THE RETURN OF EMBODIED ENERGY INVESTED IN DOMESTIC SOLAR WATER HEATING SYSTEMS

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ABSTRACT

In this paper the environmental protection offered by domestic solar water heating systems is presented. By using solar energy considerable amounts of greenhouse polluting gasses are avoided. The savings, compared to a conventional system, are about 80%, with electricity or diesel backup and about 75% with both electricity and diesel backup. 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 varies from a few months to 3.7 years according to the fuel and the particular pollutant considered. It is therefore concluded that solar systems offer significant benefits and should be employed whenever possible in order to achieve a sustainable future.

INTRODUCTION

All nations of the world depend on fossil fuels for their energy needs. However the obligation to reduce CO_2 and other gaseous emissions is the reason behind which countries turn to non-polluting renewable energy sources. Energy is considered a prime agent in the generation of wealth and a significant factor in economic development. 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 environmental problems are 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.

The principal 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.

ENVIRONMENTAL IMPACT OF CONVENTIONAL ENERGY SOURCES

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. Environmental analysis deals mainly with the effects of conventional pollutants such as sulphur dioxide (SO_2), nitrogen oxides (NO_x), particulates, and carbon monoxide (CO) as well as with other significant pollutants such as carbon dioxide

(CO_2). A detailed description of these pollutants and their impact on the environment and human life is presented by Dincer (1998).

Pollution depends on energy consumption. The main factors on which the future level of the energy consumption depends are; population growth, economic performance, consumer tastes and technological developments. 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.

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. Most of this amount is spent for hot water production and space heating.

RENEWABLE ENERGY SYSTEMS

Renewable energy systems convert 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).

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. 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.

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:

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

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

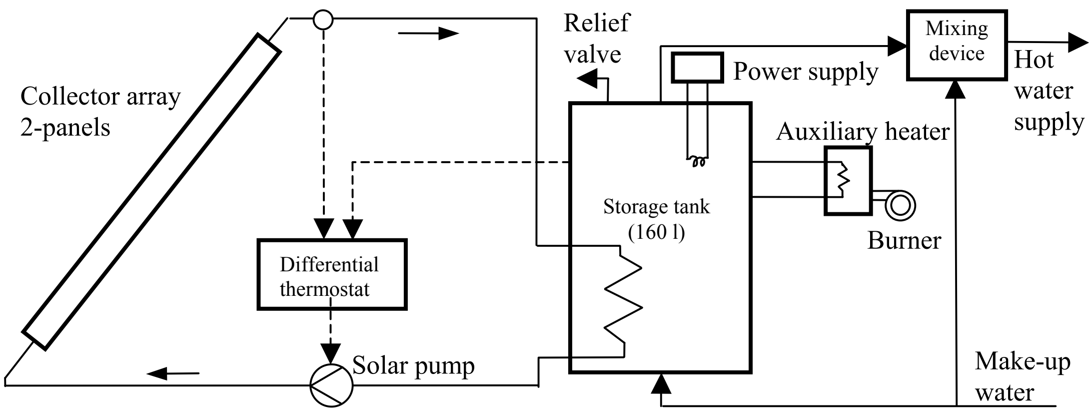

Figure 1 Schematic diagram of the solar water heating (SWH) system

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 set at 8°C ON and 4°C OFF. The storage tank is well insulated to reduce thermal loses to the environment. The specifications of the solar system considered are shown in Table 1.

Table 1 Specifications of the solar system

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)

Traditional hot water systems comprise a hot water cylinder powered either by electricity or by 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.

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. Additionally it 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%.

With respect to auxiliary energy used, three types of systems were considered, one with electric heating backup, one with a combination of electricity and boiler backup and one with only a boiler backup. In houses where a central heating exist the two last options are 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, irrespective of the requirement for heating. The second case where both electricity and boiler is used is a case which occurs frequently when in intermediate periods with no heating requirement; the users may prefer to use electricity as a backup instead of using the central heating boiler.

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, all 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	Electricity and diesel backup	Diesel backup
Solar system yield (kWh)	2046.4	2054.7	2063.1
Total auxiliary energy (kWh)	269.3	211.4 (diesel) 40.9 (electricity)	238.5
Hot water demand (kWh)	1780.0	1780.0	1780.0
Solar fraction	88.4	89.1	89.6
Note: Solar fraction = solar yield / (solar yield + auxiliary)			

Table 3. Monthly solar contribution

Month	Electricity Backup	Electricity + diesel backup	Diesel Backup
Jan	61.1	61.8	61.7
Feb	75.8	76.5	76.5
Mar	86.5	88.6	88.7
Apr	90.8	90.3	91.2
May	96.0	96.9	98.2
Jun	96.5	96.5	97.3
Jul	97.0	97.0	98.5
Aug	98.8	98.8	99.4
Sep	98.5	98.5	99.9
Oct	94.9	95.0	94.9
Nov	87.3	89.5	89.0
Dec	72.0	73.5	74.5
Year	88.4	89.1	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 all 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.

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 5-7. In the tables the eight most important greenhouse gasses are compared.

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

Parameter	Electricity	Electricity + Diesel	Diesel
Total system cost (solar)	550	550	550
Annual fuel savings (C£)	95	71	74
Pay-back time (years)	4.2	5.6	5.4
Energy costs:			
Solar energy only (C£/kWh)	0.0253	0.0252	0.0251
Solar+conventional (C£/kWh)	0.0332	0.0301	0.0293
Conventional (C£/kWh)	0.105	0.0739	0.0739
Notes: 1C£=1.72 Euro (January 2004), Solar system cost includes C£150 for the storage tank.			

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 both electricity and diesel backup

Emissions	Units	Conventional	Solar system	Savings (%)
Carbon dioxide (CO_2)	Tons/year	0.964	0.299	69.0
Carbon monoxide (CO)	g/year	796	280	64.9
Nitrogen oxides (NO_x)	g/year	728	228	68.7
Nitrous oxide (N_2O)	g/year	7	1	80.2
Methane (CH_4)	g/year	15	3	81.5
Hydrocarbons	g/year	60	11	81.9
Sulfur dioxide (SO_2)	g/year	770	148	80.9
Dust	g/year	90	51	44.1
Savings in GHG	**%**	**-**	**-**	**74.2**

Table 7. 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% whereas in the case that both electricity and diesel are employed this is 74.2%. It should be noted however that the quantities of emissions in all these 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. Today in Cyprus more than 93% of all houses have solar water heating systems installed and operating. The total number is equal to 190,000 units which correspond 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.

POLLUTION FROM SOLAR SYSTEMS

The negative environmental impact of solar energy systems includes land displacement, and possible air and water pollution resulting from the manufacture, maintenance 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 solar collectors is estimated by calculating the embodied energy invested in manufacture and assembly of 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. No allowance is made for packing, transportation and maintenance as these have insignificant contribution. The total embodied energy required to produce a 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 8 summarizes the unit materials used and lists their corresponding mass and embodied energy content. As can be seen, 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 9. 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.

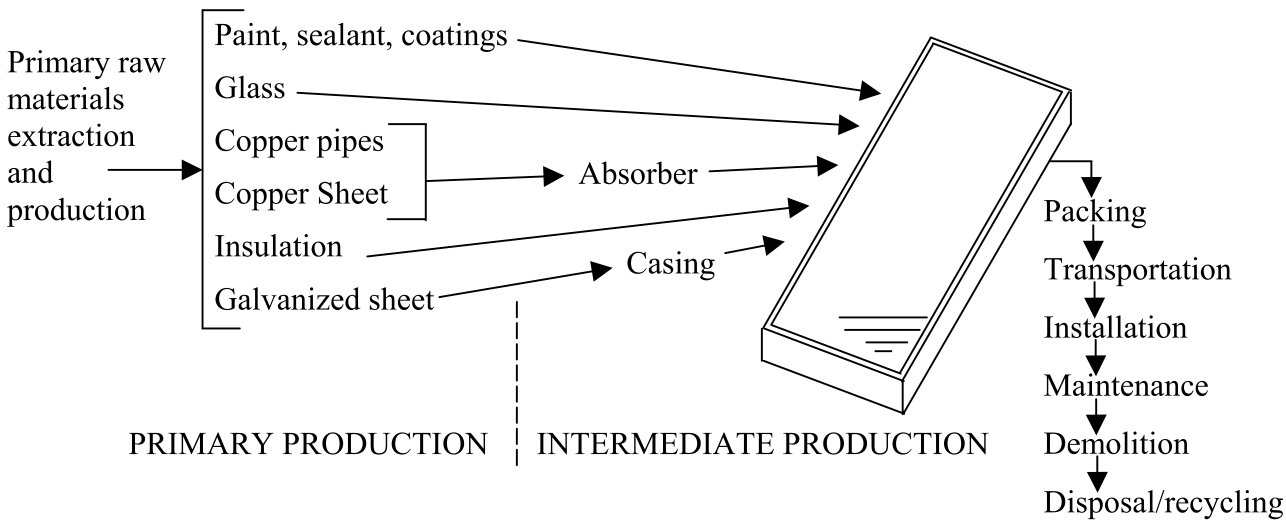

Figure 2. Factors considered in the calculation of embodied energy of a flat-plate collector

Table 8. 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 27%			415.4
Grant Total			**3540**

Table 9 Embodied energy content for the construction and installation of the complete SWH 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 9. 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 10. 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 various 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 10, 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 11 and 12. As can be seen about C£31 (Euro 51.7) are avoided per year when the system is using electricity as auxiliary, C£15.5 (Euro 25.8) are avoided when both electricity and diesel are used and C£13 (Euro 21.7) 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 12, 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, 4.6 and 4.6 years, from 4.2, 5.6 and 5.4 years (shown in Table 4) for the three types of systems considered, thus there is a further

Table 10 Pollution created for the construction and installation of the solar hot water system and payback for the three types of backup fuels considered

Emission	Pollution created from solar system embodied energy	Savings and payback of solar system		
		Electricity	Electricity and Diesel	Diesel
Carbon dioxide (CO_2)	1.934 Tons	1.582 (1.2)	0.665 (2.9)	0.517 (3.7)
Carbon monoxide (CO)	483 g	396 (1.2)	516 (0.9)	1252 (0.4)
Nitrogen oxides (NO_x)	72.5 g	59 (1.2)	500 (0.15)	1291 (0.06)
Nitrous oxide (N_2O)	7.3 g	5 (1.5)	6 (1.2)	6 (1.2)
Methane (CH_4)	12.1 g	9 (1.3)	12 (1.0)	12 (1.0)
Hydrocarbons	48.3 g	40 (1.2)	49 (1.0)	51 (0.9)
Sulfur dioxide (SO_2)	725 g	593 (1.2)	622 (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				

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.

Table 11 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		

CONCLUSIONS

In the present study the environmental protection offered by solar water heating systems is presented. The results show that by using solar energy considerable amounts of greenhouse polluting gasses are avoided. For the case of electricity or diesel backup the saving, compared to a conventional system, is about 80%, whereas for the case that both electricity and diesel backup are used, is about 75%. 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 can be concluded that solar energy systems are friendlier to the environment and offer significant protection to the environment. Therefore they should be employed whenever possible in order to achieve a sustainable future.

REFERENCES

Alcorn J., Embodied energy coefficients of building materials. Centre for Building Performance Research. Victoria University of Wellington, New Zealand, 1995.

Diakoulaki D. Zervos A., Sarafidis J. and Mirasgedis S., Cost Benefit Analysis for Solar Water Heating Systems, *Energy Conv. and Man.*, Vol. 42, No. 14, pp. 1727-1739, 2001.

Dincer I., Energy and environmental impacts: present and future perspectives. *Energy Sources*, 20(4/5), pp. 427-453, 1998.

Gantner M., Dynamische Simulation thermischer Solaranlagen, Diploma thesis, Hochschule für Technik Rapperswil (HSR), Switzerland, 2000.

Polysun, *User's manual for Polysun 3.3*, SPF, Switzerland, 2000.

Rabl A. and Spardaro J.V., The cost of pollution and the benefit of solar energy. In: Gordon J.M. (Ed.) Solar Energy: The state of the Art, ISES, James and James Ltd, London, UK, pp. 437-475, Chapter 8, 2001.

www.worldwatch.org, 2003.

Table 12 Damage cost avoided per year from some of the pollutants for domestic SWH systems

Pollutant	Amount saved (kg)			Damage cost avoided (C£)		
	Electricity	Electricity + Diesel	Diesel	Electricity	Electricity +Diesel	Diesel
CO_2	1582	665	517	27.5	11.6	9.0
CO	0.396	0.516	1.252	~0	~0	~0
SO_2	0.593	0.622	0.630	3.75	3.94	3.99
			Totals:	**31.25**	**15.54**	**12.99**