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SOLAR ENERGY AND THE ABATEMENT OF ATMOSPHERIC EMISSIONS

S. MIRASGEDIS, D. DIAKOULAKI and D. ASSIMACOPOULOS

Laboratory of Industrial and Energy Economics, Department of Chemical Engineering, National Technical University of Athens, GR-157 80, Greece

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Abstract—In spite of the fact that solar energy is a "clean" energy form, gaseous pollutants are emitted during the manufacturing of the systems necessary for its utilisation. An attempt is made in this paper to estimate the level of atmospheric pollutants emitted during the successive stages which make up the manufacture process for solar water heating (SWH) systems, and to evaluate these results in comparison with the respective pollutant emission levels attributed to the generation of electricity in Greece's conventional power plants. As energy consumption is recognised as the main source of atmospheric pollution, a Life Cycle Analysis (LCA) method was applied, focusing on the most energy-consuming stages of the SWH system production process. The conclusions of the analysis indicate that the emissions of gaseous pollutants associated with the utilisation of solar energy are considerably lower than those caused by the production of electricity in conventional systems, thereby substantiating that solar energy utilisation can make a notable contribution to the abatement of atmospheric pollution.

1. INTRODUCTION

The significant progress made recently in the field of heat and power generation from the sun's radiation has singled out solar energy as one of the most promising energy sources. The use of solar technologies enables substitution for fossil fuels consumed at the final demand or the power generation sector. Consequently, atmospheric emissions and other polluting residuals associated with conventional energy technologies can be avoided. Solar energy is thus considered to be environmentally friendly, since visual intrusion—which makes up its main impact on the environment—does not pose a serious threat either to human health or to the general balance of the ecosystem [1].

This widespread belief can nevertheless be partly disputed, since the industrial processes and other activities necessary for the manufacture of solar installations can have a significant impact on the environment. The evaluation of solar energy technologies from an ecological point of view calls, therefore, for a co-assessment of the indirect environmental impacts arising from the entire manufacturing process [2]. However, due to the wide variety of solar

systems and the methodological complications of the assessment procedure, there is a considerable divergence of opinion as to the level of environmental damage caused by solar technologies. Although most studies have reached favourable conclusions, other estimates indicate that the health and safety risk posed by solar systems is far greater than the one attributed to technologies using conventional or nuclear fuels [3].

The present paper examines, from an environmental perspective, a widely used solar technology in comparison with other competitive energy producing systems. Solar water heating (SWH) systems were selected for the purpose of this comparative analysis, as they remain the most widespread solar devices. The heat recovered with these systems—used predominantly in the domestic sector—serves primarily as a substitute for electricity supplied by the national grid. The operation and efficiency of a SWH system depends upon (i) various details of the technical design, (ii) the materials used in the manufacture of the solar collector's main components and (iii) the incident solar radiation. Having recognised the need to refer to a strictly defined technological design and geographical area, the authors proceeded to the analysis of the standard type of SWH system used in Greece, while the system's efficiency was calculated for Greece's different geographical zones. The results obtained are nevertheless representative of the wider Mediterranean area because of the comparable insolation rates and similar SWH installations in use.

The analysis focuses only on atmospheric pollution which is generally recognised as being the most important source of environmental degradation. Atmospheric emissions attributable to the SWH systems and, in particular, SO_2, NO_x and CO_2, are estimated on a per unit of energy basis by means of a Life Cycle Analysis (LCA) approach and compared to those attributed to the competitive power generation technologies used in Greece.

2. METHODOLOGICAL APPROACH

Concepts and methods for the ecological assessment of activities have been receiving increasing attention over the last twenty years, due to the growing environmental awareness. Among other instruments, the LCA is widely used to develop the "eco-balances" of products and technologies. The basic principle underlying the LCA is that the environmental burden associated with any given product can only be accurately assessed with consideration to all of the process stages, from the extraction of raw materials to the product's disposal [4]. This "cradle-to-grave" approach is particularly suitable for the ecological assessment of consumer goods characterised by a relatively short life-span and explains why most of the first LCA studies were conducted on packaging materials [5–7].

The essential difference between other up-front approaches, extensively used in energy analyses and the LCA is that, while the former have led to the development of methods focusing merely on energy flows, the latter concentrates on material flows. Recently, however, the number of environmental impact studies of different energy options conducted on the basis of LCA has increased significantly. This is particularly true for renewable energy forms and other innovative energy technologies which, compared to conventional energy production systems, are characterised by: (i) the greater quantity of materials consumed per unit of energy produced (as the installations are more capital intensive), (ii) the greater simplicity of the equipment used (a factor which facilitates the undertaking of an LCA) and (iii) the greater share of total impact attributable to the production stages (as solar installations are free from ordinary pollution forms and have a shorter life-span) [8].

Therefore, while conventional fuels can be satisfactorily evaluated solely on the basis of

the pollution generated during the fuel combustion or other fuel flow stages, the total environmental impact associated with the exploitation of renewable energy forms is more accurately estimated with the undertaking of an LCA.

Due to the numerous activities involved in the manufacture of a given product, the adoption of a number of assumptions is usually necessary to simplify the entire LCA procedure. Activities considered to have only a negligible share of the total impact are thus often omitted. At the same time, the environmental impacts are usually assessed without consideration to specific place or time factors [9].

Since energy consumption is the primary source of atmospheric pollutant emissions, the present analysis focuses mainly on the more energy-consuming stages of the SWH system's life cycle, i.e. on the processing of the main materials used to manufacture the necessary semi-finished products and on the final assembly/construction stage. The extraction of raw materials, the transportation processes linking the various life cycle stages and the components' disposal are considered to be accountable for only an insignificant share of the total emissions produced, if reduced to the SWH system's entire life cycle. These activities are, in addition, more difficult to break down and specify in terms of ore deposits, technologies, transport distances and transport means.

Detailed energy consumption data are only available for the activities performed by domestic industrial firms. The total level of emissions arising from these activities were calculated with the use of emission factors established by EUROSTAT, except for electricity generated from domestic lignite sources, where emission factors (higher than those defined by EUROSTAT) were estimated by the Public Power Corporation. As far as the imported materials are concerned, use was made of the specific emission rates (per unit of mass) reported in the relevant literature. These rates are also based on EUROSTAT emission factors and use aggregate statistical data (representative of the European industry) concerning the energy requirements of the corresponding processing activities and the composition of the electricity mix.

3. SOLAR SYSTEM SPECIFICATION

3.1. *General description*

The typical solar system used in Greece for water heating purposes is made up of a flat plate collector with a surface area of approximately 1.8 m^2 and a boiler of 130 l capacity [10]. Flat plate collectors for water heating consist of a glass-covered metal box containing an absorber plate to which an array of tubes is attached and beneath which insulation is provided. The width of the collector assembly is around 15 cm.

The absorber surface is the core component of all solar collectors. Black metal plates, which are good heat conductors, are used as absorber surfaces. However, good absorbers for solar radiation are also good heat radiators. To reduce the radiation-emitting characteristics, selective surfaces are made by painting the absorber plate with metal oxide coatings or by electroplating a thin layer onto it. Copper is the most widely used material in the manufacture of the absorbing surface and of the fluid's conduits, due to its thermal properties and its resistance to corrosion. However, as copper is a relatively costly material, it can be substituted by other metals, mainly steel and aluminium, wherever there is no contact with liquid.

The absorber surface is protected from hostile atmospheric conditions with the use of glazing. In addition to resistance to weather-induced damages, strength and hardness, the

primary requirements of glazing materials are transparency to solar radiation and opacity to emitted heat radiation. A reduction in heat loss is ensured by the presence of an air layer between the metal plate and glazing. Heat loss can be further reduced by using a second transparent cover with an air space between the two surfaces. In Greece, SWH systems are commonly provided with a single glazing. Glass (with a low FeO content) is the most widely used glazing material due to its optical properties and its moderate cost.

A layer of thermal insulation with a thickness of 2–3 cm is placed beneath the absorber plate in order to avoid heat losses through the back and the sides of the collector housing. Besides insulation properties, the material used should be temperature-resistant. Shrinking, expanding and outgasing, which are the most dangerous deterioration phenomena of insulation materials at the high temperatures attained, can seriously affect the efficiency of the life-span of the entire installation. Polyurethane foams and fiberglass are the most common insulation materials used in solar collectors.

All the above components are placed in an aluminium or steel frame which contributes to the entire ensemble's solidity and protect it against damage during transportation and installation stages [11].

SWH systems are equipped with a closed circuit where the circulating fluid transfers the absorbed heat to the water, by means of a heat exchanger. The heat transfer fluid is ordinarily water, containing anti-corrosive and anti-freezing substances. The circulation of the heated fluid is achieved by natural flow (thermosiphon system) or by a forced pump-induced flow (pumped systems). In Greece, the most widely used systems are of the thermosiphon type, their primary advantage being that they are fully automatic and, contrary to the pumped system, require no electricity. In most cases, SWH systems are equipped with an auxillary source, usually an electrical resistance.

3.2. *Material requirements*

The average material requirements of the typical SWH system, described above, were estimated with recourse to relevant bibliographical sources [10, 12] and to a market survey. These estimates, presented in Table 1, refer to the materials used for the construction of the flat plate collector (made essentially of aluminium and copper) and its metal base (essentially made of iron), as well as the additional quantities of materials used in the manufacture of the large-sized boiler (made mostly of iron, copper and aluminium). The entire system also contains small quantities of coating, welding and insulating materials.

Table 1. Total material requirements of a typical SWH system based on estimates for the Greek market (in kg/m^2 of collector surface)

Material	Weight (kg)
Iron	29.6
Copper	12
Aluminium	3.2
Insulating materials	1.4
Welding materials	0.4
Resins/coatings	1.2

3.3. *Heat recovery*

The distribution of solar radiation on the Earth's surface is usually depicted by iso-radiation curves representing mean monthly availability levels. The iso-radiation curves defined for Greece divide the country into six zones, as shown in Fig. 1 [13]. It is assumed that the entire area within each zone receives approximately the same solar radiation. Zone 1 includes Crete and other locations in Southern Greece and is characterised by the highest values of solar radiation (H). On the contrary, Zone 6, which encompasses a significant part of Northern Greece, presents the lowest values of H, as well as the lowest ambient temperatures. In the remaining four zones (2, 3, 4 and 5), solar radiation and ambient temperature levels range between these two extremes.

Due to the geographical distribution of solar radiation, the amount of energy recovered by the SWH system previously defined varies substantially depending on the location of the installation. The heat recovery of a standard SWH system is thus equivalent to 1470 kWh per year (818 kWh/m^2) in Zone 1 and 33% lower in Zone 6, recorded at 990 kWh per year (550 kWh/m^2).

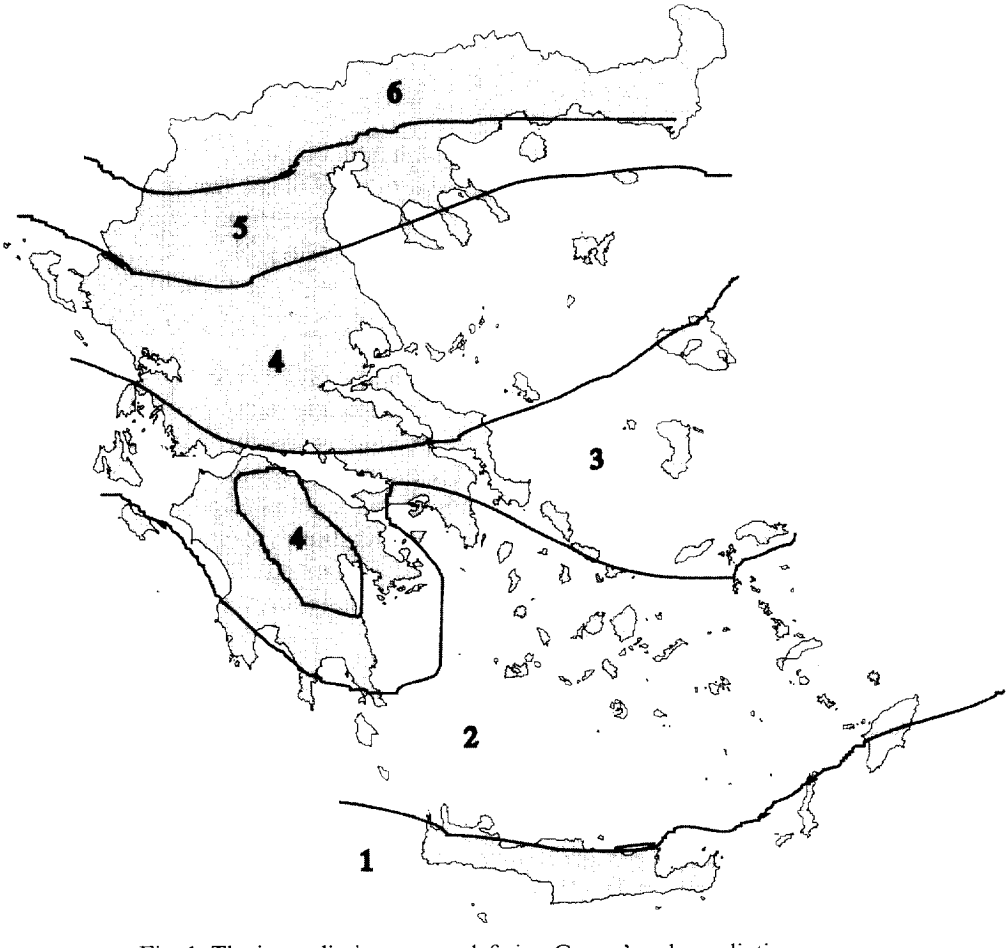

Fig. 1. The iso-radiation curves defining Greece's solar radiation zones.

4. CALCULATION OF THE EMISSION FACTORS OF SWH SYSTEMS

The total emissions attributable to the standard SWH system consist of: (i) the emissions associated with the production and processing of the necessary materials (Q_p), (ii) the emissions associated with the SWH construction and assembly stage (Q_c) and (iii) the emissions associated with the remaining life cycle stages and those due to material losses in the sequence of process activities (Q_r).

Based on the above definition, the total amount (Q_k) of a pollutant k given off by the production and use of a SWH system per unit of collector surface is determined by the model:

$$Q_k = Q_{p,k} + Q_{c,k} + Q_{r,k}. \tag{1}$$

Expansion of the first two terms on the right hand side of the equation, gives eqs (2) and (3):

$$Q_{p,k} = \sum_{i=1}^{n} m_i \cdot F_{k,i} = \sum_{i=1}^{n} m_i \sum_{j=1}^{l} e_{i,j} \cdot f_{k,j}, \tag{2}$$

$$Q_{c,k} = \sum_{j=1}^{l} e_{c,j} \cdot f_{k,j}, \tag{3}$$

where m_i is the amount of material i used in the construction of the SWH system (in kg/m^2); $F_{k,i}$ is the specific emission rate of pollutant k per unit of mass of the material i (in g/kg); e_{ij} the energy form j consumed in the production and processing of the material i (in MJ/kg); f_{kj} the emission factor of pollutant k per unit of energy form j (in g/MJ) and e_{cj} is the energy form j used in the construction of the SWH system (in MJ/m^2).

$Q_{r,k}$ is a small but indeterminate amount of pollutant k assumed to be equal to 10% of the total Q_k.

Of all the main materials used in the construction of SWH systems (see Table 1), only the aluminium is produced in Greece from domestically extracted bauxite. Energy requirements and pollutants emitted during the production of this material were thus estimated on the basis of a detailed analysis of the aluminium production process (determination of the total heat and electricty consumption in the series of productive stages, as well as of the type of fuels used for heat and power generation). The energy requirements of aluminium recycling were also estimated, since approximately 25% of the aluminium used in the processing industries is recycled [14]. The thermal energy and electricty requirements of the aluminium production process are presented in Table 2.

The rest of the materials used in the manufacturing of SWH systems are mostly imported as semi-finished products. Data regarding the energy requirements of the production processes recorded in Europe and their respective emission rates ($F_{k,i}$) were therefore drawn from relevant bibliographical sources [9]. Welding materials, resins and coatings were not taken into consideration, both because the quantities used are very low and accurate data were not available.

Finally, the energy consumed during the system's final assembly/construction in domestic plants amounts to approximately 20 kWh/m^2 and consists primarily of electricity supplied by the national grid [12].

The specific CO_2, NO_x and SO_2 emission rates $F_{k,i}$, established for aluminium with the

Table 2. Energy requirements of the aluminium production stages (in MJ/t of aluminium)

Production stage	Thermal energy	Electricity
Bauxite extraction	320*	27
Alumina production	28,000*	1,150‡
Aluminium production	2,600*	50,700
Secondary aluminium production	7,450*	1,590
Production of aluminium sheets	49,000†	6,372

*Fuel oil.
†LPG.
‡60% Provided by the PPC and 40% by a cogeneration plant using fuel oil.

Table 3. Emission rates of the processing activites involved in the manufacture of SWH systems

Material processing	CO_2	SO_2	NO_x
	(in kg of pollutant per tonne of material)		
Aluminium	21,458	105.4	44.7
Iron	2,225	17.6	8.2
Copper	2,683	31.3	12.2
Insulating materials	2,437	16.9	20.6
System construction	(in kg of pollutant per m^2 of collector's surface)		
	20.7	0.11	0.0478

use of eq. (2) and identified, for the remaining materials, in the relevant literature are presented in Table 3. The same table also presents the emissions Q_c attributed to the construction stage and calculated according to eq. (3).

The total level of emission attributable to the standard SWH system examined is calculated with eqs (1)–(3) and the values reported in Tables 1 and 3. In order to express the emission factors on a per unit of energy basis, the system's efficiency had to be taken into account. The emission factors thus obtained on the basis of an average life-span of 15 years are given in Table 4. As expected, the calculated emission factors vary considerably according to the location, since the amount of energy recovered in each of the six zones depends on the rates of insolation respectively recorded (see Section 3.3).

Table 4. Emission factors attributable to a standard SWH system

Emissions	CO_2	SO_2	NO_x
In kg per m^2 solar collector	212	1.52	0.676
In g/kWh (Zones 1–6)	17.28–25.65	0.124–0.184	0.055–0.082

Table 5. Airborne emission factors from power generation plants

Fuel	CO_2(g/kWh)	SO_2(g/kWh)	NO_x(g/kWh)
Lignite	1,300	1.8	1.6
Fuel-oil (for the interconnected electricity grid)	850	15.5	1.2
Fuel-oil (for the Islands' elecricity grid)	1,062.5	19.4	1.5

5. BALANCE OF ATMOSPHERIC EMISSIONS

Sine the use of SWH systems enables a substitution for electricity, the indirect atmospheric emissions attributed to these systems by means of a LCA approach can be weighed against the emissions per unit of energy produced in power generation plants. The emission factors estimated for the power plants which make up Greece's power generation sector are given in Table 5. The energy mix used for the generation of electricity in Greece consists of 70% lignite, 20% fuel oil and 10% hydro-power. As shown in Tables 4 and 5, the emissions induced by the production of SWH systems per unit of recovered energy are 60 times lower than the emission levels per unit of energy produced in lignite power generation systems and 40–50 times lower than those of oil-fired systems. The emissions of SO_2 and NO_x are also considerably lower compared to those attributed to the examined conventional power plants.

The total of approx. 1,500,000 m^2 of SWH systems which have so far been installed in Greece account for the conservation of substantial quantities of energy and consequently, as shown in the previous analysis, contribute to a noteworthy abatement in atmospheric pollution. Taking into account the SWH systems' geographical distribution and respective efficiency, it is estimated that the total annual level of energy conservation achieved amounts to approximately 550 GWh (the island regions accounting for 80 GWh and the mainland for the remaining 470 GWh). The annual decrease in the amount of emitted pollutants amounts to 594 kt CO_2, 3.61 kt SO_2 and 0.76 kt NO_x. Once indirect emissions associated with the manufacture of SWH systems have been taken into consideration, one obtains the net abatement in annual gaseous pollutant emissions achieved with the utilisation of solar energy for water heating purposes which amounts to 572 kt CO_2, 3.46 kt SO_2 and 0.69 kt NO_x (Fig. 2). As far as CO_2 is more specifically concerned, it should be noted that the reduction achieved corresponds to no less than 1.42% of the total CO_2 produced in 1990 by the entire Greek power generation system.

6. CONCLUSIONS

Contrary to the competitive electricity generation systems based on conventional fuels, the operation of SWH systems is not accountable for gaseous pollutant emissions. In spite of this definite advantage, gaseous pollutants are nevertheless released during the process necessary for the solar systems' manufacture. Utilisation of solar energy is therefore accountable for atmospheric pollution, even if only in an indirect manner. An attempt was made in this paper to estimate the level of indirect atmospheric pollution associated with the standard type of SWH system used in Greece.

A Life Cycle Analysis method was thus applied, so as to determine the level of atmospheric pollution caused by each of the stages of the SWH systems' manufacture. As the

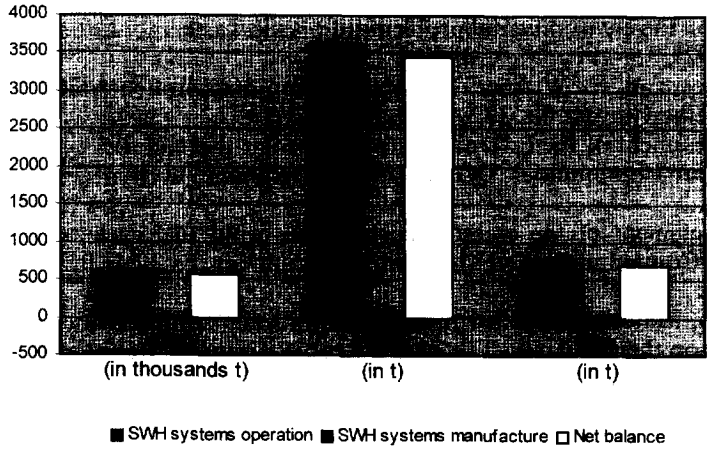

Fig. 2. Annual abatement of airborne emissions attributed to solar energy exploitation.

consumption of energy is known to be the most important source of gaseous pollutant emissions, the analysis focused on the more energy-consuming stages of the production process.

The considerable degree of uncertainty which characterises the results of the analysis is to be attributed primarily to discrepancies in (i) the weight values given to the materials used in the manufacture of the SWH systems and (ii) the energy consumption recorded at the different stages of the process. In spite of this uncertainty, the burden on the environment from the use of solar energy for water heating purposes was shown to be much smaller than the one induced by the use of electricity when produced in conventional power plants. More specifically, a substantial abatement in CO_2, SO_2 and NO_x emissions is achieved, to which one must add the reduction in other undesirable pollutant loads not examined in the scope of the present analysis. The promotion of solar energy is therefore deemed essential to any integrated energy policy aimed at ensuring environmental protection and the achievement of sustainable development.

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