ENVIRONMENTAL IMPACT OF DOMESTIC SOLAR WATER HEATING SYSTEMS

Soteris Kalogirou

Higher Technical Institute, P. O. Box 20423, Nicosia 2152, Cyprus.
Email: skalogir@spidernet.com.cy

ABSTRACT

In this paper a study on the environmental protection offered by domestic solar water heating systems is presented. The systems investigated employ electricity or diesel as back-up auxiliary energy. Both systems investigated produce about 2050 kWh of energy per year, cover about 89% of the hot water needs and give positive and very promising financial characteristics. The results show that by using solar energy for domestic water heating considerable amounts of greenhouse polluting gasses are avoided. The savings, compared to a conventional system, are about 80%, with electricity or diesel backup. With respect to life cycle assessment of the systems, the energy spent for the manufacture and installation of the solar systems is recouped in about 1.2 years, whereas the payback time with respect to emissions produced from the embodied energy required for the manufacture and installation of the systems varies from a few months to 3.7 years according to the fuel and the particular pollutant considered. Moreover the cost of damage avoided by some of the pollutants is investigated with respect to damages to crops, materials, mortality and morbidity. It was found that C£31 (Euro 51.7) are avoided per year when the system is using electricity as auxiliary and C£13 (Euro 21.7) when diesel is used. It can therefore be concluded that solar energy systems offer significant protection to the environment and cost savings and should be employed whenever possible in order to achieve a sustainable future.

1. INTRODUCTION

Energy is considered a prime agent in the generation of wealth and a significant factor in economic development. The importance of energy in economic development is recognised universally and historical data verify that there is a strong relationship between the availability of energy and economic activity. Although at the early seventies, after the oil crisis, the concern was on the cost of energy, during the past two decades the risk and reality of environmental degradation have become more apparent. The growing evidence of environmental problems is due to a combination of several factors since the environmental impact of human activities has grown dramatically. This is due to the increase of the world population, energy consumption and industrial activities. Achieving solutions to environmental problems that humanity faces today requires long-term potential actions for sustainable development. In this respect, renewable energy resources appear to be one of the most efficient and effective solutions.

One of the most widely accepted definitions of sustainable development is: "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*". There are many factors that can help to achieve sustainable development. The main ones are the rational use of energy and the use of renewable energy resources.

A few years ago, most environmental analysis and legal control instruments concentrated on conventional pollutants such as sulphur dioxide (SO_2), nitrogen oxides (NO_x), particulates, and carbon monoxide (CO). Recently however, environmental concern has extended to the control of hazardous air pollutants, which are usually toxic chemical substances which are harmful even in small doses, as well as to other globally significant pollutants such as carbon dioxide (CO_2).

Additionally, developments in industrial processes and structures have led to new environmental problems. A detailed description of these gaseous and particulate pollutants and their impact on the environment and human life is presented by Dincer (1998).

Pollution depends on energy consumption. There are a large number of factors which are significant in the determination of the future level of the energy consumption and production. Such factors include population growth, economic performance, consumer tastes and technological developments. Furthermore, governmental policies concerning energy and developments in the world energy markets will certainly play a key role in the future level and pattern of energy production and consumption (Dincer, 1999).

Problems associated with energy supply and use are related not only to global warming, but also to other environmental impacts such as air pollution, acid precipitation, ozone depletion, forest destruction, and emission of radioactive substances. Today much evidence exists, which suggests that the future of our planet and of the generations to come will be negatively impacted if humans keep degrading the environment. The three major environmental problems that are internationally known are the acid rain, ozone layer depletion and global climate change.

Today the world daily oil consumption is 76 million barrels. Despite the well known consequences of fossil fuel combustion on the environment, this is expected to increase to 123 million barrels per day by the year 2025 (www.worldwatch.org). In developed countries, energy consumption in the building sector represents a major part of the total energy budget. In the European Union this is approximately equal to 40% of the total energy consumption (Argiriou *et al.*, 1997). Most of this amount is spent for hot water production and space heating. One way to reduce this amount of energy is to employ solar energy.

1.1 Renewable Energy Technologies

Renewable energy technologies produce marketable energy by converting natural phenomena into useful forms of energy. Several potential solutions to the current environmental problems associated with the harmful pollutant emissions from the burning of fossil fuels have evolved, including renewable energy and energy conservation technologies. Many countries consider today solar, wind and other renewable energy sources as the key to a clean energy future.

Renewable energy systems can have a beneficial impact on the environmental, economic, and political issues of the world. The benefits arising from the installation and operation of renewable energy systems can be distinguished into three categories; energy saving, generation of new working posts and the decrease of environmental pollution (Diakoulaki *et al.*, 2001).

The energy saving benefit derives from the reduction in consumption of the electricity and/or diesel which are used conventionally to provide energy. Additionally, of equal importance is the ability of renewable energy technologies to generate jobs as a means of economic development to a country. The penetration of a new technology leads to the development of new production activities contributing to the production, market distribution and operation of the pertinent equipment. Specifically in the case of solar energy collectors, job creation mainly relates to the construction and installation of the collectors. The latter is a decentralised process since it requires the installation of equipment in every building or every individual consumer.

In this paper emphasis is given to solar energy systems and in particular to solar water heating systems. These are very popular systems used extensively in many countries with good sunshine potential such as the Mediterranean countries. In particular for countries like Cyprus which is a world leader on installed solar water heating systems it is of interest to know the magnitude of environmental advantage of these systems.

The objective of this paper is to analyse the environmental benefits resulting from the use of solar water heating systems. Additionally, the amount of pollution saved because of the use of solar energy against the pollution caused for the manufacture of the systems is examined.

2. SOLAR SYSTEM CONSIDERED

A schematic diagram of the solar water heating (SWH) system considered in this study is shown in Fig. 1. Flat plate collectors are used which are by far the most used type of collectors. The instantaneous efficiency of the collector considered is given by the equation:

$$n = 0.792 - 6.65\left(\frac{\Delta T}{I}\right) - 0.06\left(\frac{\Delta T^2}{I}\right) \tag{1}$$

where ΔT is temperature difference between the collector inlet and ambient temperatures and I is the global solar radiation.

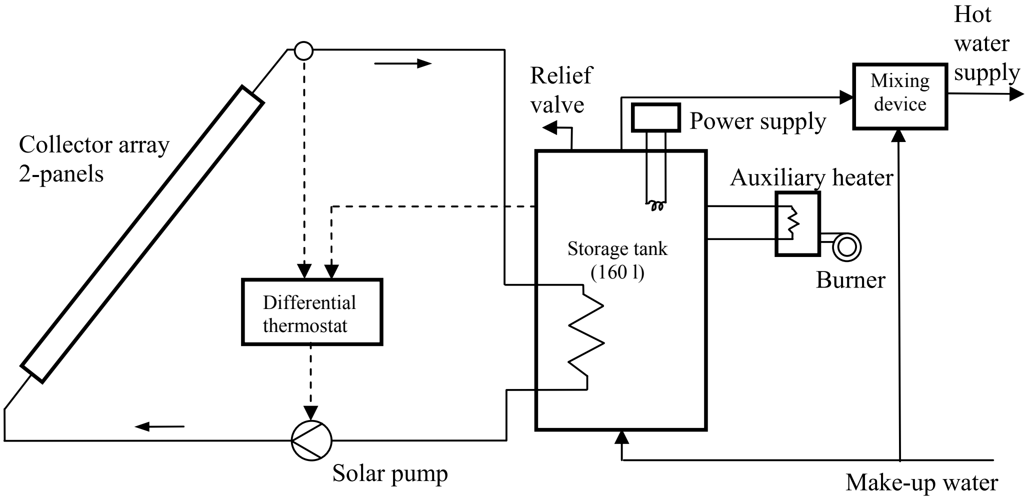

Fig. 1 Schematic diagram of the solar water heating (SWH) system

As can be seen from Fig. 1 an active solar system is considered, i.e., a pump is employed to transfer the solar thermal energy to storage, operated by means of a differential thermostat. The thermostat compares the temperature at the outlet of the solar collectors and the storage tank and whenever the collector temperature is higher than the storage temperature by more than 8°C the pump is switched on. It switches off whenever this difference is lower than 4°C. The storage tank is well insulated to reduce thermal loses to the environment and is equipped with heat exchangers for both the solar system and the auxiliary system. In SWH systems the auxiliary can be electricity or diesel. In the case where diesel is considered this is used in a central heating boiler, which supplies the energy for the heating needs of a house and is not used only as the solar system backup. The specifications of the solar system are shown in Table 1.

Traditional hot water systems comprise a hot water cylinder with auxiliary power from either electricity or diesel oil through the central heating boiler. Therefore the extra equipment required for the solar system are the solar collectors, piping to connect the collectors with the storage tank, pump and differential thermostat.

Table 1 Specification of the solar system considered

Parameter	Specification
Type of system	Active
Collector area	3.8 m^2 (2-panels)
Collector slope	40°
Storage capacity	160 l
Auxiliary capacity	3 kW
Heat exchanger	Internal
Heat exchanger area	3.6 m^2
Hot water demand	120 l (4 persons)

3. THERMAL AND ECONOMIC ANALYSIS

The system is simulated with Polysun program (version 3.3.5g) with the weather conditions of Nicosia, Cyprus (Polysun, 2000). The program provides dynamic annual simulations of solar thermal systems and helps to optimise them. It operates with dynamic time steps from one second to one hour, thus simulation can be more stable and exact. The program is user friendly and the graphic-user interface permits a comfortable and clear input of all system parameters. All aspects of the simulation are based on physical models that work without empirical correlation terms.

In addition the program performs economic viability analysis and ecological balance, which includes emissions from the eight most significant greenhouse gasses, thus the emissions of systems working only with conventional fuel and systems employing solar energy can be compared. Program Polysun was validated by Gantner (2000) and was found to be accurate to within 5-10%. The optimum slope of the solar collectors, shown in Table 1, was calculated with a special routine of the Polysun program.

Two types of solar water heating systems were considered one with electric heating backup and one with a boiler backup. In houses where a central heating exist the last option is preferred as the price of diesel is much lower than that of electricity and the owners prefer to use their central heating boiler to produce hot water, as a solar system backup, irrespective of the requirement for heating. The annual energy balance and the monthly solar contribution of the systems considered are shown in Tables 2 and 3 respectively.

As can be seen from Table 3, both variations of domestic hot water systems considered cover all the requirements during summertime and a large percentage during wintertime. The annual figure is also high. It should be noted that by adjusting slightly the consumption profile, contributions of 100% could be obtained in the months May to October, which is what actually happens in practice. The program however considers a standard consumption throughout all months that is why values slightly below 100% are given.

Table 2 Annual energy balance of the systems considered.

Parameter	Electricity backup	Diesel backup
Solar system yield (kWh)	2046.4	2063.1
Total auxiliary energy (kWh)	269.3	238.5
Hot water demand (kWh)	1780.0	1780.0
Solar fraction	88.4	89.6
Note: Solar fraction = solar yield / (solar yield + auxiliary)		

Table 3 Monthly solar contribution

Month	Electricity Backup	Diesel Backup
Jan	61.1	61.7
Feb	75.8	76.5
Mar	86.5	88.7
Apr	90.8	91.2
May	96.0	98.2
Jun	96.5	97.3
Jul	97.0	98.5
Aug	98.8	99.4
Sep	98.5	99.9
Oct	94.9	94.9
Nov	87.3	89.0
Dec	72.0	74.5
Year	88.4	89.6
Note: All values are expressed in percentage		

The results of the economic analysis are shown in Table 4. These were obtained by using the current fuel and electricity rates, a twenty years period and market discount rare of 4%. No subsidies were considered. As can be seen in both cases the solar systems give much lower specific energy costs than the conventional systems and the pay back times are reasonable. It should be noted that the cost of the boiler and other necessary auxiliary equipment is not taken into account in the economic analysis, i.e., only the cost of the extra equipment required for the solar installation is considered.

Table 4 Results of the economic analysis for the various types of fuels considered

Parameter	Electricity	Diesel
Total system cost, solar (C£)	550	550
Annual fuel savings (C£)	95	74
Pay-back time (years)	4.2	5.4
Energy costs:		
Solar energy only (C£/kWh)	0.0253	0.0251
Solar + conventional (C£/kWh)	0.0332	0.0293
Conventional (C£/kWh)	0.105	0.0739
Notes: 1. 1C£=1.71 Euro (May 2005) 2. Solar system cost includes C£150 for the storage tank.		

4. ENVIRONMENTAL BENEFITS OF SOLAR ENERGY SYSTEMS

To investigate the environmental benefits of utilising solar energy instead of conventional sources of energy, the different emissions resulting from the solar system operation are estimated and compared to those of a conventional fuel system. The emissions reported are those which are responsible for the most important environmental problems. The environmental pollution is expressed in physical units of the emitted substances per year. The quantities of the emissions depend on the solar collector size and the required auxiliary energy and are compared to a non-solar system which is using conventional fuel. The environmental analysis of the above systems which includes the different pollutants as calculated by the program Polysun is tabulated in Tables 5 and 6. In the tables the eight most important greenhouse gasses are compared.

Table 5 Environmental impact of the SWH system with electricity backup

Emissions	Units	Conventional	Solar system	Savings (%)
Carbon dioxide (CO_2)	Tons/year	1.982	0.40	79.8
Carbon monoxide (CO)	g/year	496	100	79.8
Nitrogen oxides (NO_x)	g/year	74	15	79.8
Nitrous oxide (N_2O)	g/year	7	2	79.8
Methane (CH_4)	g/year	12	3	79.8
Hydrocarbons	g/year	50	10	79.8
Sulfur dioxide (SO_2)	g/year	743	150	79.8
Dust	g/year	248	50	79.8
Savings in GHG	**%**	**-**	**-**	**79.8**

Table 6 Environmental impact of the SWH system with diesel backup

Emissions	Units	Conventional	Solar system	Savings (%)
Carbon dioxide (CO_2)	Tons/year	0.766	0.259	66.3
Carbon monoxide (CO)	g/year	1615	363	77.5
Nitrogen oxides (NO_x)	g/year	1615	324	80.0
Nitrous oxide (N_2O)	g/year	7	1	80.7
Methane (CH_4)	g/year	15	3	82.8
Hydrocarbons	g/year	62	11	82.8
Sulfur dioxide (SO_2)	g/year	775	145	81.3
Dust	g/year	136	52	61.7
Savings in GHG	**%**	**-**	**-**	**80.0**

As can be seen in all cases by using solar energy instead of conventional fuel a very large amount of pollutants are avoided. Additionally, the amount of emissions depends on the type of fuel used as auxiliary. The percentage saving obtained in the cases where electricity or diesel backup is used is about 80%. It should be noted however that the quantities of emissions in both cases are completely different and the proximity of the percentage numbers obtained is due to the generation efficiency of each system. Electrical energy is produced at a maximum efficiency of about 35% whereas in the case of diesel backup a boiler efficiency of 85% is considered. The usual type of SWH system encountered in Cyprus is of the thermosyphon type. This system uses the same collector area as the one considered here but it has no pump and differential thermostat. Its thermal behaviour is very similar to the studied system. Cyprus began manufacturing solar water heaters in the early sixties. Today more than 93% of all houses have solar water heating systems installed and operating. The total number of systems is equal to 190,000 units. In fact the number of units in operation today corresponds to one heater for every 3.7 people in the island, which is a world record. Therefore for the Cyprus case, if the above numbers are considered, one can understand the magnitude of the environmental pollution reduction per year, just for water heating.

It can be concluded from the results presented in this section that considerable amounts of polluting gases are saved by both types of systems considered, which implies that the solar water heating is environmentally friendly irrespective of the backup fuel used.

5. POLLUTION CREATED FROM SOLAR SYSTEMS

The negative environmental impact of solar energy systems includes land displacement, and possible air and water pollution resulting from manufacturing, normal maintenance operations and demolition of the systems. However, land use is not a problem when collectors are mounted on the roof of a building, maintenance requirement is minimal and pollution caused by demolition is not greater than the pollution caused from demolishing a conventional system of the same capacity. The pollution created for the manufacture of the solar collectors is estimated by calculating the embodied energy invested in the manufacture and assembly of the collectors and estimating the pollution produced by this energy.

Initially the embodied energy of one solar collector panel, 1.9m^2 in area is determined. This is the same collector considered in the performance analysis of the systems. The analysis is based on the primary and intermediate embodied energy of the components and materials as illustrated in Fig. 2. In the present analysis no allowance is made for the unit packing, transportation and maintenance as these have insignificant contribution compared to the total.

The total embodied energy required to produce a complete flat-plate collector is calculated using primary and intermediate production stages. The primary stage is established from an assessment of the various materials used and their corresponding mass. Using the embodied energy index (MJ/kg) defined by Alcorn (1995) the material embodied energy content within the unit is determined. Table 7 summarizes the unit materials used and lists their corresponding mass and embodied energy content. As can be seen from Table 7, the total embodied energy content for the production of one flat-plate collector panel is calculated at 3540 MJ. This comprise the primary embodied energy of materials and the intermediate embodied energy, i.e., the amount of energy used in the production and assembly of the component parts during the construction stage and was determined through a stage-by-stage appraisal of the power sources used. Inherent within this intermediate stage is the fabrication of purchased components like screws, glass and insulation.

An analysis of the embodied energy content of a complete solar hot water system is shown in Table 8. It should be noted that only the extra components of the solar system are considered in this analysis as the other components are standard and are also present in the conventional system. As can be seen the total embodied energy for the complete system is 8700 MJ.

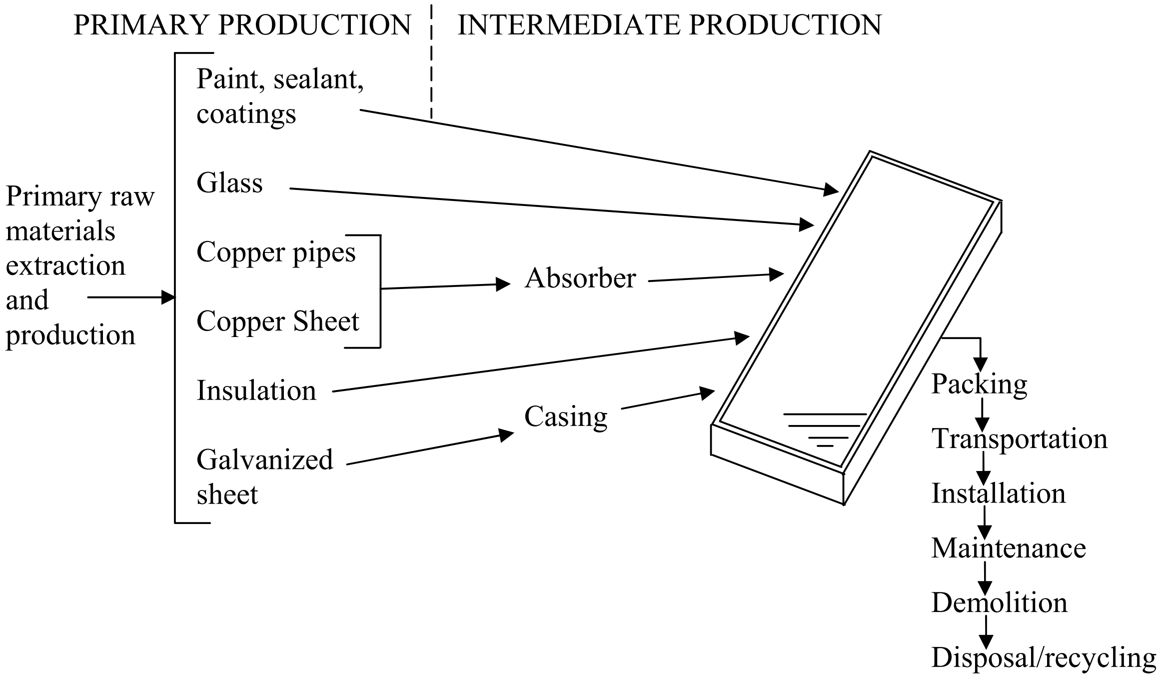

Fig. 2 Factors considered in the calculation of embodied energy of a flat-plate collector

Table 7 Embodied energy content of one flat-plate collector 1.9m^2 in area.

Description	Mass (kg)	Embodied energy index (MJ/kg)	Embodied energy content (MJ)
1.9x1x0.05m insulation	6	117	702
1.9x1x0.005m glass	13.4	15.9	213.3
2m, 22mm copper pipe	2.4	70.6	169.5
20m, 15mm copper pipe	12.4	70.6	875.5
2.3x1.3x0.005m galvanized steel sheet	11.7	34.8	408.4
6m rubber sealant	0.6	110	66
Black paint	0.3	44	13.2
Casing paint	0.9	44	39.6
20 No. screws	0.00125	34.8	Ignored
1.9x1x0.003m copper absorber	5	70.6	353
Total			2840.5
Add 10% for contingencies			284.1
Unit manufacture using a net to gross value of conversion rate of 27%			415.4
Grant Total			**3540**

Table 8 Embodied energy content for the construction and installation of the complete solar hot water system

Description	Mass (kg)	Embodied energy index (MJ/kg)	Embodied energy content (MJ)
2 No solar panels	-	-	7080
4m, 22mm copper pipe	3.8	70.6	268.3
4m, pipe insulation	1	120	120
Steel frame	30	34.8	1044
Total			8512.3
Installation			187.7
Grant Total			**8700**

The objective of this analysis is to compare the pollution created for the manufacture and installation of the solar systems against its benefits due to the lower emissions realized during the operation of the systems. Therefore, for the life cycle assessment of the systems considered the useful energy supplied by solar energy per year, shown in Table 2, is compared with the total embodied energy of the systems shown in Table 8. As can be seen the total energy used in the manufacture and installation of the systems is recouped in about 1.2 years, which is considered as very satisfactory.

The emissions created from total embodied energy for the systems considered are presented in Table 9. Additionally, these emissions are compared with the emissions saved because solar energy is used instead of auxiliary energy, according to the type of fuel used in the two cases of solar systems investigated, in order to estimate the payback period for each pollutant. In all cases the emissions are estimated by considering that all embodied energy was produced from electricity. This is not quite correct but electricity is chosen, as is the most polluting fuel, therefore it gives the worst possible results. As can be seen from Table 9, the payback periods for the cases investigated vary from a few months to 3.7 years according to the fuel and the particular pollutant considered.

Moreover the cost of damage avoided by some of the pollutants is investigated with respect to damages to crops, materials, mortality and morbidity. The results of this analysis are shown in Tables 10 and 11.

Table 9 Pollution created for the construction and installation of the solar hot water system and payback for both types of backup fuels considered

Emission	Pollution created from solar system embodied energy	Savings and payback of solar system	
		Electricity	Diesel
Carbon dioxide (CO_2)	1.934 Tons	1.582 (1.2)	0.517 (3.7)
Carbon monoxide (CO)	483 g	396 (1.2)	1252 (0.4)
Nitrogen oxides (NO_x)	72.5 g	59 (1.2)	1291 (0.06)
Nitrous oxide (N_2O)	7.3 g	5 (1.5)	6 (1.2)
Methane (CH_4)	12.1 g	9 (1.3)	12 (1.0)
Hydrocarbons	48.3 g	40 (1.2)	51 (0.9)
Sulfur dioxide (SO_2)	725 g	593 (1.2)	630 (1.2)
Notes: 1. Number in parenthesis represent payback in years 2. The units of savings are in g/year except carbon dioxide which is tons/year			

Table 10 Typical damage costs per kg of pollution emitted by power plants in Europe (Rabl and Spardaro, 2001)

Pollutant	Impact	Cost
SO_2	Crops, materials, mortality and morbidity	6.33
NO_2	Crops, mortality and morbidity	9.6
VOC (via O_3)	Crops, mortality and morbidity	0.54
CO (primary)	Morbidity	0.0012
CO_2	Global warming	0.0174
Notes: 1. Cost in C£/kg 2. Mortality refers to premature deaths 3. Morbidity refers to illness		

Table 11 Damage cost avoided per year from some of the pollutants for domestic SWH systems

Pollutant	Amount saved (kg)		Damage cost avoided (C£)	
	Electricity	Diesel	Electricity	Diesel
CO_2	1582	517 1.252	27.5	9.0
CO	0.396	0.630	~0	~0
SO_2	0.593		3.75	3.99
		Totals:	**31.25**	**12.99**

As can be seen about C£31 (Euro 51.7) are avoided per year when the system is using electricity as auxiliary and about C£13 (Euro 21.7) are avoided per year when diesel is used alone for each solar water heating system. Therefore for a more correct analysis of SWH systems the damage cost avoided, shown in Table 11, should be added to the annual fuel savings shown in Table 4. By performing this analysis the pay-back time is reduced to 3.2 and 4.6 years, from 4.2 and 5.4 years (shown in Table 4) for the two types of systems considered, thus there is a further increase in the economic viability of the systems. It is believed by the author that such type of analysis must always be considered in feasibility studies of solar systems.

6. CONCLUSIONS

In the present study, the environmental impact of energy utilization has been investigated and the potential benefits that solar systems offer are discussed in detail. From the analysis presented in this paper it can be concluded that the environmental impact of any energy system is an important factor and solar systems have the potential to reduce environmental pollution.

Crucial to discussions on prevention of global climate change are thorough evaluations of the costs of reducing emissions. Many countries through several national and international institutes and agencies have started taking actions to reduce (or eliminate) the pollutant emissions and to attain a sustainable supply of energy. One way to achieve this is by using as much as possible solar energy.

Additionally, in this study the environmental protection offered by the most widely used renewable energy system, i.e., solar water heating is presented. The results show that by using solar energy considerable amounts of greenhouse polluting gasses are avoided.

For the case of domestic water heating system with electricity or diesel backup the saving, compared to a conventional system, is about 80%. Additionally, all systems investigated give positive and very promising financial characteristics. With respect to life cycle assessment of the systems, the energy spent for the manufacture and installation of the solar systems is recouped in about 1.2 years, whereas the payback time with respect to emissions produced from the embodied energy required for the manufacture and installation of the systems varies from a few months to 3.7 years according to the fuel and the particular pollutant considered. Moreover, the cost of damage avoided by some of the pollutants is investigated with respect to damages to crops, materials, mortality and morbidity. It was found that about C£31 (Euro 51.7) are avoided per year when the system is using electricity as auxiliary and about C£13 (Euro 21.7) when diesel is used. When these are added to the annual fuel savings very satisfactory pay-back times of 3.2 and 4.6 years, for the two types of systems considered, are obtained.

It can therefore be concluded that solar energy systems are friendlier to the environment and offer significant protection of the environment. The reduction of greenhouse gasses pollution is the main advantage of utilising solar energy. Therefore solar energy systems should be employed whenever possible in order to achieve a sustainable future, thus applying the slogan "***think globally- act locally***".

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