy. Another option is the photovoltaic conversion, with which this course does not deal. The reader should be aware of the natural route, Viz., the photosynthesis which is utilized by the plants; that produce the wood, from which, the charcoal, producer gas, as needed. It is amazing to note that a blast furnace was run at Bhadravati, through wood-charcoal obtained from surrounding plantation. Bhadravati is located in present day Karnataka. It was started as the *Mysore Iron Works* on Jan. 18th 1923 by Sir M Visweswarayya.

See, http://en.wikipedia.org/wiki/Visvesvaraya_Iron_and_Steel_Plant [f]

1.8 SUMMARY

- Dwindling of fossil fuel reserves and increase in demand at an alarming rate led scientists and engineers look for alternatives.

- According to one estimate, the energy that reaches the Earth from 20 days of sunshine is equal to the energy stored in all of Earth's reserves of fossil fuels like, coal, petroleum, and natural gas.

- It is worthwhile to examine if there is any intrinsic reason for dependence on external energy resources to meet the needs of human beings, food, shelter and clothing.

- Typical power rating of human being (an athlete in 100 m sprint) is ≈ 1200 W = 1.7 h.p, s almost the peak power the human being can produce for a few seconds. 1 hp = 746 W. **A quick estimate of the energy required to produce or make available the material needs (food, shelter and clothing) of a human being exceeds the energy he can provide for himself to meet his**

requirements. This imbalance perhaps led to the dependence on external energy sources. The problem is compounded by increasing population.

- Fire served a wide variety of purposes. Lighting, cooking, and the 'heat treatment' (in present day terminology) of stone tools and making burnt clay objects. Fire is used to even provide comfort when the climate is cold.

- Utilizing or exploring 'mechanical advantage' has come to vogue,

- The man's needs and the desire to be more comfortable led to employing animal power for agriculture, transport etc. Thus, eventually, the dependence on 'external sources' for energy started to grow.

- 1 Barrel oil =158.98 lit = 42 US Gallons,
  1 Barrel oil of crude oil = 5.8×10^7 BTU = 7.12×10^9 J
- It is amazing to note that a blast furnace was run at Bhadravati, in present day Karnataka using wood charcoal. It was started as the *Mysore Iron Works* on Jan. 18th 1923 by Sir M Visweswarayya.

Thus, the energy crisis, limitation of the man, invention of tools and dependence on external fuels has been established. Along with conservation of energy, alternate sources need be explored. The distinction between alternate, renewable, non-conventional energy sources has been noted. Solar energy appears to be a promising option. This course deals with the solar thermal energy generation and utilization.