The Oil Drum: Net Energy

Discussions about Energy and Our Future

The Energy Return of (Industrial) Solar - Passive Solar, PV, Wind and Hydro (#5 of 6)

Posted by Nate Hagens on April 29, 2008 - 10:00am in The Oil Drum: Net Energy
Topic: Alternative energy
Tags: hydroelectric, passive solar, photovoltaics, solar power, wind [list all tags]

Below is 4th in a series of installments by Professor Charles Hall of the SUNY College of Environmental Science and Forestry and his students attempting to update the 'balloon graph' of EROI x Scale for fossil and renewable energy sources with help from theoildrum.com readership. Todays post deals with solar energy, specifically: Hydropower, Passive Solar, Photovoltaic, and Wind energy. Next will be Geothermal and Wave energy systems.

Previous articles/commentary from this series:

At $100 Oil, What Can the Scientist Say to the Investor?
Why EROI Matters (Part 1 of 6)
EROI Post -A Response from Charlie Hall
EROI Part 2 of 6 - Provisional Results, Conventional Oil, Natural Gas
Unconventional Oil: Tar Sands and Shale Oil - EROI on the Web, Part 3 of 6
The Energy Return on Nuclear Power

Introduction to Solar Energy

(Charles Hall)

The sun is of course the main source of all of the energy that humans depend upon. Most importantly the sun runs the great systems of climate, hydrology and ecosystems that define and create the conditions within which the human economy must operate. In the distant past, solar energy generated fossil fuels and much of the mineral concentrations that we depend upon. In a beautiful book "A Forest Journey", John Perlin traces the historical dependence of emerging human civilizations on forests as well as the crashes of civilizations that commonly followed the over-exploitation of forests and the soils they made. At issue on TheOilDrum today is the energy return on investment for the production of "industrial energy" from modern solar energy. By 'industrial' we mean electricity and heat more or less equivalent to what we get today mostly from fossil fuel. The five main sources of such "industrial" solar energy are usually thought to be hydroelectric power, passive solar, photovoltaics, wind and various types of biomass. We examine the first four of these in todays oildrum posting, and biomass at a later date. Since the EROI of wind has already been analyzed (and I might add more throughly than we have found possible for what we give today) by Cleveland and Kubiszewski, we present results for hydropower, photovoltaics (briefly) and passive solar. As usual we are doing this to seek additional references to bolster our analysis.

APPENDIX G.

HYDROPOWER SUMMARY

Billy Schoenberg, SUNY-Syracuse

Definition: “The electric current produced from water power” (Gulliver and Arndt, 2004). Because the sun evaporates water, mostly from the ocean, and through winds carries the water vapor up into the atmosphere and to the mountain tops where much of the world’s rain falls, hydropower is most properly considered solar energy. It is different from other solar energy in that it is relatively easily captured and turned into mechanical or electrical power, and relatively easily stored as elevated water behind a dam.

Hydropower currently accounts for approximately 6% of world energy consumption. Hydropower projects may be large or small scale (usually 5MW or less capacity), and may involve either construction of a dam, reservoir and/or tunnels to hold back and reroute water through a turbine reservoir (the usual), or “run of the river”, which does not involve the construction of large dams or tunnels. Large scale hydro projects, usually involving reservoirs, are the most well-researched.

Resource base

Hydropower has the technical potential to provide up to 3800 GW of power globally, but only ~2500GW is considered economically feasible. Of that only 720 GW are currently installed worldwide. Thus globally, there are many undeveloped dam sites with hydropower potential although in the US the majority of the best sites are already developed. Much of the remaining technical potential is small-scale hydro which can be placed in most streams or rivers of at least moderate size and flow. Theoretically, hydropower at some level could be accessible to any population with a constant supply of flowing water. In practice the low price of fossil fuels, particularly the low investment cost, and the environmental and social costs of dams, has meant that fossil-fueled projects are much more common.

EROI

The EROI of hydropower is very site-specific. Because hydropower is such a variable resource, used in a multitude of different geographical conditions, and involves such different technologies, one general EROI ratio is not applicable to describe all projects. Reported EROI values range from about 11.2 to 267 (both quality and not quality corrected for the fact that the output is electricity and the input is mostly oil or other fossil fuels) (Cleveland et al., 1984) and (Gagnon et al., 2002). For specific favorable sites in Quebec EROI has been reported at 205:1 (for a reservoir type) and 267:1 (for a run of the river type). It is not known if these values are quality corrected, if quality corrected these numbers, would be three times as high. Thus the EROI for favorable or even moderate sites apparently can be very high, especially if the environmental or social effects are not included.

Economics

Hydropower differs from many other energy sources in that the major investments of energy and dollars occur when the plant is constructed, and there is little energy used in maintenance and operations. In general, hydroelectric power is cheaper than other sources of electricity (about 4 cents per KWh in 2000 vs. two to three times that for electricity from other sources). Since hydropower technology has been mature since the 1930's there are probably not large changes in EROI over time except from the decreasing quality of sites used as the best ones are developed, and from small incremental changes in turbine design.

Environmental impacts

There is a large divide in the literature as to the costs and benefits of hydropower. On one side of the debate there are those who see hydropower as a clean, renewable source of energy, with only moderate environmental or social impacts. Others see hydropower as a scourge to society with environmental impacts that can be as large or larger as some conventional fossil fuels. The proponents of hydropower speak of its minimal emissions (especially CO_2), renewable nature, and its contributions to water supply and irrigation. In addition they say the impacts on people and fish can be minimized when planned properly.

Hydropower's detractors cite the effects it has had on migratory fish such as salmon, the contributions reservoirs make to greenhouse gas emissions and the harm it has done to displaced people, especially in the third world. The global effects of hydropower center around its carbon emissions and its potential to contribute to global warming, while the regional effects are centered around reservoir creation, dam construction, water quality changes, and native habitat destruction. Much of the debate centers around hydropower's effects on people and whether or not a constant supply of water for power, irrigation or drinking is worth the relocation of millions of individuals. Nevertheless most analysts agree that there is a place for additional electricity produced from hydropower in the future.

The majority of environmental impacts upstream are due to the flooding of the river valley and creation of a reservoir. The reservoir completely destroys any terrestrial ecosystems that were once present in an area. In addition sediment and nutrients get trapped behind the dam causing the dam to become less efficient over time and the potential eutrophication of the reservoir if the dam and watershed are not managed properly.

Environmental impacts also occur downstream. The alteration of the river flow and the increased erosive power of low-sediment water cuts new channels into the riverbank sometimes causing massive amounts of erosion. Or in some cases the dam will completely dry up the river below, killing all aquatic species and forcing any terrestrial organisms to migrate in order to find water. In addition some hydropower facilities operate on irregular schedules creating very un-natural pulses of water through the ecosystem, which most strongly effect the aquatic species especially the invertebrates. In addition to these concerns there is the occasional supersaturation of gases downstream of dams causing a "bends"-like condition (e.g. nitrogenembolism) in fish and other aquatic organisms.

The amount of carbon emissions produced is very site specific, varying by as much as 500 times and correlated mostly with the latitude of the construction site and the density of vegetation that was found in the flooded area. The highest producers of carbon emissions, generally methane, appear to be those in Brazil or places closer to the equator so that the majority of the best large-scale sites remaining are most likely to be large emitters of CO_2 from reservoir construction. A range of carbon emissions per kilowatt hour produced are available and those numbers range from 1 to 34 g CO_2/kWh with more usual numbers in the range of 2 to 9 g CO_2/kWh. This is substantially lower than fossil fuel sources

Social Impacts

Large dam construction almost inevitably comes at the cost of the relocation of people who live in the river valleys upstream which get flooded during reservoir creation, or sometimes for those who live in the flood plains downstream. Some 40-80 million people have been relocated and otherwise impacted by the various associated general, gender/class and health effects. For example, men are hired for several months or years to work dam construction which forces families apart, and relocation often forces women to leave not only their land, but their husbands, sons and fathers. The largest health effects come after the dam is completed, often generating a perfect habitat for many parasites or vectors for those parasites in the suddenly still water. A second category of post construction health risks is dam failure or collapse. This risk is largest in China, where dams that were constructed rapidly from 1950-1980 without much planning or good engineering, killed up to 250,000 when a few failed.. The risk of failure is always present at the rate of about 1 in 10,000 per year.

In summary dams can have very high EROI and have the potential to produce a moderate amount of additional, high quality electricity in the developing world, but are often associated with extremely high environmental and social costs. Many authors see run of river hydropower as the future because it does away with massive relocation projects, minimizes the effects on fish and wildlife and does not release any GHG emissions (because there is generally no reservoir) while retaining the benefits of a clean renewable cheap source of energy. On the other hand the relatively low power density available in run of the river projects relative to the high heads made possible with a dam limits the potential of this approach.

Table 1. Magnitude and EROI of hydroelectric power from various sources.

Magnitude	EROI	Reference
Not given	33.6:1	Cleveland et al. 1986.
Not given	48:1	Pimentel, Rodrigues 1994
Reservoir	205:1	Gagnon, Belanger, Uchiyama 2002
Run of River	267:1	Gagnon, Belanger, Uchiyama 2002
Not given	19:1	Odum et al. 1975
Run of River	26-101	Gilliland, Klopatek, Hildebrand 1981
Not Given	100-300	Gagnon et al. 2002

Table 1. Magnitude and EROI of hydroelectric power from various sources.
Click to Enlarge.

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APPENDIX G-1

PASSIVE SOLAR

Kallistia Giermek SUNY ESF

Introduction

Definition: “The use of solar energy by passive means to reduce the heating demand of a building.”

A passive solar building is designed to capture and optimize the heat and light available daily from the sun. To qualify as a passive solar system means to accomplish this without use of any collectors, pumps or mechanical parts (Cleveland 2006.) The only difference between a conventional house and a passive solar house is design. When building a passive solar house there are two main design points to take in to account: one, to maintain comfortable average equilibrium temperature by balancing heat gains and losses and two, to minimizing temperature fluctuations both for 24 hours and over the year (Wayne 1986).

Passive solar architecture is much easier to execute when designed into a house rather than added on after construction. In general but not necessarily, passive solar homes take more time, money and design effort to build. Over time these extra cost will pay for themselves with energy savings (Smith 2001). At this time it does not seem possible to give the number of houses that are building a substantial amount of passive solar into the design but it cannot be very large.

History Time line of Passive Solar Energy:

History Time line of Passive Solar Energy:	
5th century	The Greeks found that houses that faced the south would allow sun to penetrate in the winter and provide shade during the hot summers (Wayne 1986.)
6th century	A method was introduced capable of capturing solar heat. They created “Sun Furnaces” known as Heilocamini that were glass-covered structures much like a modern greenhouse (Perlin 2004.)
Early Euro Americans	Originate the “Slat Box” design houses that faced toward the winter sun with a deciduous Lattice that would hang in front of the windows. The lattice would provide shade during the summer. When the leaves were lost during the winter, the sun would warm the house (Perlin 2004.)
1930s	Germany leads a renaissance in solar building that spread throughout Europe, only to be stopped by the Nazis who declared functional architecture to be Jewish (Perlin 2004.)
Post World War I America	With the terrible slums that blighted European cities during the industrial revolution it sparked a new interest in building with the sun’s benefits. An English city planer urged, “Every house should have is face turned toward the sun whence comes light, sweetness and health” (Perlin 2004.)
Mid 1940’s	Keck’s “Solar Homes” caught the attention of the national media being featured in House Beautiful, Readers Digest and Ladies Home Journal. With fuel rationing Americans moved to more conservation methods such as passive solar (Perlin 2004.)
1948	Frank Lloyd Wright demonstrated in Jacob’s House II how an early twentieth century residence could and should take advantage of the sun to supply heat (Ferbadez-Gonzalez 2004.)
As WWI ended	The housing demand exploded. Architects used solar designs as an incentive for people to buy their houses (Perlin 2004.)
Post WWII America:	Solar heated houses had large swings in temperature because they would heat easily in the direct sun rays and cool fast due to the many windows. Solutions: Felix Trombe and Jacques Michel used the patent filled by Edward Morse to advance the masonry wall later known as Trombe walls (Perlin 2004.)
1948	Worlds first solar heated public building: 1948 It was a school and thus unoccupied during the night so heat storage was not an issue (Perlin 2004.)
2006	Jeff Lyng designed a home that runs completely on solar energy (Hall, personal comm).

History Time line of Passive Solar Energy
Click to Enlarge.

Techniques

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Passive solar heating: While passive solar designs and techniques vary by location and regional climate, the basic styles remain the same. The three basic techniques include direct gain, indirect gain and insulated gain. Each of these techniques utilizes different aspects of the fundamental laws of heat while all have one common factor, general construction elements which are :

1) Large areas/volumes of concrete or other thermal mass. This is necessary because during the winter concrete floors and walls act to hold heat in and radiate it during the night when the temperature drops. During the summer the concrete serves to absorb excess heat.

2). Windows with high thermal resistance such as highly efficient glazing.

3) Air tightness to avoid overheating in summers. Studies have shown that if designed properly the need for mechanical cooling can be eliminated. Proper ventilation is key. Moveable shades can also be added to reduce to cooling loads. (Smith 2001)

4) Natural ventilation.

5) Shading by use of an overhang or movable shutters. Because the summer sun is higher in the sky relative to the winter sun, overhangs can provide shading during the hot summer months. The overhang should be built to intersect the angle of the summer sun (United States DOE 2000.)

6) Orientation of the long axis of the house east to west.

7) Large glazed areas on the south facing side and fewer windows on the northern side (Smith 2001). Although true southern exposure is preferred, it is not mandatory. If the building is oriented 30° of due south (in the Northern Hemisphere), it will still receive 90% of the optimal winter sun.

Incorporating Active components:
Often the addition of a few active components can greatly increase the energy gained for a specific passive solar design. Fans and pumps and properly designed heat exchangers can be used to circulate air and heat to reduce indoor pollution

The three dominate forms of passive solar heating include:

Direct Gain: Direct gain is the simplest of the passive solar designs. Sunlight enters the house through the aperture (a large glazed surface) – usually on the southern facing side. This sunlight then strikes a source of thermal mass (walls and/or masonry floors) which is then stored as solar heat. To best absorb solar heat, the surface of the floors is usually dark and carpet should be avoided. As night approaches and the temperature decreases the heat stored in the floors and walls will radiate into the room (United States DOE 2001.)
To avoid overheating during the summer some form of shading is very important. Overhangs are a very popular method of avoiding over heating. Other methods include deciduous plants and/or trees covering the southern windows that would shade during the summer and lose their leaves during the winter to allow the sun in.

Pros: Very simple, does not require extensive planning or design and it is possible to utilize direct gain and day lighting with the same design.

Cons: Increased glazed area leads to greater heat loss and so greater fluctuations in household temperature. Direct gain has the largest temperature fluctuations of any of the passive solar techniques. (Ferbadez-Gonzalez 2004). Without proper shading method overheating during the summer is very common. Direct gain works only in areas where southern exposure is available, so it would not work in dense poorly planed cities or densely forested areas (Perlin 2004).

Trombe Walls: Passive solar houses tend to have temperature fluctuations greater than the average conventional house and 75% of heat energy is needed at night (Wayne 1986). To compensate for this temperature fluctuations different heat storage technologies such as the Trombe Wall have been developed (Everet 2004.) A Trombe Wall is a thick wall with a very high thermal mass. It is usually concrete, masonry or wallboard. It can even be water placed between a window and the living space leaving about a one inch area between the window and the wall. Heat penetrates through the glass and is stored in the Trombe wall. Sometime slits are cut into the Trombe wall to increase circulation of warm air when the indoor temperature falls below the temperature of the wall, the heat will begin to radiate into the room. Heat will travel through a masonry wall at the rate of 1 inch per hour. Therefore the heat that was absorbed in an 8inch wall at noon will enter the room at eight o'clock just in time to replace the heat lost from the sunset. An overhang much like that of the direct gain method is also beneficial to the Trombe wall system (Everet 2004.)
Pros: Heat it stored for the cooler hours of the night.

Cons: Trombe walls often block out most of the potential direct gain heat and daylighting and are very hard to add into a preexisting house.

Insulated gain (Conservatories): Also known as a sunspace, solar room or solarium (United States DOE 2001) a conservatory is essentially a green house attached to the south facing side of the house. It consists of a large open window on the house side to circulate the warm air throughout the house. Conservatories, due to their large glazed surface, experience a great deal of heat gain and loss. The use of thermal mass and low emission windows can control these fluctuations. Heat is stored in the house itself and in any source of thermal mass such as the back wall of conservatory, floors, etc.

Pros: Conservatories can be built as a part of an existing house or a new home. (United States DOE 2001), and the large heat gains in sunspace can be moved to other parts of the building easily with a fan

Cons: Worst overall performance of all the strategies (Ferbadez-Gonzalez 2004)- i.e. has a high heat loss

Other uses of natural energy in buildings:

Passive solar cooling: Saving money and conserving energy by heating with passive solar during the winter is best complemented by passive cooling during the summer. In many climates opening windows during the night helps to flush out heat and bring in cool fresh air, an aperture that can be opened at the top can be very helpful in doing this. To keep this cool air inside it is best to close the windows and shades in the morning to prevent further heating from solar energy (United States DOE 2000.)

Daylighting: The use of various apertures to let in sunlight to building interiors is as old aas architecture, but before the twentieth century replacing daylight with artificial light was very expensive. Today with cheap electricity daylighting has been vastly neglected despite its positive attributes. Most modern office buildings and schools are built to rely heavily on artificial light. The primary daylighting strategies are location, large glazed areas and orientation. Daylighting is most widely used in lower level schools. This is because schools are most heavily used from 8am – 4pm when the sun is out and ready to be used (Hastings 2003, Everet 2004).

Pros: Obvious savings in energy cost. Increased performance and increase test scores in students have been reported. Natural heat and light promotes better health and physical development (Plympton 2000).

Cons: Site specific.

Limitations:

Location: clouds diffuse solar energy making less readily available. For temperature, Passive solar heating alone cannot heat a home to comfortable temperatures where harsh winters are the rule (Smith 2001.) Available southern exposure limits the number of houses that can be so constructed since a house on the northern facing slope of a hill cannot absorb the strongest sun which comes from the south. Daylighting can work at any latitude although obviously in the winter it has less utility in Northern areas.

Air tightness: The most successful passive solar homes are airtight, however, if the house is airtight the threat of pollutants becoming trapped inside increases (Everet 2004.) This can be overcome by the use of fans and pumps to circulate air around the dwelling. This would lead to a hybrid passive/active solar design.

Net Energy

Because passive solar design is incredibly site specific it is very difficult to determine just what the EROI might be. Rarely does an architect get quantitative feedback on the system, finding a numerical Energy Return on Investment (EROI) is nearly impossible.(Lyng 2006, Spanos 2005). Nevertheless if various passive solar designs are built into the house from the beginning then fairly large energy gains can be obtained with little or no investments. In other words it may cost little to put most of the windows on the south side, although that may greatly increase the gain.

An EROI could be calculated for a case specific location by dividing the energy saved each year over the energy inputted to make that house passive solar. The EROI for a passive solar would be very high because building passive solar is a one time expense and houses last half a century or more. Studies have shown that the energy savings can range anywhere from 30-70%, this would cause the EROI to change vastly from case to case. If the payback period is five years and the house lasts for 50 then the EROI would be, apparently, 10:1.

Daylighting

Location	Date	Type of building	Savings	Size of Building	Reference
Raleigh, North Carolina	1997	Middle School	$21,000	13865.778 m²	1
Salida, California	1997	Elementray Scool	$9,000	4366.442 m²	1
McKinney, Texas	1997	Elementray Scool	Payback time 3-5years	6503.212 m²	1
Silverthorne Colorado	Aug-00	hardware store	38% energy	23580 m²	2
Austin, Texas	1997	Elementray Scool	$32,000	10683.849 m²	1
North Carolina	Nov-04	Middle School	46% energy	9600 m²	3

1. (Plympton 2000) 2.(Hastings 2003) 3. (Whalen 2004)

Passive Solar (Heating)

Location	Date:	Techniques	Savings Energy	Savings Money	Cost	Reference
Golden, Colorado	Nov-04	DL,SG,OH	50%	75%	$1,213/m²	1
Pueblo, Colorado	Jul-96	TM	33%	$345 per year	*	1
Golden, Colorado Tierra 1	May-04	Tm,Sg,Oh,Tm,Dl	70%	*	$807sq.meter	2 PR

Key: DL is Daylighting TW is trombe wall OH is overhang
SG is south side glazing TM is thermal Mass IN is insulation
1. (Whalen 2004) 2. (Smith 2001) PR is Peer reviewd

Table 1.(blue) Energy Savings from daylighting -
Table 2.(green) Energy Savings for Passive Solar Energy
Click to Enlarge.

Economics:

New Buildings: Some studies have shown that the prices for building a passive solar home are the same or less than other custom homes. Other studies say passive solar homes have an average of 3-5% added cost. Over time these added costs will pay for themselves in energy savings (Pimentel 1994.) After 16 years, the Tierra I house built in Colorado saved $2000 for every extra dollar spent to make the house passive solar. (Smith 2001.) While this example highlights a potentially high energy return from passive solar, it also shows that there is an upper limit to its scalability. One cannot use ones house as a vector to create Gigajoules of extra electricity, but only the heat, and perhaps some extra, that the occupants of the house require. But if used on all new houses, the overall scale could be quite large in replacing other fuels.

Adding on to preexisting structures: Installing a passive solar system into the design of a new home is generally cheaper then fitting it on to an existing home. Saving can still be accomplished but prices are generally higher and savings are lower. The easiest method to attach on to an existing home is a conservatory which is also the least efficient method of passive solar heating

(Pimentel 2001.)

Environmental Impacts:

Positives: The design and energy efficient construction for passive solar homes decreases cooling loads and reduces electricity consumption which leads to significant decline in the use of fossil fuels. For example, in Colorado 94% of electricity consumed is produced by coal fired generation power plants. Estimates show that at 4218 kg of CO_2, 14.5 kg of SO_2, and 13.6 kg of NO_2 can be avoided in a single Colorado home with passive solar technology (Whalen 2001).

Negatives: In order to utilize the sun to its fullest potential, a passive solar home must be free of any obstacles that block sunlight, such as other houses or tree. Passive solar homes work best in lightly populated areas making them more land intensive. Thus a series o f solar homes all facing south would presumably take up more land area then if they were oriented randomly.

Social Implications:

Daylighting:
Most of the modern workforce is based indoors with artificial light. In most cases workers feel uncomfortable leading to a rising trend or complaint amongst works in the idea of sick building syndrome, making people uncomfortable in their workplace and hence less productive. Passive solar buildings can provide a healthy and therefore more productive building. (Currie 2002).

In conclusion, it is obvious that designing buildings from the start to take advantage of natural heating and lighting, and to use more insulation and solar mass, have a tremendous possibility to reduce energy demand in the future. The “Green buildings” program is a very active and interesting field. But it should be realized that each new building, no matter how green, increases the energy that we use to make and in buildings, except in the sense that as the housing stock turns over we have an opportunity to replace it with less energy intensive buildings. Probably all possible decreases in the energy intensity of buildings are more than made up by increases in square footage per person (Jevons Paradox). Probably population growth and the broad economic patterns we have experienced in recent years of building and then overbuilding real estate has had far more impact on our energy use in buildings. These issues need to be on the “green building” agenda.

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APPENDIX G-2.

Photovoltaics

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It was not our original intent to undertake an analysis of Photovoltaic (PV) Systems because we were to leave that analysis in the hands of a colleague more competent for that analysis. However that analysis has not been made available so we are presenting a brief summary of our own.

EROI

Explicit net energy analysis of photovoltaic (PV) energy appears to be nearly non-existent. However several studies report the time required for "energy pay back," and if we know the lifetime of the module or system, an EROI of sorts can be calculated. A typical life-cycle analysis is from Battisti and Carrado (2005) for a reference system (of) a multi-crystalline silicon (mc-Si) PV system, grid connected and retrofitted on a tilted roof in Rome. The assumed efficiency of the cells is 10.7 percent and the materials required are 12.6 kg/m2, with a mean output of 0.106 kW/m2. No storage device was included. For this they estimate the energy costs associated with producing silicon in the form required as well as the structural aluminum, steel, glass and so on required, including the energy required to transport, install and eventually landfill the materials. Their results are typical: "All the analyzed configurations are characterized by environmental pay back times one order of magnitude lower than their expected life time (3–4 years vs. 15–30 years)." From this I calculate an EROI of 3.75:1 to 10:1, which is similar to other estimates I have heard, although I have also heard estimates that vary from 1:1 to perhaps 20:1, with much higher ratios "projected." The following table lists a similarly calculated EROI based on life-cycle analyses for a range of systems, from commercially available to theoretical:

Reference #	Year	System Desription	EROI	Availibility	LCA Boundaries
1	2000	Roof top and ground mounted grid connected (mc-Si and thin film)	3.75:1 to 10:1	commercial	Does not include utilization, decommissioning, or recycling; module lifetimes assumed to be 15-30yrs
9	2003	Indium–gallium–phosphide (InGaP) on multicrystalline silicon (mc-Si) tandem module	2.83:1 to 5.66:1	concept	Does not include balance of systems (BOS), Transport, maintenance and the disposal phase; Third-order processes, such as the production of capital goods or the building of power stations, were taken into account only for the production of electricity and industrial heat; module lifetimes assumed to be 15-30yrs
9	2003	Thin-film InGaP cell module	2.38:1 to 4.76:1	concept	Ibid.
9	2003	mc-Si module	4.29:1 to 8.57:1	commercial	Ibid.
6	2004	PV Thermal panels	7.5:1 to 15:1	commercial	Undefined
3	2005	mc-Si grid connected and retrofitted on a tilted roof	3.75:1 to 10:1	commercial	Cradle to grave
5	2005	High-concentration photovoltaic system FLATCON1 using III–V semiconductor multi-junction solar cells	10:1 to 45.45:1	theoretical	final stage of recycling and disposal could not be considered, module lifetimes assumed to be 15-30yrs
8	2006	24 kW Amonix concentrator PV system	23.08:1	operational	Cradle to grave; lifetime of 30 yrs was assumed for this assessment
11	2006	Hybrid PV thermal AIR systems	9.38 to 33.33:1	experimental	Cradle to grave, pay back time is dependant on configuration and location
10	2007	Thin-film gallium arsenide (GaAs) cell	6.00:1	development	Cradle to grave, results have an uncertainty up to approximately 40%
10	2007	Thin-film gallium-indium phosphide/gallium arsenide (GaInP/GaAs) tandem cell	6.52:1	development	Ibid.
10	2007	mc-Si module	7.14:1	commercial	Cradle to grave
4	2008	Residential photovoltaic (PV) energy systems	3.23:1	commercial	The system consists of PV modules as the main power producer, and lead–acid batteries as the medium of electricity storage, and other essential devices such as an inverter.
7	2008	100MW Very Large-Scale Photovoltaic Power Generation (VLS-PV) Systems	10:1 to 20:1	theoretical	Does not include decommissioning or beyond, the authors designed VLS-PV systems using typical PV modules of multi crystalline silicon (12.8% efficiency), high efficiency multi-crystalline silicon (15.8%), amorphous silicon (6.9%), cadmium tellurium (9.0%), and copper indium selenium (11.0%)

PhotoVoltaic EROI Table
Click to Enlarge.

However, these values are not static. As research and development continues, it is likely that the EROI for some of the systems mentioned above will change. Another factor affecting EROI trends is material flow into the industry. PV production employs the use of many metals attractive to a number of high-tech industries. For example, some 76 percent of the energy required to generate the silicon module is that which is required to make the raw silicon. These and other authors indicate that at this time the principle source of silicon for the photovoltaic industry is scraps from the computer chip industry. If the industry is to expand greatly other dedicated sources of silicon must be generated, with presently unknown effects on the energy cost.
Finally, there is the affect of intermittent energy from the sun and also energy storage issues. As sunlight is not constant 2 sites might be necessary to keep a constant flow of electricity to society in one area. This is thought to lower EROI by at least as much as ½. The energy cost of electrical storage in the form of a battery is also an issue which would lower the expected EROI of a PV system. At present lead-acid batteries are typically used for photovoltaic systems, but other storage systems include pumped storage (i.e. pumping water up hill for later generation of electricity), compressed air and flywheels. Many of these systems are quite promising, but would require considerable development.

The Future

Given that presently despite the enormous growth of PV energy the annual increment of oil, gas or coal is usually greater than the total of all photovoltaic production of energy, the increase in

capacity needed for photovoltaic energy to make a large difference is enormous. A particular concern is whether there would be material shortages with a very large and rapid growth. For example, gallium arsenide is currently more or less the material of choice for a doping material to apply to silicon. Curiously, or not so curiously, this material has the same absorbance spectra as chlorophyll. A glance at the periodic table shows this element to be under aluminum, and the principal source is aluminum mining and purification. But if the industry were to increase by a factor of ten other sources would have to be utilized, and, presumably, its cost would increase dramatically. Likewise if we were to attempt to replace liquid fuels with electricity an enormously greater amount of copper would be needed. The price of copper is already escalating sharply under pressure from the construction industry of China and it is not clear what a greatly increased demand might do. Similar issues would apply to the many other elements that might be needed to obtain higher efficiencies in the industry.
Currently, Cadmium-telluride (CdTe) and Copper-indium-gallium-diselenide (CIGS) PV modules are thought to have the highest potential for low cost electricity. However, beyond the year 2020, each is expected to suffer material restraints (Andersson 2001). Indium and Tellurium are recovered as byproducts of copper and zinc respectively, of which we may run out of this century. Ultimately, PV production may be constrained by available stock of materials and/or by the rate at which materials are recovered; and possibly by competition for metals for other end uses.

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APPENDIX G-3

WIND

Recently an excellent meta-analysis on the Energy from Wind: A Discussion of the EROI Research was completed by Ida Kubisewski and Cutler Cleveland. The details can be reviewed in theoildrum.com's link above. Here is the salient table showing the EROIs of various studies and conditions:

Reference	Year of Study	Location	EROI	CO2 Intensity (gCO2/kWh)	Power Rating (kW)	Lifetime (yr)	Load Factor (%)	Payback Time (yr)	Analysis Type	Scope as Stated	Turbine Type	On/off shore	Rotor Diameter (m)	Hub Height (m)	Wind Speed (m/s)	Remarks
7	1999	USA	23	14.4	342.5	30	24		I/O	(B)CDMOT	Kenetech KVS-33	on	32.9	36.6		25 MW farm
7	1999	USA	17	20.2	600	20	31		I/O	(B)CDMOT	Tacke 600e	on	46.0	60.0	6.1	1.2 MW farm
7	1999	USA	39	8.9	750	25	35		I/O	(B)CDMOT	Zond Z-46	on	46.0	48.5		107.25 MW farm
10	1998	Germany	21.74		1500	20	31		PA	CGMOT	3 blades		66	67		Enercon E-66
10	1998	Germany	23.81		500	20	29.6		PA	CGMOT	3 blades		40.3	44		Enercon E-40
10	1998	Germany	15.38		500	20	29.6		I/O	CGMOT	3 blades		40.3	44		Enercon E-40

11	1996	Germany	8.33	17	100	20	31.4		PA	CMO	3 blades		20	30		
11	1998	Germany	14.08		1500	20	31		I/O	CGMOT	3 blades		66	67		Enercon E-66
13	1994	Germany	14.71	8.1	500	20	36.5		PA	M	2/3 blades		39	41		
14	1991	Japan	3.97	71.7e	100	20	31.5		I/O	CMT						
15	1992	Japan	2.90	95.6e	100	20	31.5		I/O	CMOT						10% auxiliary power
16	1996	Japan	2.29	123.6e	100	30	20		I/O	CMO						downwind propeller
17	1992	Germany	11.24		0.3	20	38.8		PA	CDMOT	3 blades		1.5	11.6	9	75% recycling
18	1983	Germany	2.33		2	15	45.7		I/O	CM						average values
18	1983	Germany	3.45		6	15	45.7		I/O	CM						average values
18	1983	Germany	5.00		12.5	15	45.7		I/O	CM						average values
18	1983	Germany	8.33		32.5	15	45.7		I/O	CM						average values
18	1983	Germany	1.27		3000	20	45.7		I/O	CM	2 blades		100	100		GROWIAN prototype
20	1981	USA	0.98		3	20	26.8		I/O	CMO			4.3	20	10.1	excluding storage
21	1997	Denmark	8.33		15	20	20.5		I/O	CMO	1980		10	18		vintage model
21	1997	Denmark	8.13		22	20	19.9		I/O	CMO	1980		10.5	18		vintage model
21	1997	Denmark	10.00		30	20	19		I/O	CMO	1980		11	19		vintage model
21	1997	Denmark	15.15		55	20	20.6		I/O	CMO	1980		16	20		vintage model
21	1997	Denmark	27.03		600	20	26.5		I/O	BCDEGMOT	3 blades		47	50	15	
22	1991	Germany	11.76		30	20	14.4		PA	CGMOT	2 blades		12.5	14.8	13	Hsw-30
22	1991	Germany	20.41		33	20	29.4		PA	M	2 blades		14.8	22	11	MAN-Aeromann
22	1991	Germany	14.71		95	20	20.5		PA	CGMT	3 blades	on	19	22.6		wind farm (6)
22	1991	Germany	19.61		95	20	20.5		PA	M	3 blades		19	22.6		Tellus 95
22	1991	Germany	16.67		100	20	20.9		PA	M	2 blades		34	24.2	8	Hutter 100
22	1991	Germany	20.41		150	20	25.6		PA	M	3 blades		23	30	13	AN-Bonus 150
22	1991	Germany	27.03		165	20	23.2		PA	M	3 blades		25	32	13.5	Adler 25
22	1991	Germany	18.87		200	20	21		PA	M	3 blades		26	30	13	Adler 26
22	1991	Germany	15.63		265	20	19		PA	M	2 blades		52	30.5	8.5	Voith 52/265.8
22	1991	Germany	20.83		450	20	20		PA	GM	3 blades		35	36	18	AN-Bonus 450
22	1991	Germany	15.38		3000	20	30.4		PA	GM	2 blades		100	100	12	GROWIAN I
23	1996	Switzerland	3.12	52	30	20	7.9		PA	CDGMOT	2 blades		12.5	22	11.4	simplon
23	1996	Switzerland	4.95	28	150	20	7.6		PA	CDGMOT	3 blades		23.8	30		Grenchenberg
24	1991	Germany	18.87		45	20	33.5		PA	M			12.5			
24	1991	Germany	32.26		225	20	39.9		PA	M			27			
25	1990	Denmark	71.43		95	20	25.2		PA	M(C)	3 blades	on	19	22.6		wind farm (6 turbines)
26	1992	Japan	30.30	33.7	100	30	28		I/O	CMOT			30		13	upwind propeller
26	1992	Japan	18.52		100	30	40		I/O	CMOT	1983		30		10	downwind propeller
27	1996	Japan	2.19	123.7e	100	20	18		I/O	CMO	1984		30			demonstration plant
27	1996	Japan	5.85	47.4e	170	20	22.5		I/O	CMO			27			Mitsubishi-2
27	1996	Japan	8.47	34.9e	300	20	18		I/O	CMO			28			Mitsubishi-1
27	1996	Japan	11.36	24.1e	400	20	18		I/O	CMO			31			MICON
28	2001	Japan	6.25	39.4	100	25	34.8		I/O	CMT			30	30		Nox & Sox calculated
29	1990	Denmark	47.62	8.81	150	25	30.1		PA	M						
30	1990	Germany	32.26		300	20	28.9		PA	CMT	3 blades		32	34	11.5	Enercon-32
31	1993	Germany	21.74	11e	300	20	22.8		PA	CDMOT						recycling
32	1994	Germany	45.45		300	20	22.8		PA	MO(D)						O calculated with AEI
33	1995	UK	23.81	9.1	350	20	30		PA	M	3 blades		30	30	15	
34	1997	Denmark	50.00	15.9	400	20	22.8		PA	M(O)						Excluding imports
35	1994	Germany		18.2e	500	20	27.4		I/O	CM						Inc. factory buildings
36	2001	Brazil	14.49		500	20	29.6		I/O	CGMOT	3 blades; E-40		40.3	44		Transport Den->Brazil
37	2000	Denmark	30.30	9.7	500	20	25.1		PA	M(DT)	3 blades	on		41.5		wind farm (18 turbines)
37	2000	Denmark	21.28	16.5	500	20	28.5		PA	GM(DT)	3 blades	off	39	40.5	16	wind farm (10 turbines)
38	2000	Belgium	30.30	9.2e	600	20	34.2		PA	DM(O)						
38	2000	Belgium	27.78	7.9e	600	20	34.2		I/O	DM(O)						1980 I/O tables
40	1996	Germany		22e	1000	20	18.5		I/O	CMO	3 blades		54	55		HSW 1000
40	1996	Germany		14e	1000	20	18.5		PA	CMO	3 blades		54	55		HSW 1000
42	1996	UK		25	6600	20	29		I/O	CDMO						System not specified

Notes: I/O=Input?output-based analysis, PA=Process analysis, c=conceptual, o=operating, B=Business management, M=Manufacture, T=Transport, C=Construction, G=Grid connection, O=Operation & Maintence, D=Decommissioning, e=CO_2 equivalents including CH_4 and N_2O, ()=partly covered.

EROI From Wind - Meta-analysis
Click to Enlarge.

The average EROI for all studies (operational and conceptual) is 24.6 (n=109; std. dev=22.3).
The average EROI for just the operational studies is 18.1 (n=158; std. dev=13.7).

CONCLUSION

We find in solar (industrial) energy a very large potential but a rather small application (so far). The greatest use is traditional biomass (perhaps about 5 percent in the US) and hydropower. In general high EROI sites in the United States were developed by the middle of the last century and a further expansion is probably limited by environmental considerations. (Globally the potential is much more). In the United States existing wind power seems to have a rather good EROI (18:1) although that is likely to be decreased substantially if issues related to storage are factored in. Present generation photovoltaics have a moderate EROI (around 8:1 but with great variability and uncertainty). Both wind and photovoltaic systems appear to have a large potential for improving their EROI. The greatest potential, however, is for passive solar, although this issue seems not to have been analyzed very often using EROI explicitly. There are many reasons to favor a solar future and it is probably quite possible to get there, but we need a much more comprehensive analysis of the issues of availability and storage if applied on a very large scale.