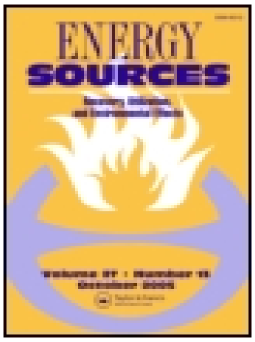

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Environmental Impacts of the Solar Energy Systems

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Abstract *Global energy consumption is expected to increase dramatically in the next decades, driven by rising standards of living and a growing population worldwide. The increased need for more energy will require enormous growth in energy generation capacity, more secure and diversified energy sources, and a successful strategy to tame greenhouse gas emissions. Solar energy systems provide significant environmental benefits in comparison to the conventional energy sources, thus contributing, to the sustainable development of human activities. Sometimes however, their wide scale deployment has to face potential negative environmental implications. These potential problems seem to be a strong barrier for a further dissemination of these systems in some consumers. We assess the potential environmental intrusions in order to ameliorate them with new technological innovations and good practices in the future power systems. The analysis provides the potential burdens to the environment, which include noise and visual intrusion, greenhouse gas emissions, water and soil pollution, energy consumption, labor accidents, impact on archaeological sites or on sensitive ecosystems, and negative and positive socio-economic effects.*

Keywords environmental impacts, photovoltaic, solar energy systems, sustainable development

Introduction

Energy is used for heating and cooling, illumination, health, food, education, industrial production, and transportation. Energy is essential to life. The development of human society and civilization has been shaped by energy. The original source of energy for all activities was human energy. The energy of human muscle provided the mechanical power necessary in the dawn of history. This era was followed by a time characterized by the control and use of fire from the combustion of wood, and with it, the ability to exploit chemical transformations brought about by heat energy to cook food, heat dwellings, and extract metals such as bronze and iron. The energy of draught animals began to play a role in agriculture, transport, and industry, supplementing human energy and energy stored in natural resources such as wood. Finally, human societies acquired control over coal, steam, electricity, oil, and natural gas (Kaygusuz, 2006).

Energy issues and policies have been concerned mainly with increasing the supply of energy. Countries around the world have considered the sufficient production and consumption of energy to be one of their main challenges. Modern economies are energy dependent. The provision of sufficient energy has been perceived as a central problem.

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Energy availability and consumption has been so important a consideration to economies worldwide that the magnitude of energy consumed per capita has become one of the key indicators of modernization and progress in a given country. Recently, attention has begun to shift toward a more balanced perspective, including concerns related both to demand-side and energy consumption patterns. Either way, there is no escaping the fact that the use of energy is a necessary and vital component of development (UNDP, 2000).

The benefits of modern energy supplies and services are unevenly distributed in the world and have yet to reach approximately one-third of the Earth's population. People living in poverty have benefited very little from conventional energy policies and their implementation. More than 2 billion people continue to cook using traditional fuels, while 1.5–2 billion people lack electricity. At the same time, it has become widely recognized that development depends on access to appropriate energy services. Developing countries, in particular, often face constraints to growth and development that are directly related to the unsustainability of current patterns of energy production and use (IEA, 2002).

Earth receives solar energy as radiation from the sun, and it receives it in a quantity that far exceeds humankind's use. By heating the planet, the sun generates wind, rain, rivers, and waves. Along with rain and snow, sunlight is necessary for plants to grow. The organic matter that makes up plants is known as biomass, and biomass can be used to produce electricity, transportation fuel, and chemicals. Plant photosynthesis (essentially, chemical storage of solar energy) creates a range of biomass products, from wood fuel to rapeseed, that can be used for heat, electricity, and liquid fuels (Farret and Simoes, 2006).

Hydrogen can also be extracted from many organic compounds, as can water. Hydrogen is the most abundant element on Earth, but it does not occur naturally in a gas. It always combines with other elements, such as with oxygen to make water. Once separated from another element, hydrogen can be burned as a fuel or converted into electricity.

The sun also powers the evapotranspiration cycle, which allows water to generate power in hydro schemes as the largest source of renewable electricity today. Interactions with the moon produce tidal flows, which can produce electricity. Although humans have been tapping into renewable energy sources (such as solar, wind, biomass, geothermal, and water) for thousands of years, only a fraction of their technical and economic potential has been captured and exploited. Yet renewable energy offers safe, reliable, clean, local, and increasingly cost-effective alternatives for all our energy needs (Bilgen et al., 2004; Farret and Simoes, 2006).

Renewable energy resource development will result in new jobs and less dependence on oil from foreign countries. According to the federal government, the United States spent $109 billion to import oil in 2000. If we fully develop self-renewing resources, we will keep the money at home to help our economy.

There are some drawbacks to renewable energy development. An example is solar thermal energy, in which solar rays are captured through collectors (often, huge mirrors). Solar thermal generation requires large tracts of land and this affects natural habitat. The environment is also affected when buildings, roads, transmission lines, and transformers are built. In addition, a fluid often used for solar thermal generation is toxic, and spills can occur. Solar or photovoltaic cells are produced using the same technologies as those used to create silicon chips for computers, and this manufacturing process also uses toxic chemicals. In addition, toxic chemicals are used in batteries that store solar electricity through nights and on cloudy days. Manufacturing this equipment also has environmental effects. So even though the renewable power plant does not release air pollution or use fossil fuels, it still has an effect on the environment (Farret and Simoes, 2006).

Table 1
World total final consumption (Mtoe)

	1971	2002	2010	2030	2002–2030*
Coal	617	502	516	526	0.2%
Oil	1,893	3,041	3,610	5,005	1.8%
Gas	604	1,150	1,336	1,758	1.5%
Electricity	377	1,139	1,436	2,263	2.5%
Heat	68	237	254	294	0.8%
Biomass and waste	641	999	1,101	1,290	0.9%
Other renewables	0	8	13	41	6.2%
Total	4,200	7,075	8,267	11,176	1.6%

*Average annual growth.
Source: IEA, 2002.

Global Energy Consumption and CO_2 Emissions

World primary energy demand is projected in the Reference Scenario (IEA, 2002) to expand by almost 60% from 2002 to 2030, an average annual increase of 1.7% per year. Demand will reach 16.5 billion tons of oil equivalent compared to 10.3 billion tons of oil equivalent (toe) in 2002 (Table 1). The projected rate of growth is, nevertheless, slower than over the past three decades, when demand grew by 2% per year. Fossil fuels will continue to dominate global energy use. They will account for around 85% of the increase in world primary demand over 2002–2030. And their share in total demand will increase slightly, from 80% in 2002 to 82% in 2030. The share of renewable energy sources will remain flat, at around 14%, while that of nuclear power will drop from 7% to 5% (IEA, 2002).

The projected trends in energy use in the Reference Scenario (IEA, 2002) imply that global energy-related CO_2 emissions will increase by 1.7 % per year over 2002–2030. They will reach 38 billion tons in 2030, an increase of 15 billion tons, over the 2002 level (Table 2). More than two-thirds of the increase will come from developing countries. By 2010, energy-related CO_2 emissions will be 39% higher than in 1990. Oil will account for 37% of the increase in energy-related CO_2 emissions over the projection period, coal for 33%, and natural gas for 30%. Emissions from natural gas will increase most rapidly, doubling between 2002 and 2030. But they will still make up only 24% of total emissions in 2030, up from 21% now. Coal's share will fall by three percentage points, to 36%, and oil's share will drop by two points to 39%.

Global Solar Thermal Market

More than one-third of global energy use is for heating. Solar heating and cooling (SHC) technologies are logical and valuable substitutes to the oil and gas currently used for heating. Solar heating and cooling covers a broad spectrum of technologies, including solar water heating, active solar space heating, and passive solar heating and cooling, all of which have been commercially available for more than 30 years. More recently, combi-systems, which combine water and space heating, emerged on the market (OECD/IEA, 2006).

The worldwide contribution of solar thermal heat to the overall energy supply is significant. An overall capacity of 92.7 GW_{th} of solar thermal collectors was installed

Table 2
Energy-related CO_2 emissions (million tons)

	OECD		Developing countries		World	
	2002	2030	2002	2030	2002	2030
Power sector	4,793	6,191	3,354	8,941	9,417	16,771
Industry	1,723	1,949	1,954	3,000	4,076	5,567
Transport	3,384	4,856	1,245	3,353	4,914	8,739
Residential and services	1,801	1,950	1,068	1,930	3,248	4,417
Other[a]	745	888	605	1,142	1,924	2,720
Total	12,446	15,833	8,226	18,365	23,579	38,214

[a]Includes international marine bunkers (for the world totals only), other transformation and non-energy use.
Source: IEA, 2002.

(Weiss et al., 2007). The worldwide market for glazed solar collectors has greatly increased over the last decade to approximately 10 million m^2 installed per year. Almost all growth in this market occurred in China. On the other hand, the cost reduction history for solar water heating systems and for the newer combi-systems shows that, over the past ten years, each doubling of the market led to a 20% reduction in installation costs. Government funding for SHC was estimated at approximately US$75 million in 2000 and US$69 million in 2001. During the same years, industry-funded Research Design & Development (RD&D) is estimated to have been at least half the amount put forth by government. RD&D projects that are not pre-competitive usually require an industry cost share of 50% or higher (OECD/IEA, 2006).

Since the beginning of the 1990s, the solar thermal market has undergone a favorable development. At the end of 2005, a total of 159 million m^2 of collector area, corresponding to an installed capacity 111.0 GW_{th} were in operation in the 45 recorded countries. These 45 countries represent 3.84 billion people, which is about 59% of the world's population. The installed capacity in these countries represents approximately 85–90% of the solar thermal market worldwide. As shown Table 3, the installed capacity is divided into 37.8 GW_{th} glazed flat plate collectors (54.01 million m^2) and 48.5 GW_{th} evacuated tube collectors (69.34 million m^2), 23.9 GW_{th} unglazed collectors (39.09 million m^2) and 0.8 GW_{th} glazed and unglazed air collectors (1.19 million m^2) (Weiss et al., 2007).

Environmental Impacts of Solar Energy Systems

Every energy generation and transmission method affects the environment. As it is obvious, conventional generating options can damage air, climate, water, land and wildlife, and landscape, as well as raise the levels of harmful radiation. Renewable technologies are substantially safer, offering a solution to many environmental and social problems associated with fossil and nuclear fuels (EC, 1995, 1997).

Solar energy systems (SESs) provide obvious environmental advantages in comparison to the conventional energy sources, thus contributing to the sustainable development of human activities (Table 4). Not counting the depletion of the exhausted natural resources, their main advantage is related to the reduced CO_2 emissions, and, normally,

Table 3
Global installed capacity of solar thermal systems in 2005 (MW_{th})

Country	Water collectors			
	Unglazed, m^2	Glazed, m^2	Evacuated tube, m^2	Total thermal, MW_{th}
Australia	2,412.90	1,190.00	2.10	3,605.00
Austria	415.31	1,665.35	25.38	2,106.03
Brazil		1,890.32		1,890.32
Canada	449.75	55.29	1.16	505.60
China		5,250.00	47,250.00	52,500.00
Denmark	15.31	229.30	0.56	245.17
France	63.62	572.59	3.49	639.71
Germany	525.00	4,059.30	596.40	5,180.70
Greece		2,133.04		2,133.04
India		875.00		875.00
Israel	14.00	3,346.00		3,360.00
Italy	11.20	327.60	34.30	373.10
Japan		4,805.22	94.40	4,899.61
Mexico	300.01	210.04		510.05
The Netherlands	218.96	215.32		434.28
Portugal		200.06		200.06
Spain		537.50	20.37	557.87
Sweden	35.80	147.43	11.94	195.18
Switzerland	148.87	241.35	16.84	407.06
Turkey		7,300.00		7,300.00
United Kingdom		140.81		140.81
United States	18,844.70	1,159.78	394.61	20,400.10
Total	23,863.87	38,804.57	48,536.65	111,205.10

Source: Weiss et al., 2007.

absence of any air emissions or waste products during their operation (Tsoutsos et al., 2005).

Concerning the environment, the use of SESs has additional positive implications such as:

- Reduction of the emissions of the greenhouse gases such as CO_2 and NOx and prevention of toxic gas emissions such as SO_2 and particulates;
- Reclamation of degraded land;
- Reduction of the required transmission lines of the electricity grids;
- Improvement of the quality of water resources;
- Increase of the regional/national energy independency;
- Provision of significant work opportunities;
- Diversification and security of energy supply;
- Support of the deregulation of energy markets; and
- Acceleration of the rural electrification in developing countries.

Table 4
Environmental and social indicators of solar energy systems

Indicator	Central solar thermal	Distributed solar thermal	Central photovoltaic power generation	Distributed PV power generation	Solar thermal electricity
CO_2 emissions savings	1.4 kg/kWh or 840 kg/m^{2}a	1.4 kg/kWh or 840 kg/m^{2}a	0.6–1.0 kg/kWh	0.6–1.0 kg/kWh	Annually 688t/MW when compared to a combined cycle plant 1.360t/MW when combined to a cola fired plant.
Production employment (EU wide)	4,000 jobs/a	4,000 jobs/a	2–3,000 jobs/a	2–3,000 jobs/a	One permanent job/MW for operation +10–15 jobs/MW for 12–18 month construction
Total employment	12,000 jobs/a	12,000 jobs/a	4–5,000 jobs/a	4–5,000 jobs/a	1,000 permanent jobs for 1,000 MW

Source: EC, 2002.

General Issues for Solar Energy Systems

The potential environmental burdens of SESs are regularly site specific, depending on the size and nature of the project. As it is obvious from Table 5, these burdens are usually associated with the loss of amenity and the impacts can be minimized by (Fthenakis, 2000; Hestnes, 1999; Tsoutsos, 2001):

- The appropriate sitting of central solar systems, which involves careful evaluation of alternative locations and estimation of expected impact; the residential solar systems can be installed anywhere, especially integrated in the roofs;
- The appropriate operational practices;
- The engagement of the public and relevant organizations in the early stages of planning, in order to ensure public acceptance;

Table 5
Grade of the potential negative environmental impacts of solar technologies

Environmental problem	Central solar thermal	Distributed solar thermal	Central PV power generation	Distributed PV power generation	Solar thermal electricity
Visual impact	++	+	++	+	+++
Accidental releases for chemicals	+	++	+++	+++	++
Land use	++	+	++	+	+++
Work safety and hygiene	++	++	++	++	+++
Effect on the ecosystem	+		+		++
Impact on water resources	++	+	+	+	+++

PV: photovoltaic.
Source: EC, 2002.

- The use of the best available technologies/techniques and the improvement of technology;
- The integration in the building's shell;
- The training of workers, use of special sunglasses during operation and construction, use of heat insulating uniforms, familiarization with the system;
- The re-establishment of local flora and fauna, giving the environment enough time to come up to its previous state again; and
- Environmental Impact Assessment Studies should be made for central solar systems.

Environmental Impacts of the Solar Energy Systems

Though the production of solar thermal (ST) systems requires reasonable quantities of materials, insignificant amounts are also consumed during their operation; at that time the only potential environmental pollutant arises from the coolant change, which can be easily controlled by good working practice. The accidental leakage of coolant systems can cause fire and gas releases from vaporized coolant, unfavorably affecting public health and safety. On the contrary, the large-scale deployment of ST technologies will significantly reduce the combustion of conventional fuels and will consequently reduce the environmental impacts associated with these fuels.

For low/medium heat systems, it is the characteristics of the chosen system, which define the land use. For instance, in the case of single-dwelling hot water or space heating/cooling, no land will be required since the system will usually be added to the roof of the existing building. Communal low-temperature systems might use some land, though again, the collection surfaces might well be added on already existing buildings. The principal additional use of land might be for heat storage.

For high temperature systems, the land-use requirements of concentrating collectors providing process heat are more problematical. Concerning the loss of habitat and changes to the ecosystem due to land use in the case of large-scale systems, provided that predevelopment assessments are carried out and ecologically important sites are avoided, these are unlikely to be significant.

During the operation of the ST system, coolant liquids may need changed every 2–3 years. Such discharges require careful handling. In some cases, the coolant will be water based; but all indirect systems are likely to contain anti-freeze or rust inhibitors, as well as substances leached from the system during use. Heat transfer fluids might therefore contain glycol, nitrates, nitrites, chromates, sulfites, and sulfates. Higher temperature applications would use more complex substances, such as aromatic alcohols, oils, CFCs, etc. The large-scale adoption of SESs might well require control on the disposal of these substances (OECD/IEA, 1998).

Theoretically, the ST placement in the shell of the buildings could increase fire risk (OECD/IEA, 1998) and water intrusion into the roof. This can be easily avoided, since only four holes per panel on the roof will be an integral part of the roof. On the other hand, other burdens applicable to central power systems only (e.g., noise—during the construction period, visual intrusion, etc.) are likely to prove insignificant (provided areas of scenic beauty are avoided), because such schemes are likely to be situated in those areas of low population density. Therefore, all the impacts of suitably located large ST schemes are expected to be small and reversible.

Environmental Impacts of the Photovoltaic Systems

Photovoltaics (PV) are seen to be generally of benign environmental impact, generating no noise or chemical pollutants during use. It is one of the most viable renewable energy technologies for use in an urban environment, replacing existing building cladding materials. It is also an attractive option for use in scenic areas and national parks, where the avoidance of pylons and wires is a major advantage (Tsoutsos et al., 2005).

The impact of land use on natural ecosystems is dependent upon specific factors such as the topography of the landscape, the area of land covered by the PV system, the type of the land, the distance from areas of natural beauty or sensitive ecosystems, and the biodiversity. The impacts and the modification on the landscape are likely to come up during the construction stage by construction activities, such as earth movements and by transport movements. Furthermore, an application of a PV system in once-cultivable land is possible to damnify soil productive areas.

During their normal operation, PV systems emit no gaseous or liquid pollutants, and no radioactive substances. In the case of copper indium diselenide (CIS) and Cadmium Tellure (CdTe) modules, which include small quantities of toxic substances, there is a potential slight risk that a fire in an array might cause small amounts of these chemicals to be released into the environment (Tsoutsos et al., 2005). In large-scale central plants, a release of these hazardous materials might occur as a result of abnormal plant operations and it could pose a small risk to public and occupational health. Thus, there must be emergency preparedness and response in case of an accidental fire or exposure to heat. Emissions to soil and groundwater may occur due to inadequate storage of materials (OECD/IEA, 1998).

The production of current generation PV's is rather energy intensive and large quantities of bulk materials are needed (thin film modules have less primary energy requirement per W than the a-Si PV modules because of the difference in cell efficiency, so that can be an answer to that problem). Also, small quantities of scarce materials (In/Te/Ga) are required, as well as limited quantities of the toxic Cd. On the other hand, the Cd emissions attributed to CdTe production amount to 0.001% of Cd used (corresponding to 0.01 g/GWh). Furthermore Cd is produced as a byproduct of Zn production and can either be put to beneficial uses or discharged into the environment (Fthenakis, 2000).

Several aspects have to be studied to minimize environmental impacts related to the production of the PV cells (Tsoutsos et al., 2005):

- Prospects for thinner cell layers;
- The full potential of the concentrator PV technologies;
- Prospects for more efficient material utilization;
- Safer materials and alternatives; and
- Module recycling technology and its efficiency.

As far as life cycle assessment is concerned, the environmental performance of the system depends heavily on the energy efficiency of the system manufacturing and especially electricity production. The emissions associated with transport of the modules are insignificant in comparison with those associated with manufacture. Transport emissions were still only 0.1–1% of manufacturing-related emissions. In the case of poly- and mono-crystalline modules, the estimated emissions are 2.757–3.845 kg CO_2/kWp, 5.049–5.524 kg SO_2/kWp, and 4.507–5.273 NOx/kWp (Hestnes, 1999; OECD/IEA, 1998).

In urban environment, modern PV systems, which are architecturally integrated into buildings, are able to provide a direct supply of clean electricity that is well matched to the demand of the building, but can also contribute to day-lighting, and the control of shading and ventilation. Also, PV panels can be used instead of mirrors directly into the facade of a building. PV systems also assist to create a supportive environment within which to encourage other means of energy saving by the building promoters, owners, and users. PV energy services are particularly obvious where only low levels of power are needed, such as in rural electrification applications, and where the users are able to benefit directly from the very high reliability of having their own PV generator. In the former case, to install a PV generator is frequently cheaper than to extend the main grid over long distances (Tsoutsos et al., 2005).

In the case of stand-alone systems, which are a small fraction of the market, the effects on the health of chemical substances included in the batteries should also be studied. A life cycle analysis of batteries for stand-alone PV systems indicates that the batteries are responsible for most of the environmental impacts, due to their relatively short life span and their heavy metal content. Furthermore, a large amount of energy and raw materials are required for their production. A module-recycling scheme can improve this situation (Fthenakis, 2000).

Environmental Impacts from Solar Thermal Electricity

The limited deployment of ST electricity to date means that there is little actual experience of the environmental impacts that such a scheme may have. Similarly to other SESs, ST electricity systems present the basic environmental benefit of the displacement or the avoidance of emissions associated with conventional electricity generation (Tsoutsos et al., 2005). During their operation, these systems have no emissions. Some emissions do arise from other phases of their life cycle, but they are lower, compared to those avoided by the systems operation.

ST electric systems are among the most efficient SESs when it comes to land use (they produce annually about 4–5 GWh/ha). To date, most sites used or considered for ST systems are in arid desert areas, which typically have fragile soil and plant communities (OECD/IEA, 1998). On the other hand, attention during the planning, construction, and operation phases can minimize the effects on vegetation, soil, and habitat. Furthermore, the shade offered by the reflectors has a beneficial effect on the microclimate around the scheme and on the vegetation, too. Provided that such schemes are not deployed in ecologically sensitive areas or in areas of natural beauty, it is unlikely that any of the above changes would be considered as significant. Central concentrator power systems could pose a danger to birds, but operational experience shows that birds avoid any danger areas (OECD/IEA, 1998; Norton et al., 1998).

Likewise, noise is insignificant in comparison to any other power option, such as the conventional, the wind power generation, and the gas turbines. The noise from the generating plant of large-scale schemes is unlikely to cause any disturbance to the public. Noise would be generated primarily only during the day; at night, when people are more sensitive to noise, the system is unable to operate. On the other hand, the Stirling engines of stand-alone parabolic dish systems are a source of noise during operation, but they are unlikely to be any noisier than the stand-by diesel generating sets, which they generally displace. Also, new (technological) advanced Stirling engines are constructed to operate noiselessly (Tsoutsos et al., 2005).

Parabolic trough and central tower systems using conventional steam plants to generate electricity require the use of cooling water. This could place a significant strain on water resources in arid areas. In addition, there may be some pollution of water resources, through thermal discharges and accidental release of plant chemicals (OECD/IEA, 1998), although the latter can be avoided by good operating practice. Stand-alone parabolic dish systems require no water, other than for periodic cleaning of reflective surfaces, and so they have little impact on water resources.

The accidental release of heat transfer fluids (water and oil) from parabolic trough and central receiver systems could form a health hazard. The hazard could be substantial in some central tower systems, which use liquid sodium or molten salts as a heat-transfer medium. Indeed a fatal accident has occurred in a system using liquid sodium. These dangers will be avoided by moving to volumetric systems that use air as a heat-transfer medium. Central tower systems have the potential to concentrate light to intensities that could damage eyesight. Under normal operating conditions this should not pose any danger to operators, but failure of the tracking systems could result in straying beams that might pose an occupational safety risk on site.

Conclusions

Solar energy systems (SESs) present tremendous environmental benefits when compared to the conventional energy sources. In addition to not exhausting natural resources, their main advantage is, in most cases, total absence of almost any air emissions or waste products. In other words, solar energy can be considered as an almost absolute clean and safe energy source. On the other hand, the use of SESs has significant socioeconomic benefits, such as diversification and security of energy supply, provision of significant job opportunities, support of the restructure of energy markets, reduction of the dependency on fuel imports, and acceleration of the electrification of rural communities in remote/isolated areas. Technologies that can be used to eliminate or minimize potential environmental impacts from SESs may involve the use of air emission, design tools for optimal design, and sitting of the installations.

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