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SOLAR POTENTIAL FOR WATER HEATING EXPLORED BY GIS

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Abstract—A method is presented for the estimation of solar energy and market potential for water heating in the residential sector. The model was developed under a Geographical Information System and provides the tools to handle the spatial and time discrepancies of solar radiation and energy demand. A geographic database with climatic data is used for estimating efficiencies and monthly/annual coverage of water heating load. Financial analysis is conducted on the basis of the energy production cost and the Net Present Value of the investment. Different financial scenarios are considered and the expected energy yields from a large-scale deployment of solar thermal systems in the residential sector of Greece are assessed. © 1998 Elsevier Science Ltd. All rights reserved.

1. INTRODUCTION

The estimation of solar potential and the evaluation of energy demand for specific end-use activities are the basic steps to determine the best policies which can facilitate the large-scale deployment of a wide array of solar energy applications.

Solar radiation is highly dependent on site location and regional climatological conditions. The mathematical framework for calculating hourly, daily and monthly average solar radiation as well as the basic design principles for solar collectors and energy conversion technologies are presented by Magal (1990), Duffie and Beckman (1980) and Kreider (1979). Recent research efforts that focus on methods which model and estimate spatial and temporal distribution of solar radiation can be found in Barr *et al.* (1996), Islam and Exell (1996), Skarveit *et al.* (1996), Olseth *et al.* (1995) and Lalas *et al.* (1982). Research on system design and models assessing the performance of specific solar systems are presented, among others, by Panteliou *et al.* (1996), Ghaddar *et al.* (1997), Tsilingiris (1996) and Michaelides and Wilson (1997).

The relation of specific geographical characteristics, technological and financial factors to local energy market potential, however, has not yet been addressed. The potential contribution of solar energy to the energy demand of specific end-use activities and the potential market for solar applications have to be analysed and the expected profits from a large-scale deployment of solar energy systems have to be identified. In this task, Geographic Information Systems (GIS) technology is a new promising approach which can reveal the spatial and time discrepancies of solar potential and energy demand.

Solar Domestic Hot Water Systems (SDHWS) is the most simple and well developed solar energy application. A large potential market exists, since, even in regions with favourable sunshine conditions the penetration of SDHWS is rather limited (EUREC Agency, 1996). In the present work, the matching of water heating energy demand to solar potential is investigated within a GIS environment. Well known methods are integrated into a consistent GIS model: the estimation of the water heating energy demand is based on demographic data attributed to geographic regions; the calculation of the regional solar radiation is based on the methods presented by Magal (1990) and Duffie and Beckman (1980) and makes use of interpolated meteorological data following the techniques presented by Barr *et al.* (1996); the assessment of the expected energy savings from the integration of SDHWS into the regional market is estimated by the f-chart method and demographic data. Finally, the expected financial profits are estimated on the basis of common economic indices. Results from a large-scale deployment of SDHWS in the domestic sector in Greece are presented as a case study.

In Section 2 the GIS approach of determining solar potential is presented, in Section 3 the obtained results are given, and in Section 4 discussion of results and methodology is presented.

2. METHODOLOGY

GIS environments handle geographical entities, attributes defining their characteristics and methods determining their behaviour and interaction. All possible geographical entities can be modelled within a GIS environment as point, line or polygon objects. Built-in attributes and methods are used to create, store and retrieve geographic objects. Attributes are stored in the form of database records and are referenced to the corresponding geographical objects. Methods can be categorised to those that handle geographic operations and set a minimum connectivity between different sets of objects and those that handle database calculations and expand the interactions of objects. The user has the flexibility to create different sets of objects defined on the basis of common characteristics and models for extensive calculations using the built-in framework of object behaviours.

The model for the estimation of solar energy potential and energy demand for water heating is built in a GIS environment with the objective to exploit its powerful features in handling all the parameters with geographic variability that influence solar radiation (latitude, sunshine duration, clearness index) and energy demand (population, number of households). An additional objective is to reveal the spatial interrelations between solar radiation availability and the expected energy savings achieved from a large-scale implementation of SDHWS. The GIS that has been used is MAPINFO Professional for Windows.

The model structure for the estimation of solar potential for water heating is presented in Fig. 1. The evaluation procedure consists of three steps: the estimation of solar radiation, the estimation of energy demand for water heating, and the financial analysis. The appropriate database structure has been dictated by the inputs needed by the models and the obtained results at each step of the methodology. In the following paragraphs, the calculations in each step of the evaluation procedure are outlined and the geographic objects, attributes and methods used are described.

2.1. *Estimation of solar radiation*

Among the most important factors influencing the solar radiation reaching a horizontal or tilted surface in a region is the latitude and the sunshine duration. Solar radiation on horizontal or tilted surfaces is evaluated by the calculated solar radiation at the top of the atmosphere and estimations of the clearness index from sunshine measurements for each residential area. The inputs and results of this step are formed as attributes of geographical objects (points) corresponding to residential areas. GIS provides the built-in method to estimate the latitude of each residential area while additional methods have been developed for the estimation of the sunshine duration. The methods that handle the calculations in this step make use of the attributes of the residential areas' objects. Screening effects from the surrounding horizon have not been introduced for the estimation of total radiation reaching a tilted surface because topography effects (i.e. mountains, hills, large obstacles blocking the sun) become substantial on latitudes more than 60° and because other effects (e.g. trees or buildings near the collector, roof orientation) would be useful in a roof-by-roof analysis which is not pursued in the present work. Methods to introduce such effects on solar radiation estimations can be found elsewhere (Olseth *et al.*, 1995).

Reliable long-term sunshine measurements are sparse and available only for regions where meteorological stations are operating. In the regions where there are no data available the sunshine duration has been estimated using a simple weighted interpolation method (inverse squared distance) of measured values from meteorological stations with similar climatological conditions, as suggested by Barr *et al.* (1996). The ratio of sunshine duration to the maximum sunshine duration for each residential area was used to obtain the clearness index for the area. The clearness index, defined as the proportion of the radiation at the top of the atmosphere which reaches the surface of the earth, was then used to estimate the average monthly radiation on horizontal and tilted surfaces. Additional attributes for the residential areas' objects have been used to host the estimated values of clearness index and average monthly solar radiation and the methods to calculate the solar radiation have been developed in the GIS environment.

The meteorological stations used for the estimation of clearness index are selected on the basis of similar climatological conditions. A digital map is developed, setting the boundaries of regions of the same sunshine conditions. The regions are a subclass of polygon objects with boundaries defined by the large mountain chains (considered to have a significant impact on the

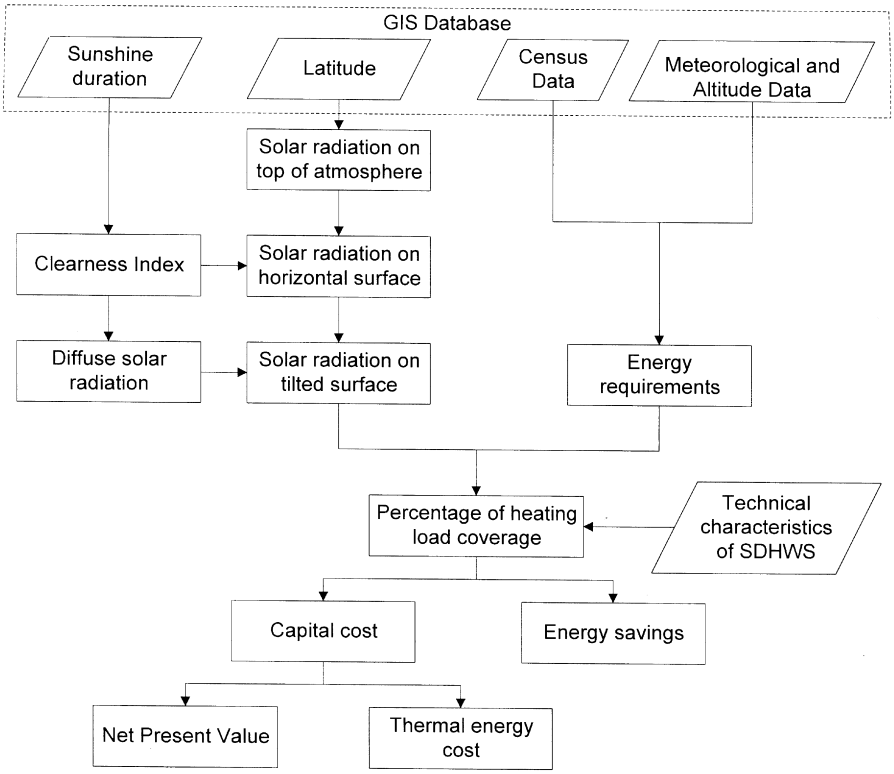

Fig. 1. Flowchart for the evaluation of the solar potential for water heating in the domestic sector.

cloudiness of surrounding regions). The meteorological stations are a subclass of point objects and their attributes contain the measured values for sunshine duration. For each residential area within a region, the clearness index is estimated using data from the meteorological stations sited in the same region. The identification of the residential areas and meteorological stations within the same region and the calculation of the distance between meteorological stations and residential areas is performed by geographic operations that provide the relative geographical location of point and region objects. The methods for the implementation of the inverse square distance interpolation of sunshine duration measurements and the estimation of the clearness index have been added to the residential areas' objects.

2.2. *Energy demand for water heating*

All households residing in one and two-storey buildings are considered as potential users of solar thermal systems for hot water production. The solar radiation that can be harvested is restricted by space or market availability (area available on the roofs of buildings and number of households which have already installed SDHWS).

The average monthly energy needs for water heating of a household (Appendix, eqn (1)) are estimated taking into account the distribution of household size (number of household members) and the assumption that energy needs for water heating are proportional to the household members. The monthly energy demand is a function of the temperature in the water distribution networks. The results are stored in a database which is attached to the geographical objects corresponding to the residential areas.

The monthly average percentage of energy needs for water heating covered by the solar system is calculated by the f-chart method (Beckman *et al.*, 1977). Inputs for the f-chart method are the average monthly solar radiation on a tilted surface, the monthly energy needs for water heating, the technical characteristics of the solar thermal system and the average monthly ambient temperature. The f-chart method calculation is performed on the attributes of the residential areas' objects and identifies the spatial interrelation of energy demand and solar energy potential. The dependence of energy needs covered by a SDHWS on ambient temperature is addressed taking also into account the dependence of ambient temperature on altitude. It is assumed that the ambient temperature decreases with the altitude at a rate of 1°C/103 m (Seinfeld, 1986). The altitude of each residential area has been set equal to that of the nearest iso-altitude line. Monthly ambient temperature data are sparse and a weighted inverse squared distance method is used to interpolate measured values. Spatial and temporal variability of solar radiation, ambient temperature, water temperature and water heating demand for each type of households have to be introduced by the GIS in order to correctly apply the f-chart method in each residential area and type of household.

2.3. Financial analysis

The expected energy savings as well as the thermal energy production cost are calculated in the financial analysis step. The GIS is used to address the geographic allocation of consumers and energy needs in conjunction with the solar radiation variability. In addition, GIS is used to present the geographic variability of thermal energy cost which mainly depends on the energy needs covered by the SDHWS.

The expected energy savings represent the amount of thermal energy produced by electricity that can be replaced by solar energy and are estimated with the assumption that all households in one or two-storey buildings, without a SDHWS, will install a solar thermal system. The expected total energy savings depend on the geographic distribution of households in areas of different solar radiation and ambient temperature.

The annual cost of thermal energy produced by a SDHWS is estimated taking into account the amortisation of the investment cost and depends on the percentage of coverage of water heating load. The Net Present Value (NPV) for various discount rates is estimated considering that the cost of a SDHWS represents the capital cost of the investment and the amount of electricity savings represents an annual income which otherwise would be spent for the hot water production needs. In addition, sensitivity analysis for the capital cost and the efficiency of the SDHWS is conducted for a specific investment.

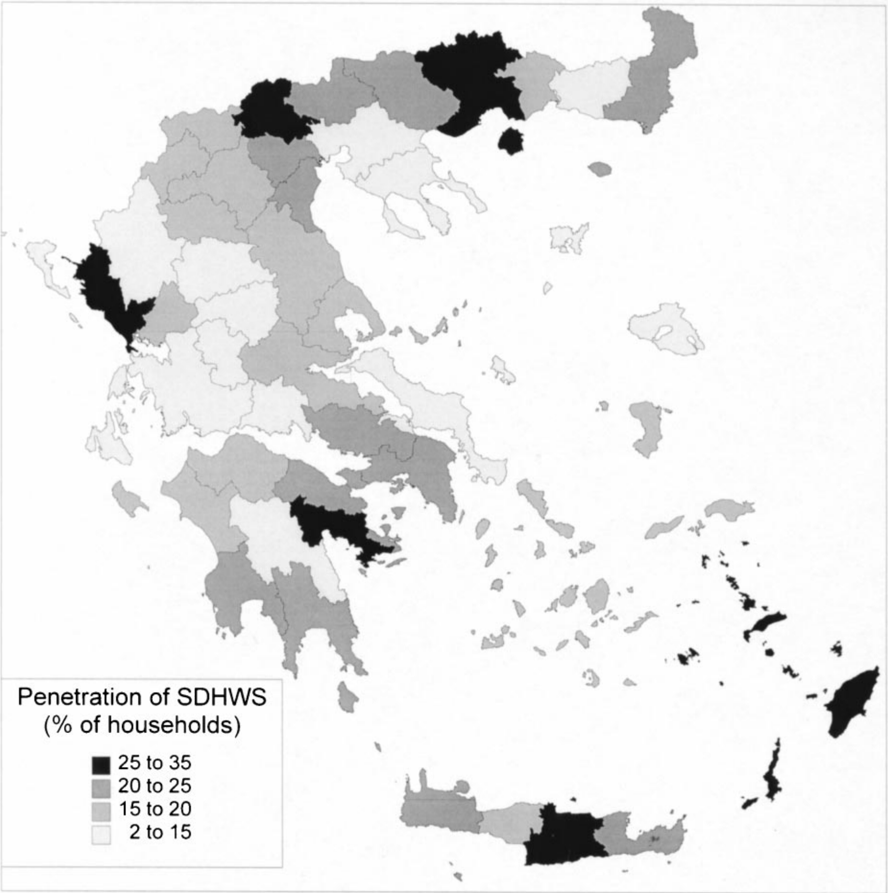

Fig. 2. Present penetration of Solar Thermal Systems for Water Heating.

3. CASE STUDY

The financial incentives for SDHWS offered in Greece during the last few decades boosted the market in the domestic sector. In 1995 the total installed collector area, in Greece, was about 2,000,000 m^2 and 95% of them are SDHWS. More than 600,000 households use a SDHWS which provides about 80% of the energy needed for hot water and thus reduces CO_2 emissions by 1,500,000 ton each year (European Commission, 1996). The level of the existing penetration is in the range of 2–30% of households and varies from region to region. This is considered very low compared to regions with similar climate (Cyprus, Israel) where a penetration of more than 90% has been realised. A wide market survey performed by the Greek Solar Industries Association has found that more than 90% of the owners of solar systems are satisfied and if they replace the old solar system they will invest in a solar system again. Fig. 2 presents the geographic distribution of the current penetration of solar thermal systems for water heating in Greece.

The developed methodology has been used for the estimation of the solar potential for water heating in the residential sector in Greece. The data used are:

A digital map with the location of residential areas and census data on the number of households and buildings up to two storeys.

A digital map of prefecture boundaries with data on the existing penetration of solar thermal systems.

A digital map of altitude lines.

Radiation measurements on horizontal surface.

A digital map of the meteorological stations' locations with measurements of sunshine duration, and ambient temperature.

Technical characteristics of typical solar thermal systems.

Monthly average water temperature in the water distribution networks.

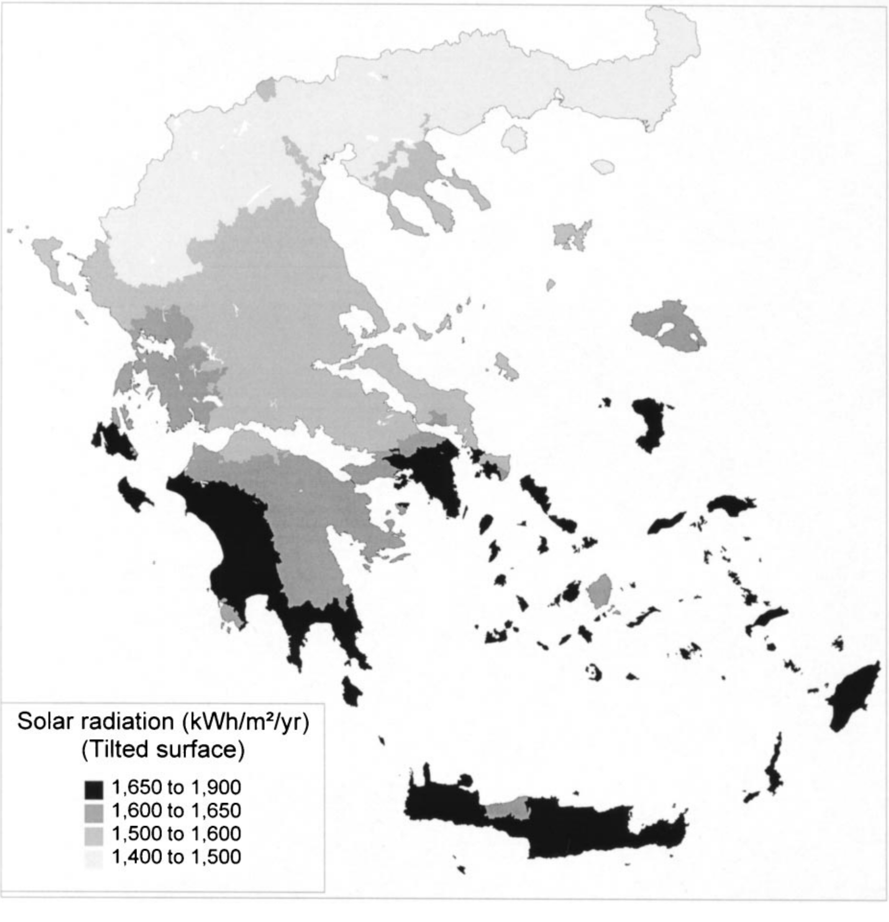

Fig. 3. Annual solar radiation on 40° tilted surface.

Table 1. Technical characteristics of a typical SDHWS using a flat collector with selective surface and one glass

$Fr \times U_L$	4.07 ($\mathrm{W\,m^{-2}\,{}^{\circ}C^{-1}}$)
$Fr \times (\tau\alpha)_n$	0.69
(Fr'/Fr)	0.95
$(\tau\alpha)/(\tau\alpha)_n$	0.94
Collector tilt	40°

The location of all the municipalities in Greece is recorded on a layer (map) and each geographic object is indexed to the database record with all data for the corresponding residential area. Solar radiation on a horizontal or tilted surface has been estimated for all residential areas of the country. Fig. 3 presents the monthly average solar radiation on a 40° tilted surface.

The monthly coverage of water heating demand of all households with 1–6 members living in one or two-storey buildings and not already possessing a SDHWS (75% of the total number of households in Greece) has been estimated. The technical characteristics of a typical flat-plate, single-glazed selective solar collector, which has been used in the present application, are presented in Table 1. The area of the collector covering the hot water needs of a family is estimated at 1 $\mathrm{m^2}$ per household member and the tank volume ranges from 75–150 l for families with 1–6 members (for the Greek climatic conditions). Fig. 4 presents the mean annual coverage of water heating load for each community in Greece.

The investment cost for a SDHWS has been estimated using a correlation derived from market prices of various systems available in Greece (Appendix, eqn (2)). The investment cost includes the collector, hot water tank and installation costs. The cost of the thermal energy produced by the SDHWS has been estimated for each city or village and each type of household considering that the lifetime of the investment is 15 years, the discount rate is 10% and the inflation rate is 8%. The total energy savings have been estimated for each city using the total number of households. Table 2 presents the energy savings by solar thermal systems for each category of households distributed accord-

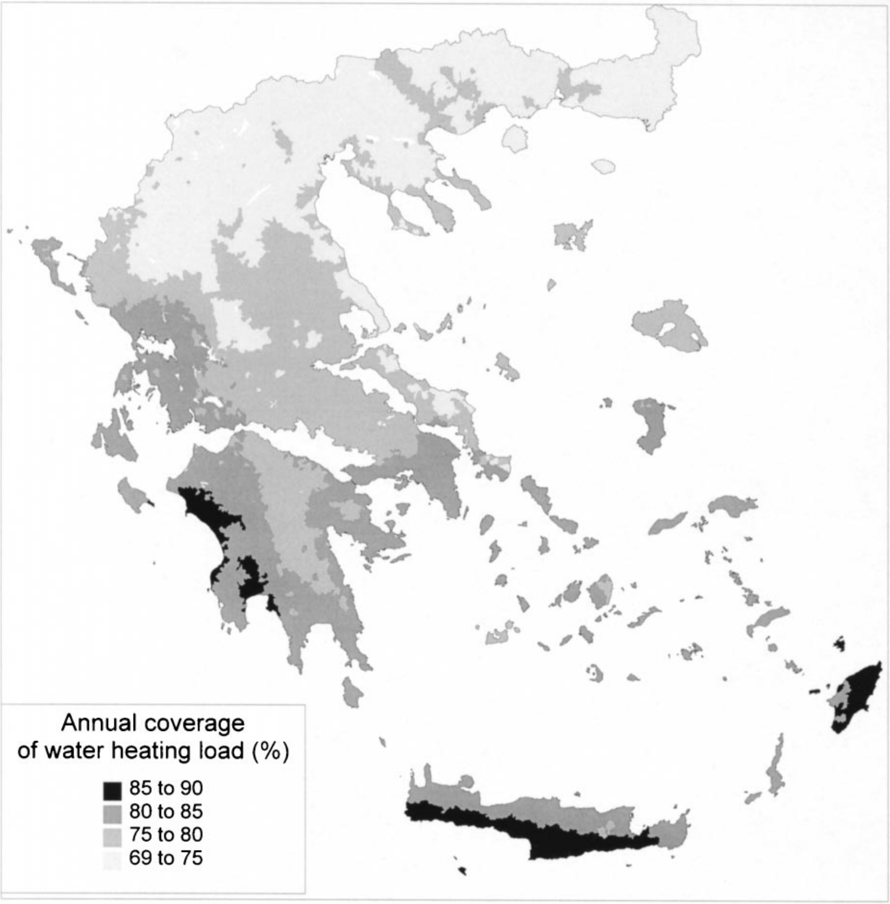

Fig. 4. Mean annual coverage of water-heated load.

Table 2. Energy savings ($GWh_{th}\ yr^{-1}$) using solar thermal systems

Energy cost ($mECU\ kW\ h^{-1}$)	Number of members per household 2	3	4	5	6	Total ($GWh_{th}\ yr^{-1}$)
36–40	0	0	0	10	117	127
40–44	0	0	7	339	152	127
44–48	0	0	668	225	16	909
48–52	0	45	461	1	0	507
52–56	0	465	64	0	0	529
56–60	0	269	0	0	0	269
60–64	27	13	0	0	0	40
64–68	346	0	0	0	0	346
68–72	110	0	0	0	0	110
72–76	193	0	0	0	0	193
76–80	12	0	0	0	0	12
Total	690	795	1204	580	291	3169

ing to the thermal energy production cost of a SDHWS. Fig. 5 presents the geographical distribution of energy cost for three-member households.

A comparison between the cost of thermal energy produced by an electrical system and a SDHWS for each category of households is summarised in Table 3. The electricity cost for individual consumers throughout Greece is $0.07\ ECU\ kW\ h^{-1}$. The cost of the thermal energy produced by an electrical system is estimated considering the amortisation of the initial investment and the energy needs for each household type.

The effect of capital cost and efficiency loss of the system on the viability of the investment

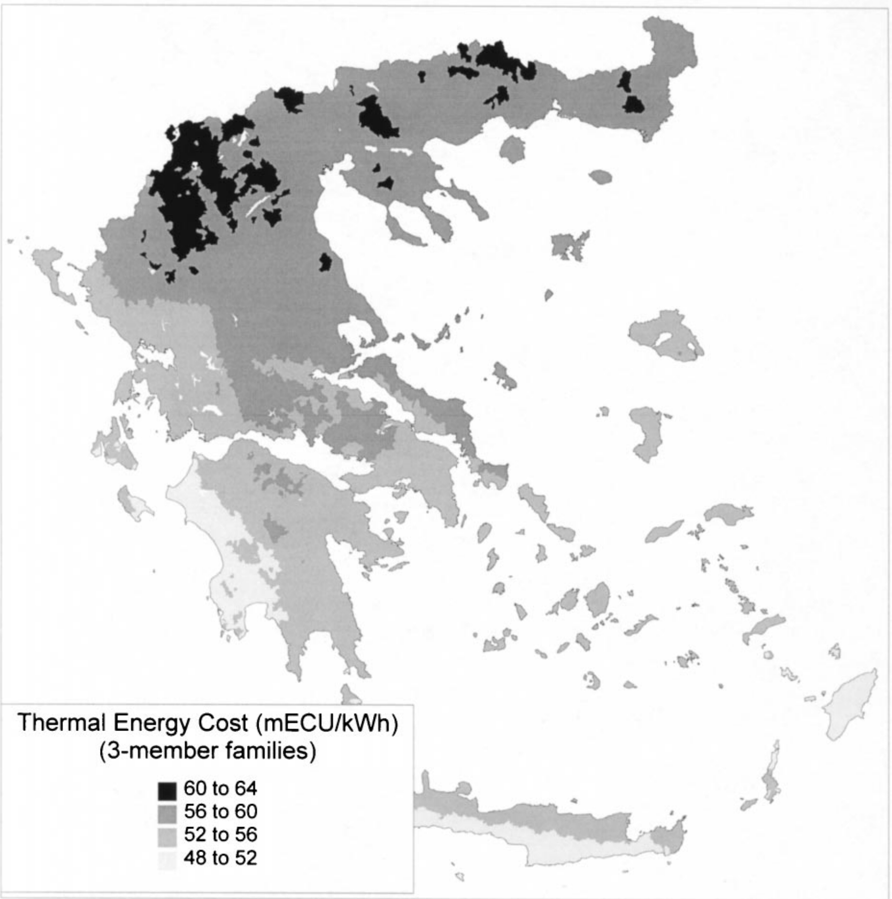

Fig. 5. Cost of thermal energy produced by SDHWS for three-member families. The electricity cost for the same case is $82.5\ mECU\ kW\ h^{-1}$.

Table 3. Cost of thermal energy produced by electricity and solar domestic hot water systems (mECU kW h_{th}^{-1})

Members per family	Thermal energy cost with electricity	Thermal energy cost with SDHWS
2	85.3	60–80
3	82.5	48–64
4	81.1	40–56
5	80.2	36–52
6	79.7	36–48

is demonstrated by the sensitivity analysis for those parameters. Fig. 6 presents the sensitivity analysis for the capital cost for a specific SDHWS investment for a four-member family in Athens. It is assumed that the capital cost is reduced by 10 and 20%. Fig. 7 presents the sensitivity analysis for the efficiency of the system for a specific installation in Athens. In this case, the energy produced by the SDHWS is assumed to be reduced after the fourth year of operation with an annual rate of 5–10%, a fact which results in a diminution of the annual cash flow.

The obtained results show that the annual demand of energy for water heating for a typical family can be covered by solar thermal systems at a percentage of 65–87% (varying by type of household and region).

The energy cost is higher for two-member families and decreases as the number of members per family is increased while the percentage of water heating demand covered by solar systems is increased.

The current energy savings using of $2\times10^6\,\text{m}^2$ of solar collectors are about 1200 GWh yr^{-1} of thermal energy. The present analysis shows that additional 3169 GWh yr^{-1}

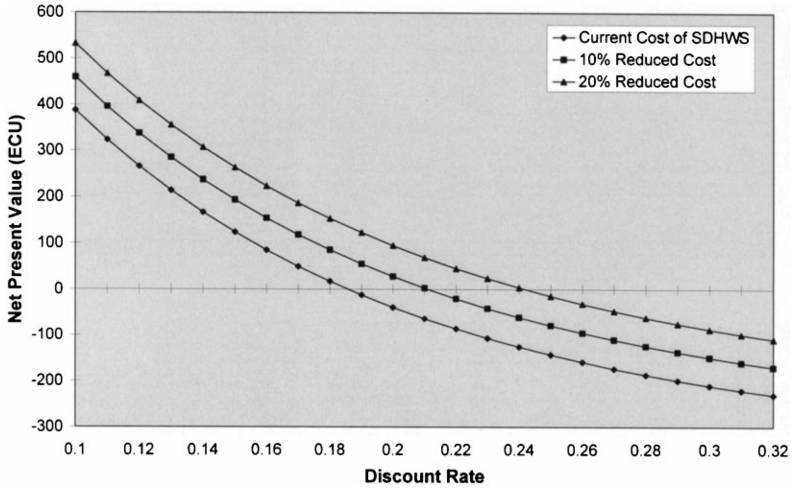

Fig. 6. Sensitivity analysis for the capital cost for a four-member family in Athens.

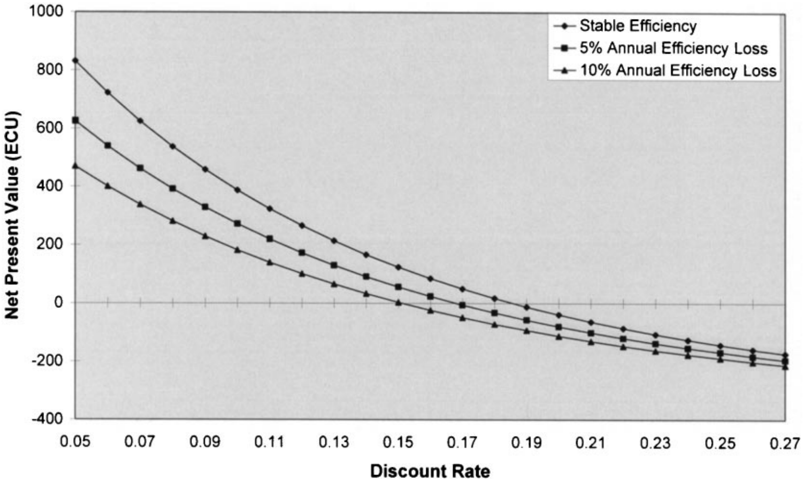

Fig. 7. Sensitivity analysis for the efficiency of SDHWS for a four-member family in Athens. It is considered that the efficiency of the system is steadily reduced after the fifth year.

of thermal energy savings could be obtained if the 75% of remaining households install a SDHWS.

The cost of thermal energy produced by SDHWS is well below the cost of electricity for all types of households and their installation is a good investment for almost all the regions of Greece. Financial incentives with the aim to reduce the capital cost of SDHWS would make such installations even more attractive to consumers.

4. CONCLUSIONS

The GIS method for the estimation of solar potential for water heating, presented in this work, takes into account the geographic distribution of solar radiation and the market for solar thermal systems and identifies the allocation of the expected energy savings and profits from a large-scale deployment of SDHWS. The adoption of the GIS environment provides some new spatial insight on the results obtained by well known methods applicable to each stage of the analysis. The matching of solar radiation and energy demand on a geographic basis offers the necessary information for energy policy decisions.

The spatial variability of the energy demand covered by a SDHWS revealed by the introduction of the geographic discrepancies of all spatially-dependent parameters makes the results of the proposed methodology even more interesting to policy makers.

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APPENDIX

Energy needs. The average monthly energy for water heating needed for each household is estimated by eqn (1):

$$L_w = N_p \times N_d \times V_w \times \rho \times C_p \times (T_w - T_m) \qquad (1)$$

Where L_w = energy load for water heating, N_p = number of persons per household, N_d = number of days per month, V_w = daily average hot water consumption for each person (40 l), ρ = water density, C_p = water specific heat, T_w = required hot water temperature (55°C) and T_m = average monthly temperature of water in the distribution network.

Financial analysis The capital cost of the investment in ECU is estimated by eqn (2):

$$C_c = 177 \times A_c + 333 \qquad (2)$$

Where C_c = capital cost of the solar thermal system and A_c = collector surface.