INTRODUCTION

01

We are called upon to imagine a great new field of solar energy, one with an expansive view that includes sustainability, ethics, systems thinking, policy, and markets in addition to device and energy conversion systems engineering. As an educator and a researcher, I contribute to a field that has seen cycles of emergence and adoption, followed by dispersion and knowledge loss (largely coupled to the accessibility of geofuels). The global solar industry is exploding in growth. The solar electric industry in the USA alone has doubled in scale seven times in the last decade, and solar energy technologies have the benefit of widespread social acceptance. Solar energy has a bright future, and we must be ready for solar to emerge along new frontiers. The new wave of solar research and entrepreneurship will lead to amazing changes and diversification in applications.

Solar energy is dead. Long live solar energy!

Geofuels:

- coal [*Sun-derived],
- petroleum [*],
- natural gas [*],
- tar sands and oil shales [*],
- gas hydrates [*],
- fissile material for nuclear power [not from sunshine].

With expansion of interest and adoption, the next generation of solar research will explore systems knowledge, incorporating a great diversity of approaches, analogous to the broad fields of ecology or geology. In turn, a newly emergent field solar energy discovery within the context of the environment, society, and technology could be termed *solar ecology*, leading to the applied design and engineering of *solar energy conversion systems*.

Now we are a new generation of energy explorers. There are no firm "rules" to solar engagement and entrepreneurship other than those specified by the coincident emergence of policy and law. Imagine what we can do with the *patterns* of solar energy conversion systems and sustainable design, beyond

Solar Ecology: interactive systems study of solar energy within the context of the environment, society, and technology.

Solar Energy Conversion Systems. http://dx.doi.org/10.1016/B978-0-12-397021-3.00001-6

photovoltaics and solar hot water panels—solar chimneys, greenhouses for power and food, solar gardens (shared solar arrays) for community power or district heating, solar water treatment, cooking with solar energy, even simple lighting design to improve indoor air quality and reduce electricity costs. There are amazing opportunities already in society and new patterns to explore for our future. I encourage *you,* the young generation of professionals in renewable energy, to explore the undiscovered potential of solar energy in society.

> "The use of clean energy technologies—that is, energy efficient and renewable energy technologies (RETs)—has increased greatly over the past several decades. Technologies once considered quaint or exotic are now commercial realities, providing cost-effective alternatives to conventional, fossil fuel-based systems and their associated problems of greenhouse gas emissions, high operating costs, and local pollution.
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> In order to benefit from these technologies, potential users, decision and policy makers, planners, project financiers, and equipment vendors must be able to quickly and easily assess whether a proposed clean energy technology project makes sense."[1]

[1] Canada Natural Resources, editor. *Clean Energy Project Analysis: RETScreen Engineering* & *Cases*. Minister of Natural Resources, 2005.

DESIGN CONCEPT

This text has been designed to open up the language of solar energy conversion to a broader audience, to permit discussion of strategies for assessing the solar resource (energy exploration techniques) and for designing solar energy conversion systems (integrative design). As such, the text applies a *whole systems* approach that explores *relationships, transformation, and feedback* in solar energy conversion systems, the solar resource, society, and our supporting environment. Here, *design* is used with the systems language of *patterns*, as *pattern with a purpose*. In turn, *patterns* are used to convey relationships in systems. Underpinning the language of solar energy conversion is the central goal of Solar Design (as solar energy engineer, economist, or architect): within the scope of sustainability ethics and maintaining or increasing ecosystems

Design is pattern with a purpose.

Whole systems design: integrating systems of systems to solve for complex challenges, a transdisciplinary approach to arrive at solutions that increase client well-being and **ecosystems services** in a given locale.

services, one seeks to *maximize the solar utility of the resource for a client or stakeholders in a given locale*. This will become a well-used mantra through the entire text, so we should get accustomed to it. Each participant in the integrative teams for solar design is in turn agents of change for a sustainable future. As will be noted later in the text, solar design strategies should both increase client well-being and strengthen ecosystems services within the given locale. Throughout the text learners are encouraged to be active participants transitioning to a new energy approach with solar design strategies, and to engage in lifelong learning of solar science and technology.

Locale: what can it mean?

- Address
- Place
- Placement
- Climate regime
- Frequency
- Time horizon

There is a continuity among all solar energy conversion systems, but it was not always perceived as such. In the past, researchers in solar energy came largely from three fields: one from a mechanical engineering background (solar thermal), one from an electrical engineering background (photovoltaics), and a third from architecture (passive solar home design). The photovoltaic field tended to remain focused on device physics and component optimization independent of the outside environmental constraints or the measured solar resource constraints of a locale. To a small extent, this still continues—a tradition that we hope to shift. Those from the mechanical background and architecture tended to create a then useful distinction between *active* and *passive* solar conversion systems. From a mechanical standpoint, an active system required pumps and motors and made extensive use of fluid and heat transfer, while a passive system functioned on fields and pressure differentials that were intrinsic to the whole collector.

Participants in solar design have **agency** to effect change that will increase client well-being and strengthen ecosystems services.

Active Solar and **Passive Solar** systems are from a framework language used in building science to identify systems approaches with pumps and fans (active) from systems that operated with field and pressure gradients derived from solar gains (passive).

Today, the language of the active/passive distinction begins to wear thin, and the majority of the *active* solar field is consolidated into what we now term *Concentrating Solar Power* (CSP), for utility-scale thermal cycle electrical power conversion and industrial solar processing. At the residential and light-commercial level of solar technology, we now have commercially available solar hot water systems that have no active pumps (called bubble or geyser pumps, based on Albert Einstein and Leó Szilárd's work in a novel refrigeration cycle from 1928)[2] and we continue to have photovoltaic systems with no moving parts, driven by intrinsic electric and effective fields. Meanwhile, even properly

[2] Susan J. White. Bubble pump design and performance. Master's thesis, Georgia Institute of Technology, 2001.

designed solar homes are equipped with active circulation and control systems to force air about, and depend on the essential balance of the Sun to keep the surrounding air intake warm (at one time designed to be solely *passive solar systems*).

Solar Energy Conversion Systems (SECS):

- **Aperture**
- **Receiver**
- **Distribution mechanism**
- **(Storage)**
- **Control mechanism**

Systems Solutions:

- Team effort
- Many players
- Transdisciplinary
- Engage clients early and often
- Integrative design
- Agents of change

In this text, we explore a pattern language, or a systems logic for solar energy conversion devices that includes an *aperture*, *receiver*, *distribution mechanism*, potentially a storage mechanism, and a *control mechanism*. We will generalize them as *tubular*, *flat plate*, and *cavity* systems, and then explain the detail of their functioning as a specific *optoelectronic* (solar to electric) or *optocaloric* (solar to heat) technology.

The approach in the text is to inform the design process, and to reveal that *systems solutions* in solar design require a transdisciplinary and integrative design team that engages a client or stakeholders into the design and planning process. The course for which this text was developed focuses on solar energy conversion and the economics of deploying solar energy conversion systems for energy engineers and economists, but should also complement a more general degree program addressing renewable energy, systems design, and sustainability. We will examine the principles of solar energy conversion systems (SECS) and build a foundation for explaining the basic concepts and implementation of conversion processes.

We shall begin by describing the historical context of solar energy conversion systems and the integrative design process, followed by the properties, availability, and utility of solar radiation and geometric relationship of Sun/collector. We will include steps to evaluate the economic or sustainability criteria for decision making in energy systems deployment. As such there are strong emphases on the solar resource and solar economics, as well as applying the lens of sustainability and ecosystems services into systems design. Physical materials (absorbers, reflectors, covers, fluids) are crucial for conversion of radiant forms of energy, and special treatment is included for materials throughout the text. The latter portion of the text covers the role of specific device/collector technologies as a part of a larger systems logic for integration. These chapters will describe the principles of photovoltaic conversion (optoelectronic and optocaloric processes) and design, as well as describe the procedures for solar thermal design in residential and industrial processes, and explore solar concentration for heat and power conversions.

As was stated then in 1985 by solar research expert Ari Rabl,[3] the full extent of solar energy conversion can no longer be contained in a single textbook. Exploring developments in the solar collector alone is a great field of research. In this text, we emphasize the *systems approach* to thinking about solar energy conversion as a useful application for society. The following chapters serve to create a new framework to evaluate design and implementation of solar energy conversion linked with non-solar energy conversion technologies. The systems approach emerges from the strong foundations of solar energy conversion research, design, and practice established in the decades of the 1950s through the early 1980s, which established the core material for all solar energy conversion technologies.

[3] Ari Rabl. *Active Solar Collectors and Their Applications.* Oxford University Press, 1985.

A key realization for the newcomer to solar energy conversion is that *the technology and the economics have been changing rapidly*, and we would like to cultivate a generation of solar practitioners with *general systems skills* that will be relevant to developing technologies in 5 years, as well as in 50 years. In assimilating the content of this text, we have identified much of the systems connectivity that will prove useful to current and future scientists, engineers, economists, and policy makers, regardless of the specific solar energy conversion technology of the day.

Technological advancement is only one lever to engage adoption of a SECS by society. See the chapter on solar economics for more levers!

INSTRUCTIONAL APPROACH

For educators using this text as a complementary tool to engage students in a course on solar energy conversion systems analysis and project scoping (project design and rudimentary project finance), I have identified the educational objectives below. The target audience is for students in the third or fourth year of undergraduate degrees in engineering, physical science, and environmental/energy economics, or for graduate students in those fields. I have also sought to provide accessible content for students of policy, architectural design, and

This text is intended to be interdisciplinary.

planning, as a part of an interdisciplinary course of study. Problems have been listed at the end of each chapter, which can be modified or expanded as needed.

Software skills should be developed for design teams. Solar energy uses multi-parameter solvers in project design.

Where called for, I have recommended the use of software to solve multi-parameter problems and to process large data sets. As such, students are encouraged to develop critical thinking skills for addressing the problem and core material rather than how to process the arithmetic of large data. Many of the useful tools in solar energy systems design are open to the public, and I hope to demystify several of the approaches used in industry to measure and quantify the criteria for systems design. Concepts in project finance and energy analysis come together using the simulation engine SAM (Systems Advisor Model), provided freely by the US Dept. of Energy's National Renewable Energy Laboratory.[4] The simulation tool incorporates many of the desirable component-based systems simulation tools found in the powerful software TRNSYS,[5] while offering an accessible front end that works on multiple platforms to explore project estimation from beginning to advanced levels.

As mentioned before the text is written for an interdisciplinary course with students coming from diverse backgrounds of science, engineering, policy, business, and economics. The topics and contents have been tested over the last 5 years, teaching to classrooms of 30–50 students a session. In addition to the main body of text and several vignettes of historical or scientific significance, I have included subsections that go into significantly greater detail, explaining core concepts throughout the textbook for more advanced study such as radiant transfer physics, spherical trigonometry, meteorology, or device behavior. These detailed sections can be found in numerous other texts as well, and address fundamental concepts for solar energy science, but are often equation-heavy and completely new to an already advanced student. In my own classroom experiences I humorously coin these detailed breakdowns as "Robot Monkey" sections, given the general surprised reactions of a student cohort to an unfamiliar dense body of scientific writing that seems ordered and intended to illuminate a topic, but which simultaneously appears as though intelligent monkeys with typewriters wrote it. I would like students to be aware that these sections may be passed over the first time, but that they are encouraged to come back to these

[4] P. Gilman and A. Dobos. System Advisor Model, SAM 2011.12.2: General description. NREL Report No. TP-6A20-53437, National Renewable Energy Laboratory, Golden, CO, 2012. 18 pp; and System Advisor Model Version 2012.5.11 (SAM 2012.5.11). URL https://sam.nrel.gov/content/downloads. Accessed November 2, 2012.

[5] S. A. Klein, W. A. Beckman, J. W. Mitchell, J. A. Duffie, N. A. Duffie, T. L. Freeman, J. C. Mitchell, J. E. Braun, B. L. Evans, J. P. Kummer, R. E. Urban, A. Fiksel, J. W. Thornton, N. J. Blair, P. M. Williams, D. E. Bradley, T. P. McDowell, M. Kummert, and D. A. Arias. TRNSYS 17: A transient system simulation program, 2010. URL http://sel.me.wisc.edu/trnsys.

sections later in their lifelong learning of solar energy topics if at first the written materials appear to have been written for all intents and purposes by a well-meaning, but truly challenging Robot Monkey.

Educational Objectives

- Understand the historical complement of solar energy conversion with conventional heat and power technologies
- Solidify a working knowledge of solar energy conversion and systems integration given the spatial relations of moving bodies
- Explain meteorological spatio-temporal measures for estimating variance and expected values from the solar resource
- Express familiarity and competence with processes and materials for solar to thermal and electric energy conversion (optoelectronic and optocaloric transformations)
- Develop tools to assess project finance of solar goods and services to society
- Develop skills to integrate ecosystems services and sustainability in solar project design, including portfolio diversification and awareness of the solar commons in decision making
- Develop sustainable energy systems approaches to maximize solar utility for the client in a given locale
- Understand and explore the broader meanings of "solar utility," "locale," and "client/stakeholders."

SUGGESTED COURSE SCHEDULE WITH TEXT

- *Context and Philosophy of Design*
  - History of Solar Design and Ethics of Sustainability
  - Laws of Light
  - Physics of Light, Heat, Work, and Photoconversion
  - The Sun, Weather, and Uncertainty
  - Spatial Relations of Moving Bodies

- *Economics and Sustainability Criteria*
  - Measurement and Estimation of the Resource
  - Economics of Market Goods and Services
  - Project Finance
  - The Sun as Commons

- *Systems Logic of Devices and Patterns*
  - Pattern Language in SECS
    - Cavity Collectors
    - Flat Plate Collectors
    - Tubular Collectors
    - Parasoleils
  - Optocalorics
  - Optoelectronics
  - Concentration

- *Systems Integrated Solar and Project Design*
  - Integrative Design
  - Solar Utility for the Client and Locale
  - The Goal of Solar Design

COMMUNICATION OF UNITS AND A STANDARD SOLAR LANGUAGE

Language is critically important in the field of solar energy. Because of the integration of several disciplines, each with their own specialized use of scientific and technical language, the solar field calls for an effective language to communicate solar conversion and applied device design in the literature and in group discussions. Prior work exists that will help us to begin the conversation adequately. In 1978, a consortium of solar researchers came together to agree upon a set of standards for discussing solar energy conversion topics. The paper was revisited and reprinted in recent years, and it shows precedent for a detailed system of notation and language used in the solar energy world, one that has been in use for decades. The original authors have established the following observations:

Transdisciplinary: integration of common effort across several diverse disciplines, creating a holistic approach to solving systems of problems.

> "Many disciplines are contributing to the literature on solar energy with the result that variations in definitions, symbols and units are appearing for the same terms. These conflicts cause difficulties in understanding which may be reduced by a systematic approach such as is attempted in this paper…
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> …Many disciplines are contributing to the literature on solar energy with the result that variations in definitions, symbols and units are appearing for the same terms. These conflicts cause difficulties in understanding which may be reduced by a systematic approach such as is attempted in this paper."[6]

Even in 1978 it was recognized that people would enter the solar field of science, design, and engineering from many supporting fields, and bring with them skills and language to contribute. There is a place for people from many backgrounds to expand and explore the field of SECS, and we should be aware of the common language used to communicate among ourselves, among our clients, and with the public. The authors go on to describe the vernacular for communicating values and coefficients. It was recognized that even a list of symbols and units would not be permanent or mandatory, but that a listing of terms and units could have value to the multitudes entering the transdisciplinary efforts of the solar field. We choose to use the guidelines from this paper in sections dealing with the spatial relations of moving bodies, in the physics of heat for radiative transfer, and in terms of meteorological assessment of the solar resource for quantifying variability of the resource in project design.

[6] W. A. Beckman, J. W. Bugler, P. I. Cooper, J. A. Duffie, R. V. Dunkle, P. E. Glaser, T. Horigome, E. D. Howe, T. A. Lawand, P. L. van der Mersch, J. K. Page, N. R. Sheridan, S. V. Szokolay, and G. T. Ward. Units and symbols in solar energy. *Solar Energy*, 21:65–68, 1978.

In terms of **energy**, the S.I. (*Systèm International d'Unités*) unit to be used is the joule ($J = kg\,m^2\,s^{-2}$), while the calorie and derivatives are not acceptable. There is no distinction between forms of energy, such that electrical, thermal, radiative, and mechanical energy are all measured in joules. The singular exception being the use of the watt-hour (Wh) itself an energy unit used extensively in metering of electrical energy from the grid.

Joule: S.I. unit of *energy* [J].

Watt: S.I. unit of *power* [W = J/s].

Watt-hour: commercial electricity unit of *energy*. Keep in mind that a watt-hour or a kilowatt-hour (kWh) is a unit of energy, *not* a unit of power. This is a really common mistake by students and early practitioners.

In terms of **power**, the S.I. unit is the watt ($W = J/s = (kg\,m^2)/s^3$). The watt, kilowatt (kW), megawatt (MW), gigawatt (GW), or terawatt (TW, rare) is to be applied for measures of power or the rate of energy generation/ demand. Again the watt is to be used for all forms of energy and wherever one is describing instantaneous energy flow. We will not express the rate of energy production or use in other units such as J/h. In turn, the measure of the **energy flux density** shall be expressed in terms of watts per square meter (W/m^2), which we have used in terms of *irradiance* so far. Also, the measure of the **specific thermal conductance** shall be expressed in terms of $W/(m^2\,K)$. Finally, when a rate of energy flux density or the rate of energy generation/ demand (power) is integrated for a specified time interval, we shall express the energy in units of J/m^2 (energy density) and joules, respectively. For example, a power generation (rate of energy production) measure of 4.1 kW would yield 14.8 MJ if maintained over the interval of 1 h. Consider that there are 3600 s/h and 0.001 MW/kW.

There is 3.6 MJ/1 kW when power is integrated over an hour of time (**1 kWh = 3.6 MJ**).

$$
\begin{aligned}
1\ \text{kW} \cdot 1\ \text{h} &= [1\ \text{kW} \times 1000\ \text{W/kW} \times 1\ (\text{J/s})/\text{W}] \cdot \\
&\quad\ [1\ \text{h} \times 60\ \text{min/h} \times 60\ \text{s/min}] \\
&= 3,600,000\ \text{J} = 3.6\ \text{MJ}. \qquad (1.1)
\end{aligned}
$$

In addition, when referring to energy for a specific interval of time one states an "hourly energy of 14.8 MJ" rather than 14.8 MJ/h, and a "daily energy of 355 MJ" rather than 355 MJ/day.

A **British thermal unit (Btu)** is a common energy unit to describe the energy content in heating fuels for the USA. It is defined as the energy called for to increase the temperature of one pound of water by 1 °F. 1 Btu = 1055 J, or ~1.1 kJ. For natural gas systems, the convention is such that 1 MMBtu (one million Btu) is equivalent to 1.05 GJ.

Symbols for radiance/irradiance and radiation/irradiation are split into several terms throughout this text. The energy flux density as derived from a general blackbody is given as E_b, while the specific energy flux density of

Angular Measure	Symbol	Range and Sign Convention
General		
Altitude angle	α	0° to +90°; horizontal is zero
Azimuth angle	γ	0° to +360°; clockwise from North origin
Azimuth (alternate)	γ	0° to ±180°; zero (origin) faces the equator, East is +ive, West is −ive
Earth-Sun Angles		
Latitude	ϕ	0° to ±23.45°; Northern hemisphere is +ive
Longitude	λ	0° to ±180°; Prime Meridian is zero, West is −ive
Declination	δ	0° to ±23.45°; Northern hemisphere is +ive
Hour angle	ω	0° to ±180°; solar noon is zero, afternoon is +ive, morning is −ive
Sun-Observer Angles		
Solar altitude angle (compliment)	$\alpha_s = 1 - \theta_z$	0° to +90°
Solar azimuth angle	γ_s	0° to +360°; clockwise from North origin
Zenith angle	θ_z	0° to +90°; vertical is zero
Collecter-Sun Angles		
Surface altitude angle	α	0° to +90°
Slope or tilt (of collector surface)	β	0° to ±90°; facing equator is +ive
Suface azimuth angle	γ	0° to +360°; clockwise from North origin
Angle of incidence	θ	0° to +90°
Glancing angle (compliment)	$\alpha = 1 - \theta$	0° to +90°

Table 1.1: Table of angular relations in space and time, including the symbols and units used in this text.

solar irradiance is given as G (G is for "global irradiance"). The global *solar irradiation* for the interval of a day is given as H, while the global solar irradiation for the interval of an hour is given as I.

When describing **spatial relationships** on continuous, near-spherical surfaces like the Earth and sky, Greek letters are preferred. When communicating distances, lengths, time, and Cartesian coordinates, we tend to use Roman letters. A full listing of symbols is described in Appendix B (see Table 1.1).