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ENVIRONMENTAL PERFORMANCE OF THERMOSYPHONIC DOMESTIC SOLAR HOT WATER SYSTEMS UNDER DIFFERENT CLIMATIC CONDITIONS: A CASE STUDY FOR GREECE

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ABSTRACT
Undoubtedly, sun is the cleanest energy source. Specific systems are needed however for the collection and transformation of solar energy and the manufacturing processes of such systems, as well as the production of the raw materials required, are associated with impacts to the environment. As a result, the life cycle environmental impact of solar systems depends on the type and the size of the systems. System characteristics and also the climate of the installation area, affect the substituted conventional energy (solar coverage). In this paper, the net environmental gain of flat plate thermosyphonic solar systems for domestic use is determined, accounting for the household size (different collector sizes) and the installation area (different solar coverage and transportation distance) for the major cities of Greece. Calculations are based on the "Eco-Indicator '99" methodology and database and it is proved that substituting electricity with solar energy is always environmentally beneficial for systems installed in all major cities of Greece.

KEYWORDS: solar energy, solar hot water systems, lca, environmental impacts

INTRODUCTION

About 94% of the manmade CO_2 emissions in Europe are attributed to the energy sector as a whole, the fossil fuels being the prime culprits with oil consumption accounting for 50%, natural gas for 22% and coal for 28%. In terms of activity, electricity and steam generation sectors are responsible for 37% of CO_2 production, transport for 28%, households for 14%, industry for 16% and the services sector for 5% (European Commission, 1999).

Key factor in the global warming fight is the rational use of energy and the further utilization of renewable energy sources (RES). In the White Paper for the Community Strategy and Action Plan (European Commission, 1997), European Commission sets an indicative objective of 12% contribution of RES to the EU's final energy mix by 2010, with the "Campaign to Take-Off" (CTO) setting mid-way targets for 2003.

Regarding solar energy utilization, the targets set at EU level are:

- CTO: 15.000.000 m^2 of solar collectors installed by 2003 (10.000.000 m^2 having already been installed by 2000),
- White Paper: 100.000.000 m^2 of solar collectors installed by 2010.

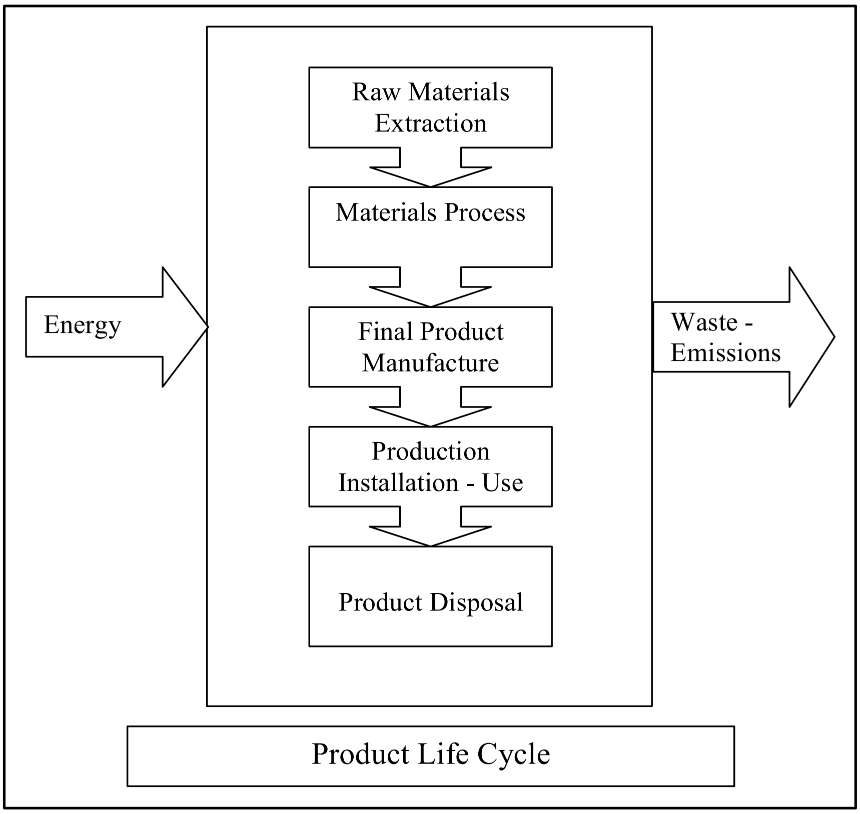

Figure 1. Product's Life Cycle and its transactions with the environment

Greece is one of the most successful countries world-wide in the use of solar thermal systems. The first systems were produced in mid 70's and by 1990 they had reached 1.760.000 m^2. Nowadays, more than 800.000 households (more than 25% of the total) use domestic solar hot water systems (DSHWS) and the country holds the second position in Europe not only in terms of installations but also in terms of production of DSHWS. In 2001 more than 40% of the solar collectors production was exported (European Solar Thermal Industry Federation, 2003).

The installed solar collector area per capita in Greece has been the highest in Europe for a number of years, reaching an average of 0,264 m^2/capita, tenfold higher the EU's average (European Solar Thermal Industry Federation, 2003), the figure including not only households but also hotel, industry, sports centre and greenhouse applications.

Although sun is the cleanest energy source available, important transactions with the environment are taking place over the whole lifecycle of a DSHWS (materials, manufacturing, transportation, utilization and final disposal). The consequences of these transactions include the depletion of natural sources, the greenhouse effect, acid rain etc. Therefore, and in view of the planned rapid expansion and enlargement of DSHWS utilization, it is necessary to evaluate solar technology, accounting for the indirect environmental impacts over its whole lifecycle (Figure 1). In this paper, the life cycle analysis (LCA) methodology is applied for the assessment of the environmental impact of DSHWS. A typical DSHWS, installed in a number of major Greek cities, distributed over the entire country, sized to fulfil the needs of different sizes of households, is evaluated, the evaluation accounting also for the environmental gain by the substitution of electricity, the main conventional energy used.

LCA METHODOLOGY

Life cycle assessment is a technique for assessing the environmental performance of a product, process or activity from "cradle to grave", i.e. from the extraction of raw materials to final disposal. Today's LCA originates from "net energy analysis" studies, first published in the 70s (Boustead., 1972; Hannon, 1972; and Sundstrom, 1973). These studies considered only energy consumption over the lifecycle of a product or a process. Some later studies included wastes and emissions (Lundolm and Sundstrom, 1985; and Boustead, 1989), but none of them went further than just quantifying materials and energy use. At this point it was clear that a more sophisticated approach to complex environmental issues was needed. As a result, in 1990, the Society for Environmental Toxicology and Chemistry (SETAC) initiated activities to define LCA and develop a general methodology for conducting the LCA studies. Soon afterwards, the International Organization for Standardization (ISO) started similar work on developing principles and guidelines on the LCA methodology (ISO/DIS 14040, 1997).

The methodology consists of four stages:

- First stage. The goal and the scope of the assessment are determined. The functional unit of the product is also defined in this stage.
- Second stage. Inventory analysis of the materials and of the processes end energy data (input to the system, output to the environment).
- Third stage. Consequences assessment and environmental impact calculation. The results of this stage allow for the comparative evaluation of different products.
- Fourth stage. Environmental impact interpretation of the distinct stages in product's life cycle, conclusions and suggestions for improvements.

While ISO methodology is still under development, the SETAC approach is widely accepted among LCA practitioners (Azapagic, 1999). In this paper, the "Eco-Indicator '99" methodology and the relevant database, covering a variety of manufacturing procedures and impacts, is adopted.

The Eco-Indicator of a material or process is a number, indicating the environmental impact of the material or process, based on data from a life cycle assessment. The standard "Eco-Indicator '99" values, termed Eco-Indicator points (Pt), are dimensionless figures, representing the 1/1000 of the annual environmental load of an average European inhabitant (Goedkoop *et al*., 2000). The "Eco-Indicator '99" methodology, used for the calculation of these standard values, conforms well to ISO-14042, although some deviations in details exist. The "Eco-Indicator '99" database provides standard values for (Goedkoop *et al*., 2000):

- Materials. Indicators for the production of materials needed for the final product. They include all the processes from the extraction of the raw material up to the last production stage. Transport processes along this path are also included. They are expressed in Pt/kg of material.
- Production. Indicators for the production processes during manufacturing as well as for the production of the energy needed. They are expressed in appropriate units (e.g. Pt/m^2 of rolled steel, Pt/kg of extruded plastic etc.).
- Transportation. Indicators of the final product transportation from the manufacturing to the installation site. They include the emissions from the extraction and production of fuel up to the final usage of fuel on the vehicle. They are usually expressed in Pt/km-tonne, assuming an average loading factor of the vehicle and possibly an empty return trip.
- Energy generation. The indicators account for the power plant fuel extraction and preparation, fuel utilization for the electricity generation and also electricity transportation efficiency. They are expressed in Pt/kWh.
- Final disposal. The indicators are calculated according to the material and the final disposal method (incineration, landfill, recycling etc.) and they are expressed in Pt/kg.

CASE STUDY

DSHWS are assumed to be installed in 14 major cities, distributed over the country (Figure 2). The cities for installation were selected in order to cover a broad range of climate conditions, with more than 50% of the country's population (Table 1). The majority of DSHWS are manufactured close to Athens in Central Greece and in Thessaloniki in Northern Greece. For the purposes of the study, DSHWS are assumed to be manufactured only in the Thessaloniki industrial area. The DSHWS analyzed is the flat plate collector type (Figure 3), typical for Greek climate conditions. The collector consists of copper tubes extended with copper foils and, in order to boost absorbency, sprayed with black solar powder. A layer of expanded polyurethane (30 mm average thickness) is sprayed at the back of the collector for insulation. The sides of the collector are insulated with 20 mm thickness rock wool. The back cover of the collector is galvanized steel, while the sides consist of aluminum. The front area of the collector is covered with a single solar glass. The boiler (Figure 4) consists of a stainless steel mantle heat exchanger, with stainless steel sheet casing (0,5 mm thickness). A high density expanded polyurethane layer between boiler and casing is used for thermal insulation.

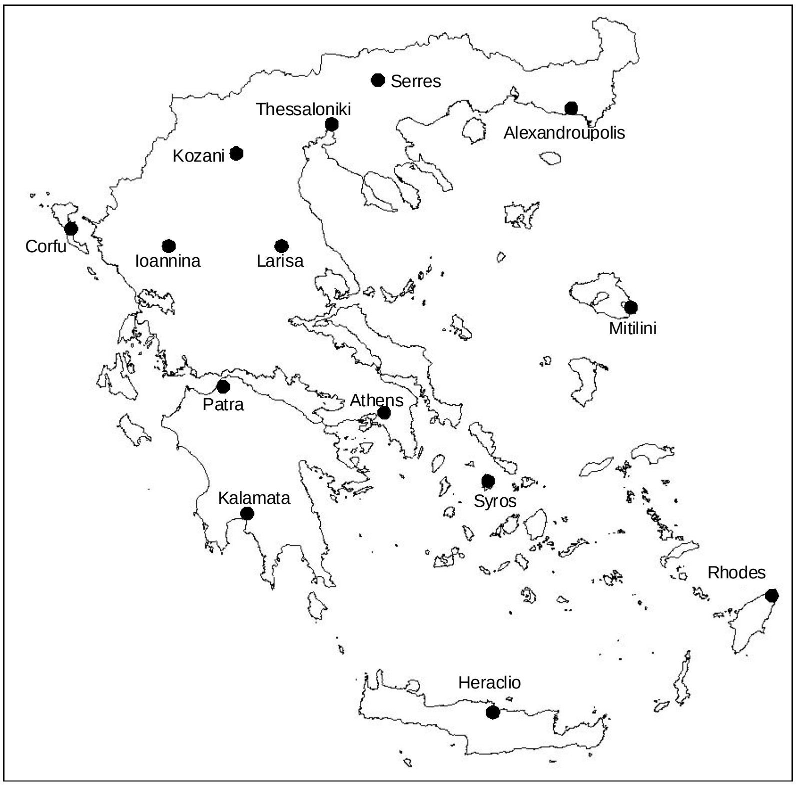

Figure 2. Location of the DSHWS installation sites

Table 1. Data for the installation locations analysed

Region	City	Co-ordinates		Altitude [m]	Population [x1000] (Census 2001)	Annual Solar Radiation, Horizontal plane [kWh/m^2,year]	Annual Average Air Temperature [^{o}C]	Annual Average Grid Water Temperature [^{o}C]
		Long.	Lat.					
Crete	Heraclio	35,33	25,14	47	137,8	1631	19,0	21,0
Dodecanese	Rhodes	36,45	28,22	35	54,8	1686	19,0	19,2
Peloponnese	Kalamata	37,04	22,11	5	56,9	1596	18,6	18,5
Cyclades	Syros	37,45	24,93	9	14,1	1621	18,5	18,8
Central Greece	Athens	37,98	23,80	107	3689,5	1581	17,8	17,8
Peloponnese	Patra	38,24	21,73	15	164,5	1479	17,8	18,5
North Aegean	Mitilini	39,11	25,55	3	35,5	1539	17,8	18,7
Ionian	Corfu	39,63	19,92	132	41,1	1493	17,7	17,1
Thessaly	Larissa	39,63	22,42	73	124,4	1433	16,2	17,0
Epirus	Ioannina	39,66	20,86	483	70,2	1357	14,7	14,2
Macedonia	Kozani	40,32	21,80	810	48,1	1361	16,1	14,7
Macedonia	Thessaloniki	40,64	22,95	30	831,7	1403	16,0	15,6
Thrace	Alexandroupolis	40,86	25,88	10	52,6	1368	16,5	15,4
Macedonia	Serres	41,10	23,55	32	56,1	1380	15,3	16,0

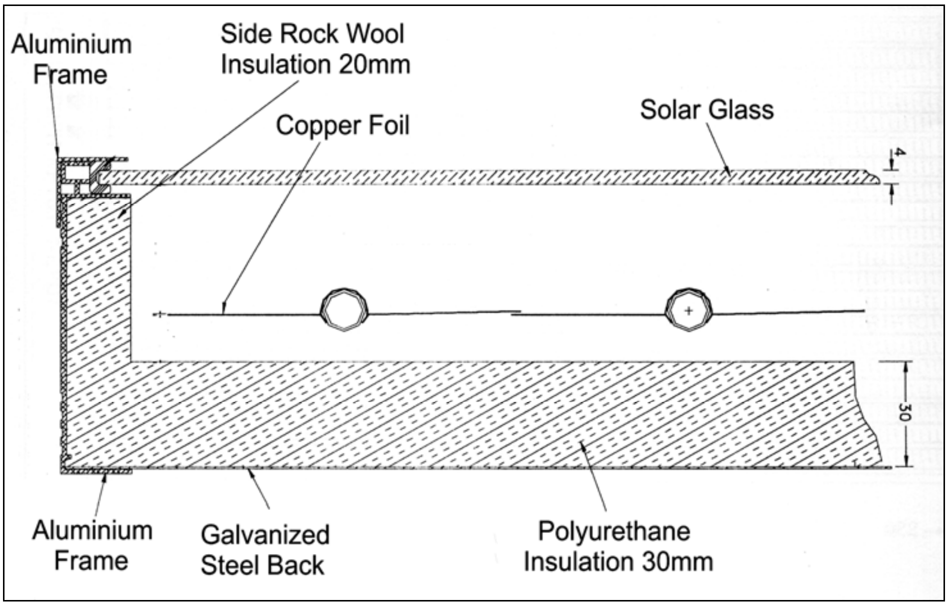

Figure 3. Cross section of the solar collector

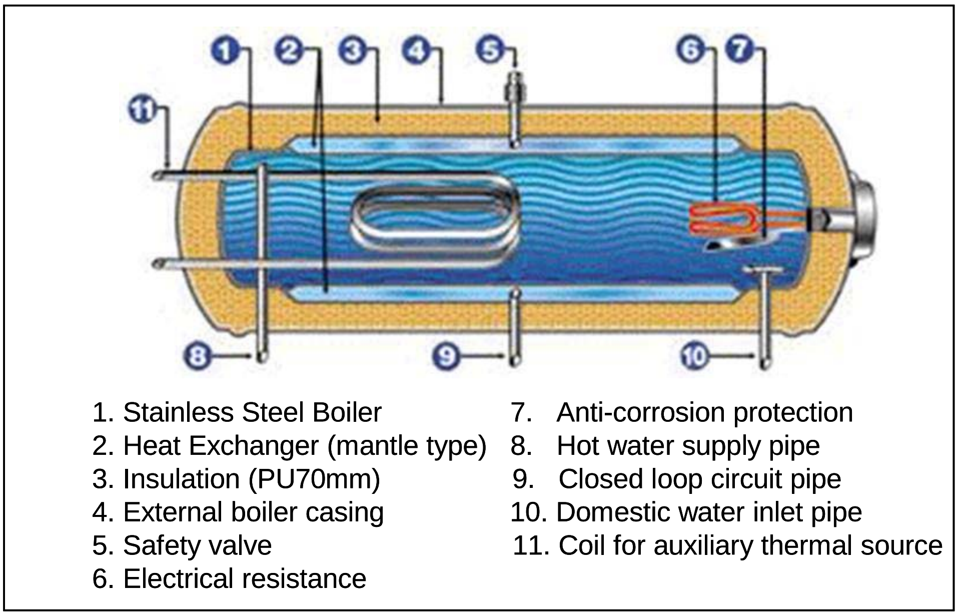

Figure 4. Cross section of the boiler

The inclination of the collector is set at 45° for all locations, well within the recommendation (latitude ± 15°) of the literature (Lunde, 1979).

The households considered are two, three, four and five person's families and the corresponding DSHWS sizes usually used are listed in Table 2, with the technical characteristics summarized in Table 3.

Normally, domestic hot water is produced by the use of electrical heaters. Consequently, and for the purposes of this analysis, it is accepted that DSHWS substitutes electricity. Since the case is only partial electricity substitution, the electrical heater is considered as already existing; therefore its manufacturing environmental impact is not accounted for.

RESULTS

LCA requires a detailed description of the materials and the procedures related to a product. Figure 5 shows a simplified LCA chart for a DSHWS. Based on the technical information of the systems analyzed, the quantities for each of the materials and procedures listed in Figure 5 can be estimated and then translated to environmental impact (Pt), with the "Eco-Indicator '99" database and methodology.

Table 2. Systems Analysed

Household Size	**DSHWS Size**					
	$2m^2$ \ 120l	$2m^2$ \ 180l	$4m^2$ \ 180l	$4m^2$ \ 200l	$6m^2$ \ 180l	$6m^2$ \ 200l
2	x	x				
3		x	x			
4			x		x	
5				x		x

Table 3. Characteristics of the analysed DSHWS

Collector Type	Flat-Plate, Copper Tube with Copper Foils
Glazing	Single Glass
Selective Paint	Black Solar Powder
$F_R U_L$	8,42 W/m^2K
$F_R(\tau\alpha)_n$	0,76
Collector Inclination	45^o
Collector Area	2 – 4 – 6 m^2
Tank Capacity	120 – 180 – 200 l
Hot Water Temperature	50 ^oC

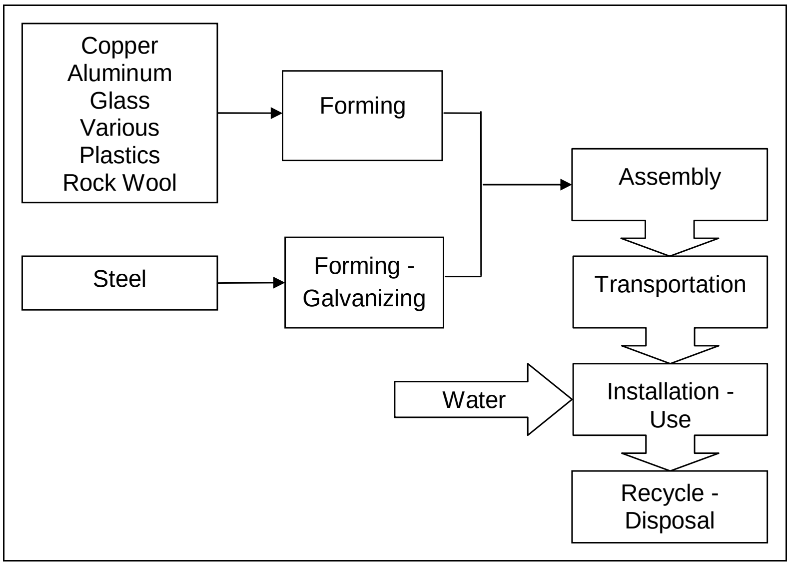

Figure 5. Simplified life cycle flow chart of a DSHWS

For the transportation of the final product it is accepted that in the case that the distance between manufacturing and installation site is less than 20 km (i.e. for installations in Thessaloniki area) a 3,5 t truck is used with an environmental impact of 140 mPt/km-tonne. For longer distances a 28t truck is used with an impact of 22 mPt/km-tonne, including return trip (average European value with 40% load). For sea transport an impact of 5,1 mPt/km-tonne is used.
The systems are assumed to be transported from Thessaloniki port to Mitilini by sea. For Corfu, the product is transported by land to the port of Igoumenitsa (opposite of Corfu) and then by ship to the island, while for Rhodes, Syros and Heraklion the systems are transported by land to Piraeus port (seaport of Athens) and then by ship to the corresponding ports (see also Figure 2).
The results of this calculation are listed in Table 4 (the figures in parenthesis are the transportation contribution, in percent). From the data in Table 4 it is clear that the environmental impact of the DSHWS varies from 74,90 to 142,27 Pt, depending on the system size and site of installation. The transportation impact depends on the distance between manufacturing and installation site and on the transportation means, but in any case it is practically

Table 4. DSHWS total environmental impact [Pt] including transportation. In parenthesis the contribution of transportation to the total impact [%]

City	DSHWS sizes					
	$2m^2$\120l	$2m^2$\ 180l	$4m^2$\ 180l	$4m^2$\ 200l	$6m^2$\ 180l	$6m^2$\ 200l
Heraclio	76,31 (2,17)	87,34 (2,10)	111,44 (2,35)	116,60 (2,31)	136,50 (2,51)	141,66 (2,47)
Rhodes	76,40 (2,28)	87,44 (2,21)	111,58 (2,47)	116,75 (2,43)	136,69 (2,64)	141,85 (2,60)
Kalamata	76,60 (2,53)	87,66 (2,45)	111,90 (2,74)	117,07 (2,70)	137,10 (2,93)	142,27 (2,89)
Syros	76,28 (2,13)	87,30 (2,06)	111,39 (2,30)	116,55 (2,16)	136,43 (2,46)	141,59 (2,42)
Athens	76,08 (1,87)	87,08 (1,81)	111,07 (2,02)	116,22 (1,99)	136,02 (2,16)	141,16 (2,13)
Patra	76,01 (1,77)	87,00 (1,72)	110,96 (1,92)	116,10 (1,89)	135,87 (2,05)	141,01 (2,02)
Mitilini	75,27 (0,81)	86,18 (0,78)	109,79 (0,88)	114,90 (0,86)	134,34 (0,94)	139,45 (0,92)
Corfu	75,72 (1,39)	86,67 (1,35)	110,50 (1,51)	115,63 (1,48)	135,26 (1,61)	140,39 (1,59)
Larisa	75,09 (0,57)	85,97 (0,55)	109,50 (0,61)	114,60 (0,60)	133,96 (0,66)	139,06 (0,65)
Ioannina	75,42 (1,01)	86,35 (0,98)	110,04 (1,10)	115,15 (1,08)	134,66 (1,17)	139,78 (1,16)
Kozani	75,01 (0,46)	85,89 (0,45)	109,38 (0,50)	114,47 (0,49)	133,80 (0,54)	138,89 (0,53)
Thessaloniki	75,01 (0,47)	85,89 (0,45)	109,38 (0,51)	114,48 (0,50)	133,81 (0,54)	138,90 (0,53)
Alexandroupolis	75,59 (1,23)	86,53 (1,19)	110,30 (1,33)	115,42 (1,31)	135,00 (1,42)	140,13 (1,40)
Serres	74,90 (0,32)	85,77 (0,31)	109,21 (0,35)	114,30 (0,34)	133,58 (0,37)	138,67 (0,37)

Table 5. Annual Solar Coverage (*f*) for each location, family size and DSHWS

City	2 persons		3 persons		4 persons		5 persons	
	$2m^2$\ 120l	$2m^2$\ 180l	$2m^2$\ 180l	$4m^2$\ 180l	$4m^2$\ 180l	$6m^2$\ 180l	$4m^2$\ 200l	$6m^2$\ 200l
Heraclio	0,690	0,717	0,581	0,792	0,717	0,819	0,651	0,772
Rhodes	0,720	0,745	0,602	0,821	0,745	0,847	0,676	0,801
Kalamata	0,680	0,708	0,562	0,792	0,708	0,821	0,635	0,770
Syros	0,666	0,693	0,549	0,777	0,693	0,806	0,621	0,755
Athens	0,660	0,686	0,545	0,770	0,686	0,799	0,616	0,748
Patra	0,624	0,651	0,512	0,739	0,651	0,769	0,582	0,716
Mitilini	0,641	0,669	0,532	0,747	0,669	0,775	0,601	0,727
Corfu	0,622	0,649	0,509	0,735	0,649	0,765	0,578	0,713
Larisa	0,581	0,608	0,474	0,695	0,608	0,726	0,541	0,672
Ioannina	0,513	0,540	0,413	0,629	0,540	0,662	0,475	0,604
Kozani	0,532	0,559	0,427	0,651	0,559	0,686	0,491	0,625
Thessaloniki	0,563	0,590	0,456	0,679	0,590	0,712	0,521	0,655
Alexandroupoli	0,541	0,568	0,436	0,659	0,568	0,693	0,500	0,634
Serres	0,539	0,566	0,436	0,654	0,566	0,687	0,500	0,630

negligible, as it is always below 3% of the total. The contribution of individual components of the DSHWS to its total environmental impact has been analysed and presented in previous work (Tsilingiridis *et al.*, 2004). In case that the manufacturing site of the DSHWS was in Athens, the transportation impact would be lower for the southern and island installation sites, and higher for the cities of Northern Greece. In all cases the impact remains practically negligible, less than 3,5% of the total.Using the f-chart method makes it possible to calculate the annual percentage of solar coverage of load for domestic hot water production (Duffie and Beckman, 1991). The required data (air temperatures, grid water temperatures and solar radiation) are taken from the literature (Pelekanos, 1982). The monthly variation of solar radiation for the cities in study on 45° plane is shown in Figure 6. Solar coverage results are listed in Table 5. As it can be seen, for the same location and collector area, increasing the tank size from 120 to 180 l, i.e. by 50%, results only in a slightly increase of coverage, 3,5 to 5%, depending on the location. With the same tank size, doubling the collector area from 2 to 4 m², results in an average coverage increase of 45%, while this increase is reduced to 21% when the collector area is increased by 50%, from 4 to 6 m^2. The influence of location and collector size is more apparent in Figure 7, where the maximum and minimum coverage are plotted as a function of the solar radiation. The data of Table 5 translated to annual energy values are listed in Table 6 and the environmental cost, calculated as the ratio of the environmental impact over the total energy covered by the DSHWS, is listed in Table 7. Even though the environmental impact increases with the size of the DSHWS, for the same location and household size, the environmental cost decreases with the size of the collector, due to the resulting increased solar coverage.

As already mentioned, hot water is normally produced with electrical heaters. DSHWS undertakes a part of this duty, as listed in Table 6. Assuming an overall efficiency of 95% for the electrical heater and using the "Eco-Indicator '99" standard value for electricity (61 mPt/kWh), the total environmental impact for the 15 years hot water production can be calculated from the data of Table 6 for the electrical only and for the combined DSHWS plus electrical heater systems, taking into account the DSHWS production impacts, the results listed in Table 8.

Figure 8 shows the overall environmental impact of the hot water production with electrical heater for the 15 years period and the net environmental gain achievable with the combined electrical heater plus DSHWS, expressed as percentage. The lower gain, for the systems we have analysed, results for 2 persons household and it is roughly 50% for the cities of Ioannina, Kozani and Serres, all of them in the northern part of the

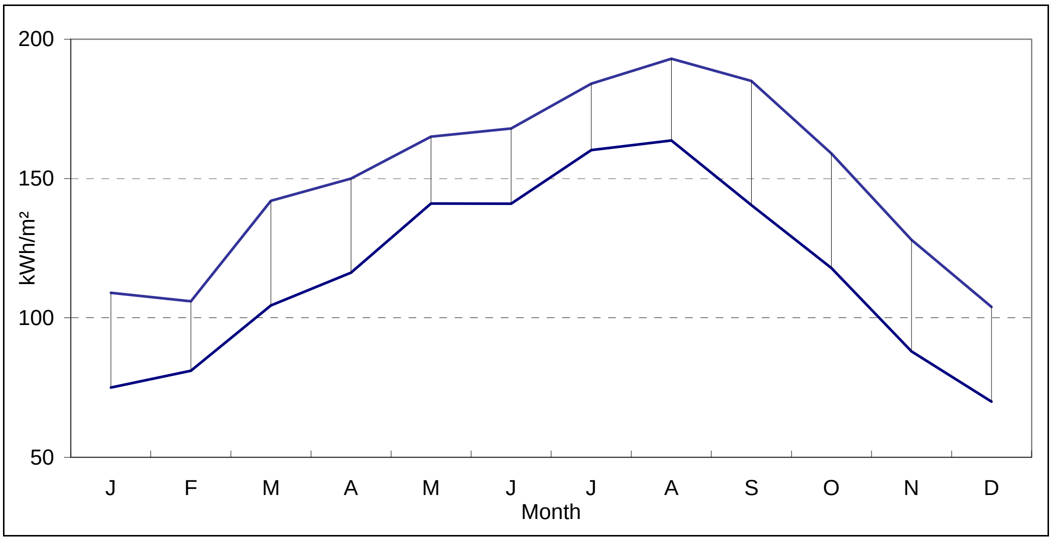

Figure 6. Solar radiation on a 45^o plane. Range for all cities under consideration

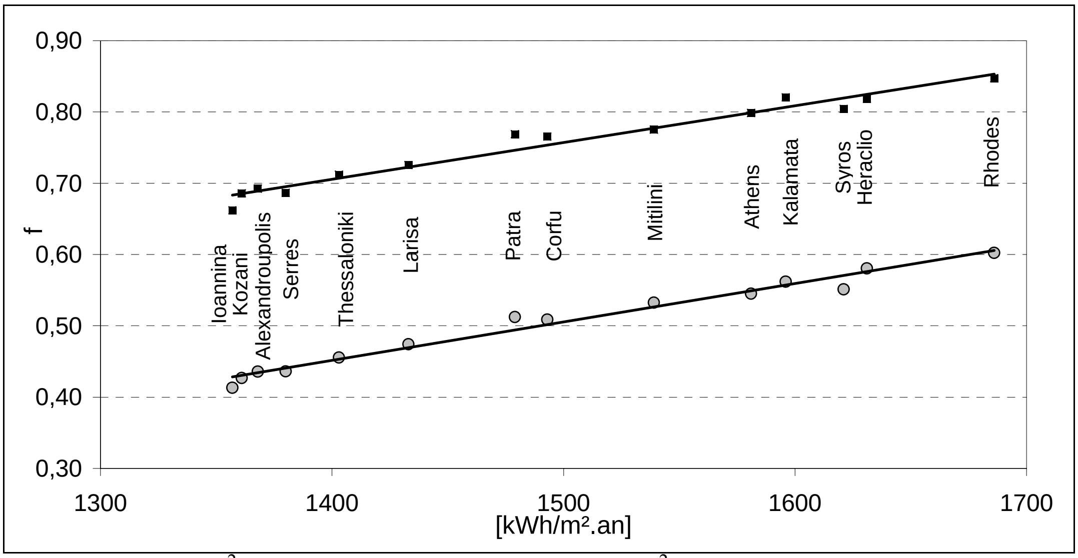

Figure 7. Maximum (6m^2/180l, 4 persons) and minimum (2m^2/180l, 3 persons) annual solar coverage in correlation with solar radiation

Table 6. Total and Covered thermal load for each location, family size and DSHWS [kWh/year]

City	2 persons			3 persons			4 persons			5 persons		
	Total	Covered Load		Total	Covered Load		Total	Covered Load		Total	Covered Load	
	Load	$2m^2$ \ 120l	$2m^2$ \ 180l	Load	$2m^2$ \ 180l	$4m^2$ \ 180l	Load	$4m^2$ \ 180l	$6m^2$ \ 180l	Load	$4m^2$ \ 200l	$6m^2$ \ 200l
Heraclio	1229	848	881	1844	1070	1461	2458	1762	2013	3073	2001	2374
Rhodes	1304	939	971	1956	1178	1607	2608	1942	2210	3260	2205	2612
Kalamata	1332	906	943	1998	1123	1583	2664	1885	2186	3330	2114	2566
Syros	1322	881	916	1983	1093	1539	2645	1833	2127	3306	2059	2493
Athens	1363	899	935	2044	1114	1574	2725	1871	2176	3406	2099	2548
Patra	1332	831	868	1998	1023	1476	2664	1735	2048	3330	1937	2385
Mitilini	1325	850	886	1988	1058	1486	2651	1773	2055	3313	1993	2408
Corfu	1391	865	903	2087	1061	1535	2783	1806	2130	3479	2011	2480
Larisa	1399	813	851	2098	995	1458	2798	1702	2030	3497	1891	2351
Ioannina	1517	779	819	2276	940	1431	3035	1638	2010	3794	1802	2292
Kozani	1496	796	836	2243	958	1461	2991	1671	2052	3739	1835	2338
Thessaloniki	1455	819	858	2182	994	1482	2909	1715	2072	3637	1896	2383
Alexandroupolis	1463	792	831	2195	957	1446	2927	1662	2027	3658	1830	2319
Serres	1441	776	815	2162	943	1414	2883	1631	1979	3603	1801	2270

Table 7. Environmental Cost of Solar kWh for each location, family size and DSHWS [mPt/kWh_{sol} for 15 years]

Cities	2 persons		3 persons		4 persons		5 persons	
	$2m^2$ \ 120l	$2m^2$ \ 180l	$2m^2$ \ 180l	$4m^2$ \ 180l	$4m^2$ \ 180l	$6m^2$ \ 180l	$4m^2$ \ 200l	$6m^2$ \ 200l
Heraclio	6,00	6,61	5,44	5,09	4,22	4,52	3,89	3,98
Rhodes	5,43	6,00	4,95	4,63	3,83	4,12	3,53	3,62
Kalamata	5,64	6,20	5,20	4,71	3,96	4,18	3,69	3,70
Syros	5,77	6,35	5,32	4,83	4,05	4,28	3,77	3,79
Athens	5,64	6,21	5,21	4,71	3,96	4,17	3,69	3,69
Patra	6,10	6,68	5,67	5,01	4,26	4,42	4,00	3,94
Mitilini	5,90	6,48	5,43	4,93	4,13	4,36	3,84	3,86
Corfu	5,84	6,40	5,44	4,80	4,08	4,23	3,83	3,77
Larisa	6,16	6,73	5,76	5,01	4,29	4,40	4,04	3,94
Ioannina	6,45	7,03	6,12	5,13	4,48	4,47	4,26	4,07
Kozani	6,28	6,85	5,98	4,99	4,36	4,35	4,16	3,96
Thessaloniki	6,11	6,68	5,76	4,92	4,25	4,31	4,02	3,89
Alexandroupolis	6,09	6,66	5,71	4,97	4,25	4,36	4,01	3,92
Serres	6,43	7,01	6,07	5,15	4,47	4,50	4,23	4,07

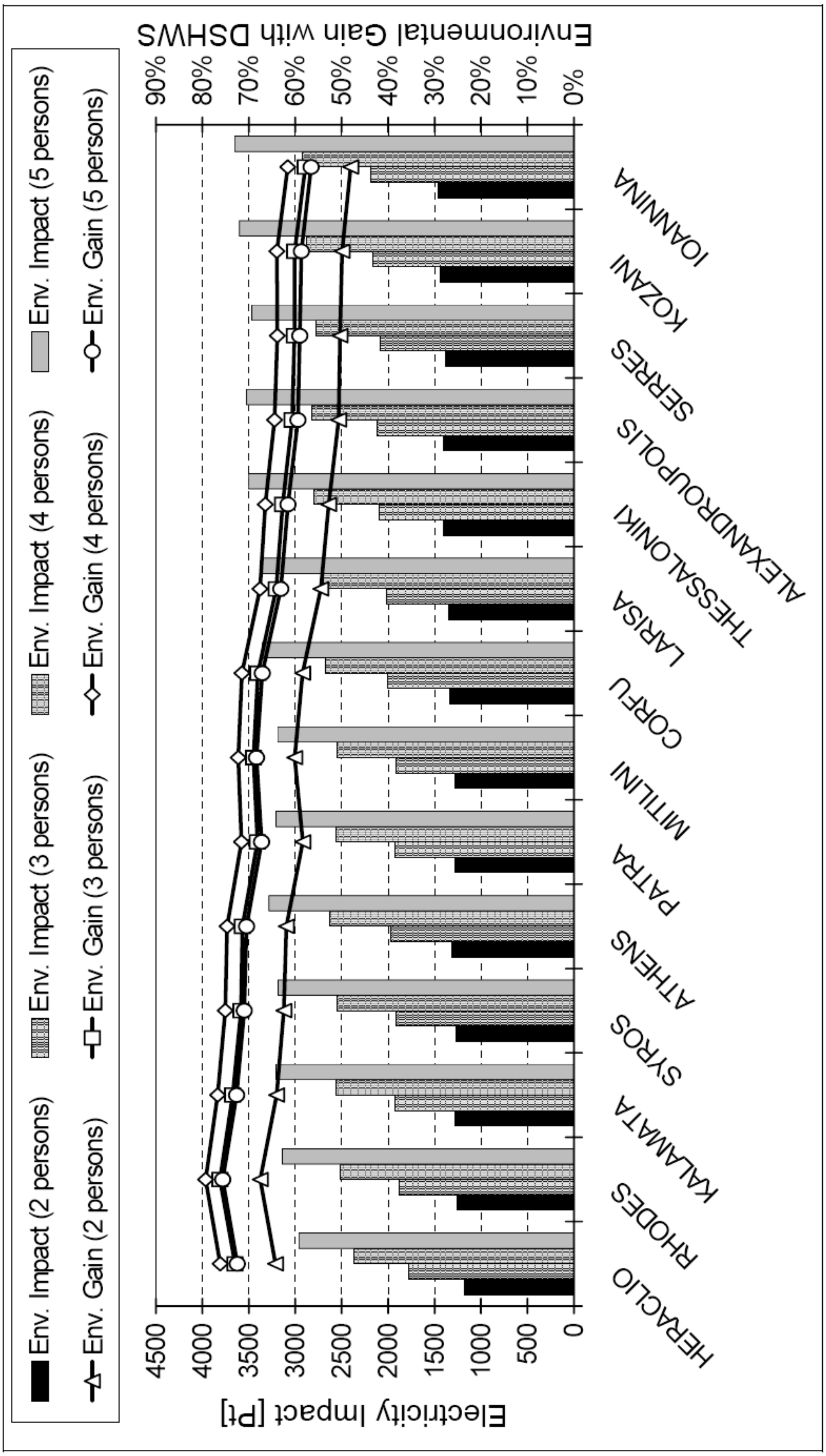

Figure 8. Environmental Impact of total thermal load covered by electricity and environmental gain in case of DSHWS use, for the cities and household sizes selected

Table 8. Environmental impact of total thermal load if covered a) by electricity and b) by the combination of DSHWS and auxiliary electricity for each location, family size and DSHWS size [Pt for 15 years]

City	2 persons			3 persons			4 persons			5 persons		
	Electricity Impact	DSHWS + Aux. Electricity Impact		Electricity Impact	DSHWS + Aux. Electricity Impact		Electricity Impact	DSHWS + Aux. Electricity Impact		Electricity Impact	DSHWS + Aux. Electricity Impact	
		$2m^2$ \ 120l	$2m^2$ \ 180l		$2m^2$ \ 180l	$4m^2$ \ 180l		$4m^2$ \ 180l	$6m^2$ \ 180l		$4m^2$ \ 200l	$6m^2$ \ 200l
Heraclio	1184	443	423	1776	833	480	2367	782	565	2960	1149	815
Rhodes	1256	428	408	1884	837	448	2512	753	520	3140	1133	766
Kalamata	1283	487	462	1924	930	512	2566	862	597	3207	1288	878
Syros	1273	501	478	1910	945	541	2548	893	635	3184	1318	925
Athens	1313	523	499	1969	983	564	2625	934	665	3281	1375	968
Patra	1283	559	534	1924	1026	614	2566	1006	729	3207	1458	1051
Mitilini	1276	533	509	1915	982	593	2553	955	708	3191	1386	1011
Corfu	1340	582	557	2010	1075	642	2680	1052	764	3351	1530	1103
Larisa	1347	640	614	2021	1148	726	2695	1165	874	3368	1661	1243
Ioannina	1461	786	759	2192	1373	924	2923	1456	1122	3654	2034	1586
Kozani	1441	749	722	2160	1324	863	2881	1381	1038	3601	1948	1488
Thessaloniki	1401	688	661	2102	1230	784	2802	1259	940	3503	1791	1347
Alexandroupolis	1409	722	695	2114	1279	832	2819	1329	1002	3523	1876	1430
Serres	1388	715	689	2082	1260	830	2777	1315	1004	3470	1850	1423

country, with the lowest solar radiation and ambient temperature.

The highest gain results for the 4 persons household and for the installation sites with the highest solar radiation and temperatures, as expected. It is roughly 80%, remaining however above 60% for the lower radiation sites as well. It is worth noticing at this point that the "Eco-Indicator '99" standard value for electricity production used in this paper is the country's average, including both lignite and diesel oil power plants. Mainland cities are connected to the national power supply network, operating mainly on lignite, while in the islands electricity is locally produced in diesel oil plants. This means that the electricity consumption in mainland has more severe environmental impacts than in islands, and a more detailed calculation can reveal the difference, making DSHWS even more environmental friendly in mainland.

CONCLUSIONS

The lifecycle environmental impact of a DSHWS is between 75 and 142 Pt, depending on the system size and the distance and means of transport between manufacturing and installation sites. However transportation impact was found not to exceed 3% of the total in all cases and it can therefore be considered insignificant.

The environmental impact increases with the size of the DSHWS, for the same location and household size, but the environmental cost (ratio of the environmental impact from the DSHWS over the total energy covered by its use) decreases with the size of the collector, due to the resulting increased solar coverage.

The efficiency of solar systems, and the relevant environmental gain, depends not only on the geographical position and the solar radiation of the installation site but also on other parameters, like ambient air and grid water temperatures.

The production and utilization of a DSHWS has a net environmental gain over electricity of at least 670 Pt and up to 2145 Pt (50 to 80% respectively). These figures do not include the impact from the production of the electrical heaters, since their installation cannot be avoided. Even in the worst case examined (2 persons household in the less favourable for solar applications site in northern Greece) the overall net environmental gain resulting from the utilization of DSHWS is at least 50%, proving that solar energy is a truly clean form of energy. Boustead, 1972; Hannon, 1972; Sundstrom, 1973.

REFERENCES

Azapagic A. (1999), Life Cycle Assessment and its application to process selection, design and optimization, *Chemical Engineering Journal*, **73**, 1-21.

Boustead I. (1972), The Milk Bottle, Open University Press, Milton Keynes.

Boustead I. (1989), Environmental Impact of the Major Beverage Packaging Systems – U.K. data 1986 in response to the EEC directive 85/339, INCPEN, London, 1-4.

Duffie J.A. and Beckman W.A. (1991), Solar Engineering of Thermal Processes, Wiley Publication.

European Commission (1997), White Paper: Energy for the future: Renewable sources of energy.

European Commission (1999), Green Paper: Towards a European strategy for the security of energy supply.

European Solar Thermal Industry Federation (2003), Sun in Action II, Vol.2.

Goedkoop M., Effting S. and Collingo M. (2000), The Eco-Indicator'99 – A damage oriented method for Life Cycle Impact Assessment – Manual for Designers, Pre Consultants B.V., Second Edition.

Hannon B. (1972), System Energy and Recycling: A Study of the Beverage Industry, Center for Advanced Computation, University of Illinois, Urbana, IL.

ISO/DIS 14040 (1997), Environmental Management - Life Cycle Assessment-Part 1: Principles and Framework.

Lunde P. J. (1979), Solar Energy, pp 23-115.

Lundolm M.P. and Sundstrom G. (1985), Resource and Environmental Impact of Tetra Brik Carton and Refillable and Non-Refillabel Glass Bottles, AB Tetra Pak, Malmo.

Pelekanos A. (1982), Meteorological Data for implementation of solar applications in various cities in Greece, Proceeding of 1st National Conference for the Renewable Energy Sources, Volume A', Institute of Solar Technology, Thessaloniki. (In Greek).

Sundstrom G. (1973), Investigation of the energy requirements from raw materials to garbage treatment for 4 Swedish Beer Packaging Alternatives, Report for Rigello Park AB, Sweden.

Tsilingiridis G., Martinopoulos G. and Kyriakis N. (2004), Environmental impact of a domestic solar flat-plate thermosyphonic system during its life cycle in comparison with conventional energy forms, *Renewable Energy*, **29**, pp 1277-1288.