Solar Ecology: Transdisciplinary Vehicle for the Energy-Water-Food Nexus

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Solar photovoltaics are established global commodities, and solar electricity is being planned at the gigawatt scale internationally, a phenomenal success story. This growth has coincided with a rapid maturation of the solar field, involving a grand opportunity to explore other solar goods and services in the wake of photovoltaic successes, and a common message of "what next?" has emerged among solar colleagues. This work discusses solar in transition, moving from a wave of photovoltaic growth as of 2015, toward major global food-water-energy impacts in the next century. Photovoltaic goods are identified as a bellwether for future opportunities that include integrative "solar" expressed across three existing cultures of design. "Solar utility" is the vehicle aiding project development in solar ecology, describing the client/stakeholders' preference for solar goods and services fit within the dynamic perspective of the locale. The broader field of "solar ecology" is described as an emerging transdisciplinary systems field of solar energy within the context of the environment, society and technology–connecting science with design, business, lifestyle, health, and well-being. A solar ecology framework will contribute to a shared wave of coupled discoveries, inventions, and social change strongly influencing the energy-water-food nexus by 2100.

Figure 1: The global commodity for photovoltaics is creating a wave of opportunity for the solar ecology school of thought.

Solar Ecology: interactive systems study of solar energy within the context of the environment, society, and technology—affecting water and food systems coupled to locale-based climate regimes.

With expansion of interest and adoption of solar photovoltaics as a bellwether, the next generation of solar researchers are pressed to explore systems knowledge (cumulative energy debt, GHG impacts, water impact, weather risk management, and policy development for solar rights),[2] incorporating a great diversity of approaches, analogous to the fields of biology and geology coupled with the development of food/biofuels and petrochemicals/geofuels within society, respectively. The fields of meteorology and geography, along with the social sciences and energy/environmental economics will enable exploration of the patterns of solar energy and form the common frameworks for integrative analysis, engineering, and planning.

The security and resilience of the systems of energy, water, and food have been identified as deeply coupled, and critical to policy and planning for global infrastructure.[3] In turn, one can identify that the systemic nexus of **energy** $\otimes$ **water** $\otimes$ **food systems** presents an *ecology*, a study of the "home". As such, the systemic interactions of humans and other biota derived from the favorable energy imbalance

[2] V. Fthenakis, H. C. Kim, and E. Alsema. Emissions from photovoltaic life cycles. *Environ. Sci. Technol.*, 42:2168–2174, 2008. DOI: 10.1021/es071763q; M. Dale and S. M. Benson. Energy balance of the global photovoltaic (PV) industry–Is the PV industry a net electricity producer? *Environ. Sci. Technol.*, 47(7):3482–3489, 2013; and J. R. S. Brownson. *Solar Energy Conversion Systems*. Academic Press, Amsterdam, Netherlands, 2013a

[3] H Hoff. Understanding the nexus : Background paper for the Bonn2011 Nexus Conference. In *Bonn2011 Conference: The Water, Energy and Food Security Nexus: Solutions for the Green Economy*, Stockholm, November 16-18 2011. Stockholm Environment Institute

of solar irradiance upon Earth is thus termed **solar ecology**, a transdisciplinary vehicle for the energy-water-food nexus. The scope of solar ecology as a framework for research and design reveals many opportunities among science, technology, and society from energy-water-food relations (e.g. energy conversion and storage, moving and purifying water, food systems in society, and water use within building systems), both in terms of present day systems analyses, and planning for the scope of a climate changed by 2100.

Foundations of Solar Ecology

As noted decades ago in the developing research of ecologist H. T. Odum, economists N. Georgescu-Roegen, H. Daley,[4] and others, the flow of shortwave radiative energy as light from the Sun is one of the fundamental energy resource units for life, diversity, and well being for Earth systems. Additionally, solar energy has been documented as part of the story of society in architecture, agriculture, and active solar energy conversion technologies for over 6,000 years.[5]

A complimentary motivation of solar ecology research is to shift from analysis of the end products of solar conversion, to the flow of the resource units themselves *before* conversion, or analysis of solar irradiance as a flow of supplied "fuel". Typically, the products of solar energy conversion and their respective demands from society are assessed as independent and isolated focii of distinct disciplines, (e.g. electricity from electrical engineering, light and heat from architecture, lumber from forestry, food and biofuel from agriculture). By identifying the commonality of resource flows (e.g. solar irradiance), new frameworks can be explored in a transdisciplinary approach. As such, we are participants in an emerging era of renewable energy expansion and a transition from *stock-* to *flow-based* energy supplies (solar, wind, hydro).[6] The implications of flow-based systems analysis already drives research to address spatio-temporal resource assessment, resource allocation, ecosystems services integration, societal feedback on land use choices, and the strongly coupled systems dynamics.[7]

[4] Howard T. Odum. Energy, ecology, and economics. *Ambio*, 2(6):220–227, 1973; Nicholas Georgescu-Roegen. Technology assessment: The case of the direct use of solar energy. *Atlantic Economic Journal*, 6(4):15–21, December 1978; and H. E. Daly and J. Farley. *Ecological Economics: Principles And Applications*. Island Press, 2nd edition, 2011

[5] John Perlin. *Let it Shine: The 6,000-year Story of Solar Energy*. New World Library, 2013

Unifying Approach: Shared awareness and analysis of the the flow of solar resource units (light; solar irradiance) *prior to conversion*, and then on the resulting products from conversion.

[6] J. R. S. Brownson. *Solar Energy Conversion Systems*. Academic Press, Amsterdam, Netherlands, 2013a; and K. Calvert and W. Mabee. Energy transition management as a 'spatial strategy'? Geographical implications of the transition toward renewable energy, 2014

[7] J. R. S. Brownson. Framing the sun and buildings as commons. *Buildings*, 3: 659–673, 2013b

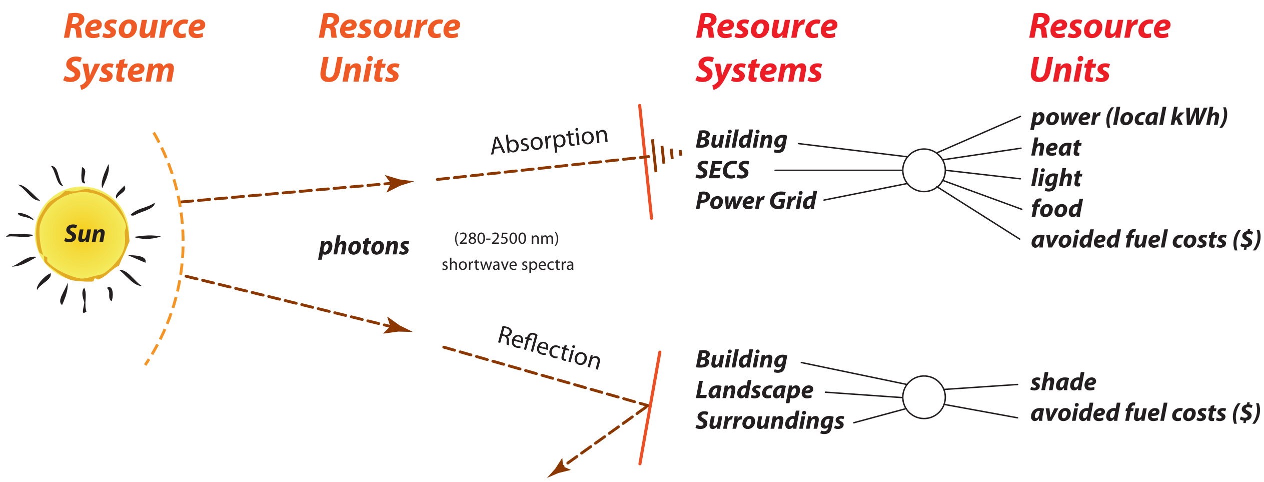

Figure 2: Schematic of the Sun (and emitted shortwave light) as a *resource system*, and the resulting *resource units* that are appropriated by the clients who own a solar energy conversion system. From Brownson, *Framing the Sun and Buildings as Commons* 2013.

As science is the *exploration of patterns* in our universe, then **design** can be specified as **pattern with a purpose**. Three distinct **cultures of design** have evolved to address the systems question of solar energy: the **culture of architecture** and the built environment, **agriculture** (and in turn, forestry) for food, structural materials, and bioenergy, and the **culture of solar energy conversion systems** (SECS–energy engineering) for heat and power. Each of these cultures is place-based, flow-based, and fully engaged with the water cycle. Each of these cultures are on a path to be aligned and integrated within the framework of solar ecology. Stated another way: solar culture elements are strongly coupled.[8] As climate change and water scarcity drive society to develop new skills in solar energy as environmental technologies, major research opportunities will emerge for the newly discovered patterns.[9] The emergent systems research field of *solar ecology* fits within the context of the environment, society, and technology, and will facilitate integration within the cultures for design and engineering.

[8] J. R. S. Brownson. Framing the sun and buildings as commons. *Buildings*, 3: 659–673, 2013b

[9] Wendell Berry. *Home Economics*. North Point Press, 1987

Applications of Solar Ecology

The effect of research results from solar ecology will impact society in terms of markets, policy, and planning, as well as core cultural approaches to design and engineering. In the culture of design for active solar energy conversion systems, all projects are based on the client-locale relationship. The goal of solar design is to maximize the *solar utility* (considered as preference for solar goods and services) for impacted *stakeholders* within a given *locale*. Locale is specified to encompass a range of factors in both time and space: tied to the meteorology, energy economics, ecosystems services, and tied to the policies and incentives available the stakeholders.[10] A solar design team for a solar photovoltaic farm will be solving for patterns on behalf of the clients/stakeholders, within the larger constraints of the broad solar ecology embodied by the locale (Fig. 3). There are several important frameworks already under study ready to draw from solar ecology in today's context: water cycles, land use, and food systems.

[10] J. R. S. Brownson. *Solar Energy Conversion Systems*. Academic Press, Amsterdam, Netherlands, 2013a

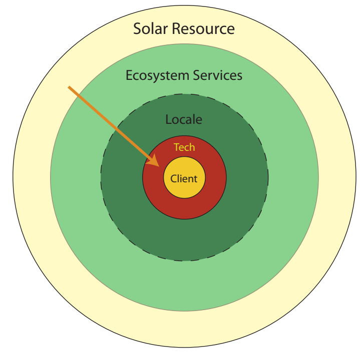

Figure 3: Schematic of the solar ecology tied to the central technologies of a SECS. Outer two rings reflect the environmental systems interplay of the dynamic *solar resource* and *ecosystems services* for a locale. Three central rings reflect localized sociological/personal interactions among *solar technology* (core), *stakeholders/clients*, and the *locale* motivating the goal of solar design: *to maximize the solar utility for the client in a given locale*.

Water Cycles and Solar

The water cycle is directly coupled with solar energy, and the associated energetics are fundamentally driven by dynamic Sun-Earth-Atmosphere systems interactivity (e.g. energy conversion and storage, moving and purifying water, food and fuel systems in society, and water use within building systems). The water cycle within the atmosphere also defines the dynamics of renewable energy intermittency from solar photovoltaic power and wind power generation. Pressure for common pool resource management among stakeholders with water resources are already coupled with solar and food resources, calling upon research to guide policy and legal development in the future of constrained/scarce water. The water-energy relationship is critical to society both in terms of present day systems analyses, and planning for the scope of a climate changed by 2100. As such, adapting and planning for water demand with respect to environmental resilience and ecosystems services is deeply interconnected with meteorology, climatology, and radiative balances. Combined constraints in cost and GHG emissions with water demand will change optimal power planning schemes, suggesting a power supply rich in photovoltaic and wind electricity.[11] With the exponential growth of the photovoltaic and wind industries, and the potential for solar to replace fuel-based power technologies, society may even observe a reduced coupling of water from the power sector.

[11] M. Webster, P. Donohoo, and B. Palmintier. Water-CO_2 trade-offs in electricity generation planning. *Nature Climate Change*, 3:1029–1032, December 2013

Land Use Patterns and Ecosystems Services

Solar ecology is an effective vehicle to research this interface. Solar energy conversion systems consume large land areas, yet are localized sources of energy and financial revenue production. As an example, one could foresee studies of the exponential growth of solar photovoltaic technologies in a region or state, coupled with changing land use patterns and local economics. In turn, complimentary arcs of study are possible that link spatio-temporal systems dynamics between land use patterns and solar climate regimes.

Another implication for the field of solar ecology is the exploration of connective frameworks among ecosystems services and human well-being in distinct sites/regions for the **energy** ⊗ **water** ⊗ **food** nexus,[12] including land use patterns and social feedback patterns to inform to the applied design and engineering of solar energy conversion systems.

[12] W. V. Reid, H. A. Mooney, A. Cropper, D. Capistrano, S. R. Carpenter, K. Chopra, P. Dasgupta, T. Dietz, A. K. Duraiappah, R. Hassan, R. Kasperson, R. Leemans, R. M. May, T. McMichael, P. Pinagali, C. Samper, R. Scholes, R. T. Watson, A. H. Zakri, Z. Shidong, N. J. Ash, E. Bennett, P. Kumar, M. J. Lee, C. Raudsepp-Hearne, H. Simons, J. Thonell, and M. B. Zurek. Ecosystems and human well-being: Synthesis. Technical report, Millennium Ecosystem Assessment (MEA), Island Press, Washington, DC., 2005

Food Systems

Solar ecology offers yet another facet in terms of food systems and nutrition. Agriculture and forestry are inherently defined by solar transformations, and yet beyond that are the steps to process food using solar methodologies. Within the wake created by solar photovoltaics, Solar cooking and solar food processing is rapidly expanding as a form of societal change for women and avoided fuel use and health benefits in in Central America, Asia, and Africa.[13]

[13] L S Brown and W F Lankford. Sustainability: Clean cooking empowers women. *Nature*, 521(7552): 284–285, 2015; and The Solar Food Processing Network, June 2015. URL `http://www.solarfood.org/`

Social Systems

Barriers to solar research and design are deeply internalized within societal norms and scientific practice, held as contextual values (generally anthropocentric and visual) that influence lines of inquiry, which topics are ignored about solar energy, or even whether solar energy is the subject of research. Hence solar ecology is also a vehicle for social research, exploring the cultural barriers to integrative solar research thus far, the cultural cognition of risk associated with solar,[14] solar rights and access, and the implications of drawing focus specifically to systemic solar research questions.

[14] D Kahan. Fixing the communications failure. *Nature*, 463(7279):296–297, 2010

Transformations to Solar Ecology

A new field of study is imminent, engaging the relationship between the flow of shortwave radiation from the Sun to Earth and the emergent nexus of dynamic ecological systems impacted by Solar irradiance over space and time. These initial observations reflect the complex embedded ethics of radiative-coupled regime research as a new field. In order for the burgeoning field of solar ecology to grow into a fully adaptive, rich, and diverse energy systems community, we will need to develop grand challenges that **align motivation for research**, tied to **common language**, and **capacity development** within a **common framework**. Solar ecology will continue to develop applications in the next generation of sustainable energy power systems such as solar photovoltaics, because energy instances in society (the power grid, district heat, electricity markets, commercial buildings) must be approached as whole systems within a shared conceptual framework. What will be truly invigorating, will be the shared wave of coupled discoveries, inventions, and social change emerging from the growth

SOLAR ECOLOGY FRAMEWORK OFFERS HIGH POTENTIAL FOR TRANSDICIPLINARY SYSTEMS RESEARCH COLLABORATION:

- Energy Engineering
- Energy/Environmental Economics
- Geography
- Meteorology
- Urban Planning
- Rural Sociology
- Agricultural Extension
- Building Systems Science and Architecture
- Liberal Arts: Ethics, Policy, Communication

and transformation of the solar ecology field as a transdisciplinary vehicle for the energy-water-food nexus leading toward 2100.

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