

Article

Economic and Environmental Analysis of Investing in Solar Water Heating Systems

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Academic Editor: Francesco Asdrubali

Received: 26 August 2016; Accepted: 2 December 2016; Published: 8 December 2016

Abstract: Solar water heating (SWH) systems can provide a significant part of the heat energy that is required in the residential sector. The use of SWH systems is motivated by the desire to reduce energy consumption and especially to reduce a major source of greenhouse gas (GHG) emissions. The purposes of the present paper consist in: assessing the solar potential; analysing the possibility of using solar energy to heat water for residential applications in Romania; investigating the economic potential of SWH systems; and their contribution to saving energy and reducing CO₂ emissions. The results showed that if solar systems are used, the annual energy savings amount to approximately 71%, and the reduction of GHG emissions into the atmosphere are of 18.5 tonnes of CO₂ over the lifespan of the system, with a discounted payback period of 6.8–8.6 years, in accordance with the savings achieved depending on system characteristics, the solar radiation available, ambient air temperature and on heating load characteristics. Financially, the installation of SWH systems determines net savings of 805–1151 Euro in a 25-year period in the absence of governmental subsidies. According to the sensitivity analysis, installing a SWH system with subsidies of up to 50% determines the reduction of the discounted payback period to 3.1–3.9 years and the increase of net savings to 1570–1916 Euro. These results indicate that investing in these systems is cost-effective for Romanian households as long as the governmental subsidies increase.

Keywords: solar energy; solar water heating; solar fraction; energy savings; GHG emissions; sensitivity analysis; governmental subsidies; economic analysis; environmental analysis

1. Introduction

The development of energy production from renewable resources is one of the priority goals of the European Union [1] in the energy field. The renewable resources development aims to reduce the import dependence on fossil fuels, and also to reduce CO₂ emissions. In areas where solar intensity is high, and the share of fossil fuels in the supply of the domestic hot water is substantial, the solar energy can be used to achieve significant energy savings, as well as a mechanism for sustainable development [2,3].

Solar systems can cover a significant part of the hot water needs depending on local and seasonal climatic conditions [4]. They present both economic and ecological benefits. These systems

use renewable energy for water heating and produce no direct emissions with greenhouse effect. Considering the whole life cycle, solar water heating (SWH) systems produce greenhouse gas (GHG) emissions although they are low compared to fossil reference systems, thus contributing to the reduction of GHG emissions and to the improvement of the air quality locally [5–9]. Moreover, SWH systems can substantially reduce fossil fuel consumption [10].

Solar water heating systems are a fully mature technology. These systems have been used for several decades to provide heat energy to households. In most cases, solar systems can provide only a certain part of the energy needs, meaning a complementary heating system is required.

More than 50% of dwellings within Romania are individual houses where about 60% of the total inhabitants live. At least 50% of these homes are suitable for solar installation. According to the Census of Population and Houses from 2011 [11], the average size of a household is lower in urban areas—2.5 persons/household—compared to rural areas—2.8 persons/household.

Rural population of Romania was approximately 46% of the Romanian population in 2011 [11]. This percentage reveals the potential of replacing the conventional water heating systems with solar systems in rural areas. Romania has a great potential of solar energy, as shown in Figure 1.

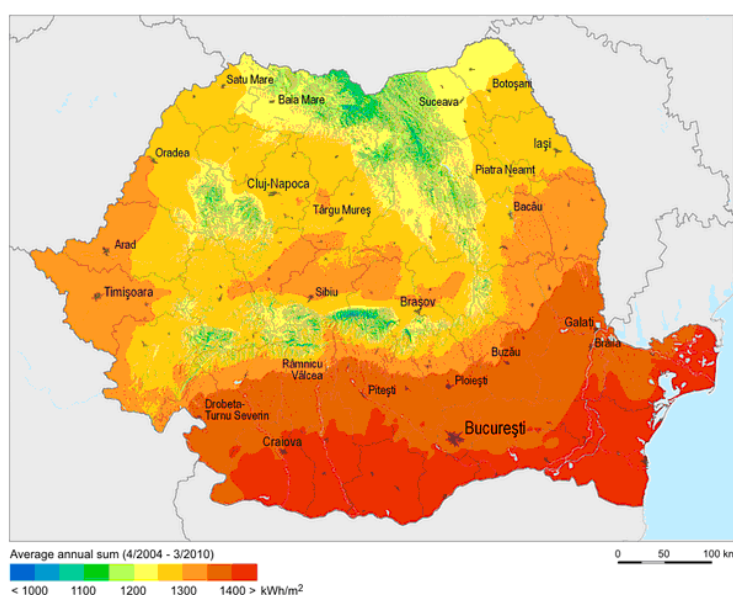


Figure 1. Average monthly global irradiation received on a horizontal plane in Romania [12].

The average monthly solar radiation in Romania is very good for solar applications and varies between 0.9 and 1.46 kWh/m² in the coldest month and between 4.87 and 6.86 kWh/m² in summer [13]. The annual average of daily global solar radiation in Romania is 3.34 kWh/m². The intensity of solar radiation is higher in Eastern and Southern Regions of Romania. Despite the excellent solar potential, the use of solar water heating systems in Romania is only of 5%, these systems being installed mainly in new homes.

Thus, the purpose of this paper is to assess the solar potential and to analyse the possibility of using solar energy to heat water for residential applications in Romania. The present paper also aims at investigating the economic potential of solar water heating systems and their contribution to saving energy and reducing CO₂ emissions.

2. Solar Water Heating Systems

Energy used for heating water is an important part of total energy consumption in the residential sector [14]. However, the distribution of energy consumption for various uses of homes cannot be determined accurately because of the lack of recorded statistics. Therefore, any available information

results either from empirical surveys or approximate calculations based on the analysis of the actual need for hot water of different categories of users. According to these approaches, water heating accounts for about 20% of the total energy consumption in the domestic sector [15].

The most popular and economical way to use the solar energy is the solar water heating. Due to the small number of system components and since the investment and operating costs are relatively low, solar water heating systems are suitable for low temperature applications under 50 °C.

Basically, there are two types of SWH systems: active (with pump) and passive (no pump) [16]. A typically active solar system consists of a collector, storage tank, pump, heat exchanger and an auxiliary heating system. The working fluid may be pure water, glycol, or another fluid with a high specific heat. The main types of solar collectors used in common applications are flat plate collectors and those with vacuum tube. Flat plate collectors are more widely used because of the lower price.

Solar water heating systems with natural circulation (passive systems) are the simplest and most widely used devices for collection and use solar energy [17]. They are intended to provide hot water for households and rely on natural circulation or thermosiphon principle. They provide hot water at a temperature of about 50 °C and consisting of a collector, storage tank and connecting pipes.

A SWH system reduces, but does not eliminate, the need for electric or gas heating water. The performance of a SWH system can be defined by solar fraction. The effective solar fraction of a SWH system depends on the intensity of solar radiation, the technical characteristics of the individual system and the load characteristics.

SWH system is one of the most common application of solar energy utilization system, but their globally installation is not commonly employed due to its high initial cost. Using SWH system will bring economic benefits compared to conventional systems over the long span time. The paper focuses on long-term economic feasibility analysis of SWH systems. SWH systems payback period varies from one region to another, as it depends on many factors such as the price of fossil fuels, the consumption of hot water, solar radiation, etc. [18].

After studying the specialty literature, we observed a considerable technically development and application of SWH systems [18–22], in order to assess their contribution to reduction of conventional energy and greenhouse gas emissions [23], substitute the fossil fuels used in heat production and increase the exploitation of renewable energy sources. Thus, the intensive research in the field of solar thermal collectors has had the aim to improve the specification of solar thermal collectors to increase their efficiency within approximately 20 years [24–27]. However, they still have a higher initial cost than conventional water heating systems, this being a major obstacle to its adoption by low income families and leading to the need for an economic analysis of this system. For this reason, many government authorities have created public policies to encourage the use of these technologies primarily among the low-income population [5,28–30].

From constructive and functional standpoint, SWH systems are of different types depending on the requirement and location parameters that affect its performance. Mugniera and Selemea (2015) studied these systems based on an innovative and energy efficient concept to optimize solar energy valorisation all year long, showing the high interest of such strategy to combine long term quality, simplicity of use and economic efficiency [31]. Considering economic and environmental benefits, SWH system must have an affordable price, especially for low-income families, in order to motivate people to use renewable energy and SWH system. Hence, it is necessary to analyse the economic feasibility of this system.

Over time there were made a series of studies on the economic performance of SWH systems compared to conventional systems that use electricity. Mateus and Oliveira (2009) studied three different locations and climates: Berlin (Germany), Lisbon (Portugal), and Rome (Italy), regarding energy use and economic benefits, according to different local costs for energy (gas, electricity and water), and highlighting savings in CO₂ emissions and the optimization of solar collector size and other system parameters [32].

The majority of studies found that in terms of installation expenditures and energy cost over the total life of the system, solar water heating technology has proven to be cost efficient for several domestic and industrial applications, this being proved by analyses of the systems performances [16]. This is the reason for the SWH systems widespread usage and applications in both domestic and industrial sectors. Shukla (2013) showed that SWH is not only environmentally friendly but also requires minimal maintenance and operation cost compared to other solar energy applications. SWH systems are cost effective with an attractive payback period of 2–4 years depending on the type and size of the system, and generate extensive researches performed to further improve the thermal efficiency of solar water heating [33].

In Serbia, Jovanovic et al. (2011) developed a method of multi-criteria analysis in order to analyse possible substitutions of fossil fuel used for hot water production in a heating plant with biomass and solar energy. When the ecological indicator had priority, the Gas + Solar + Biomass and Gas + Solar energy options showed the best level of sustainability. The Biomass energy option was in the group of energy options with low levels of sustainability in this case, due to calculation of the ecological indicator, and the atmospheric concentrations of CO₂ emitted have been calculated for combustion of biomass in life-time of boiler and they assumed that the carbon from biomass is not entirely “biogenic” [34].

In Polish conditions, Chwieduk (2010) studied active systems with flat plate solar collectors that can be used with good efficiency for many different applications. In Poland, domestic hot water systems are effective during spring and summer, especially from May to the end of August. In average in that time they can provide about 80%–100% of total demand. Economic efficiency expressed by the payback time of active SWH system investment differs depending on the solar system producer and the fuel/heat source that is substituted, and can range from 6 to 16 years [35]. From the economic cost-effectiveness analysis of SWH systems, Sawicka-Chudy et al. (2016) found that the simple payback time of modernization is around 16 years [24].

Argiriou et al. (1997) found a better cost–benefit ratio, a low payback period for SWH systems and a reduction of CO₂ emissions by 40% in Greece [36]. Martinopoulos and Tsalikis (2014) demonstrated in their study in Greece that discounted payback period is strongly influenced by the climatic zone of the building and the type of fossil fuel substituted. In all cases, the solar system covers at least 45% of the total space and water heating loads while the payback period is as low as 4.5 years with an annual abatement of more than 50 t of CO₂ in the worst case scenario [37].

In Croatia, Lugarić et al. (2010) developed a study for choosing the appropriate location for household SWH systems installation, using three investment strategies, varying in financial resources according to profiled income categories of households in the country. Their results show that without using loans or subsidies, net present value varies between 459.32 Euro and 1197.40 Euro, simple payback period between 11 and nine years and internal rate of return between 13% and 19%. When loans and subsidies are considered, net present value varies between 1222.60 and 2034.53 Euro, simple payback period between nine and eight years and internal rate of return between 22% and 52% [28]. The financial analysis of SWH systems installation in six cities from Serbia showed that 20% subsidy is justified already by CO₂ mitigation potential of SWH systems, while 50% subsidy reduce payback period to 5.5–6 years [30].

2.1. Experiences in Solar Water Heating Systems in Europe

The most important application of SWH systems is for heating domestic hot water. In 2013, 94% of the energy provided by SWH systems was used worldwide for heating domestic hot water, 84% mainly by small-scale systems in single family houses and only 10% by larger applications attached to multi-family houses, hotels, schools, etc. Globally, in 2013, SWH systems contributed about 1.2% to the overall domestic hot water and space heating demand in buildings [38].

Most large-scale solar systems in Europe have been built in central and northern Europe, mainly in Sweden, Denmark, The Netherlands, Germany and Austria. These are used to provide heat demand

for space heating and domestic hot water for large housing estates (central solar heating plants with seasonal storage (CSHPSS)) or to supply heat to large multiple dwellings, hospitals, hostels or to the district heating systems of large housing estates (solar systems with diurnal heat storage) [39,40].

In Europe, Germany is typically at the forefront of alternative energy production. The 2013 capacity of this country to use solar water heating technologies accounted for 3.3% of the global market, and since then it has had the largest number of new installations throughout the European Union. While in Europe considerable progress has been recently made in the development of organic Rankine cycle (ORC) systems for small-scale power generation from solar energy, in Romania the level of installation of simple solar water heating systems is the lowest in Europe [41,42].

Table 1 shows that Romania ranks 7th in terms of the number of inhabitants out of the 31 countries listed. In terms of solar radiation intensity, we can notice that Romania is among the top 10 countries that have large amounts of solar radiation, but despite these favourable conditions, the installed solar collector area per 1000 inhabitants is very low, Romania ranking 29th place. Another very important factor that could be decisive for this situation is the minimum income per month, which in Romania is 237 EUR/month, being among the smallest in Europe, while the European average is 810 EUR/month, according to the Table 1.

Table 1. Total solar collector area installed by the end of 2012 in Europe (revised 2015) (m²).

No.	Country	Inhabitants	Total Installed Solar Collector Area (m ²)	Installed Solar Collector Area per 1000 Inhabitants (m ² /1000 inh.)	Horizontal Radiation (kWh/m ² /Year)	Monthly Minimum Wage (EUR)
1	Albania	3,011,405	111,921	37	1604	160
2	Austria	8,221,646	4,929,656	599	1126	-
3	Belgium	10,444,268	429,533	41	971	1501
4	Bulgaria	6,981,642	122,100	17	1188	214
5	Croatia	4,475,611	120,000	26	1212	407
6	Cyprus	1,155,403	709,923	614	1886	924
7	Czech Republic	10,609,762	891,738	84	998	360
8	Denmark	5,556,452	684,673	123	989	-
9	Estonia	1,266,375	6520	5	960	430
10	Finland	5,266,114	48,502	9	948	-
11	France	65,951,611	2,186,269	33	1112	-
12	Germany	81,147,265	16,675,320	205	1091	1473
13	Greece	10,772,967	4,122,000	382	1585	684
14	Hungary	9,939,470	236,550	23	1199	358
15	Ireland	4,775,982	271,968	56	949	1545
16	Italy	61,482,297	3,446,766	56	1419	-
17	Latvia	2,178,443	4040	1.8	991	370
18	Lithuania	3,515,858	6000	1.7	1001	350
19	Luxembourg	514,862	39,800	77	1037	1923
20	Macedonia	2,087,171	36,890	17	1381	210
21	The Netherlands	16,805,037	864,642	51	999	1502
22	Norway	5,085,582	39,088	7	971	-
23	Poland	38,383,809	1,211,500	31	1024	430
24	Portugal	10,799,270	858,995	79	1686	530
25	Romania	21,790,479	110,700	5	1324	237
26	Slovakia	5,488,339	147,000	26	1214	405
27	Slovenia	1,992,690	186,800	93	1115	791
28	Spain	47,370,542	2,962,824	62	1644	757
29	Sweden	9,647,386	450,000	46	934	-
30	Switzerland	7,996,026	2,141,490	267	1094	-
31	United Kingdom	63,395,574	728,673	11	943	1398

Source: Data extracted from [43–46].

2.2. Rural Energy Program

Energy policy tends to be written by and for the urban population and this ignores half of European citizens, which results in a limitation of their abilities to improve their livelihoods and to

contribute to environmental goals. Rural areas represent 90% of all territory in the EU 27 and 56% of the population [47].

In Romania, rural communities face considerable challenges because the income per household is 30% lower than in urban areas, unemployment tends to be higher too, as does fuel poverty [48]. They need help and support, particularly when it comes to energy choices.

Rural regions in Romania have different characteristics in terms of energy access and use compared to urban areas and they rely more on carbon intensive fuels that include coal, diesel and wood. In some remote areas, the rural inhabitants have no access to electricity supply and gas and therefore they have a more limited choice of energy solutions. Moreover, the rural buildings are relatively old, sub-optimally insulated and equipped with inefficient heating units, so the people from these areas may face higher energy bills [49].

The distribution of dwellings by type of building, on area of residence are shown in Table 2, which also reveals that in rural areas, single dwelling buildings are predominant, and account for approximately 98% of all buildings.

Table 2. The number of dwellings grouped by type of building, by residence in 2009.

	Total	Urban	Urban	Rural	Rural
TOTAL dwellings	7,383,643	4,257,683		3,125,960	
Single dwellings	4,182,986	1,134,468	26.65%	3,048,518	97.52%
Two dwellings	63,601	41,249	0.97%	22,352	0.72%
3–16 dwellings	439,744	405,702	9.53%	34,042	1.09%
Over 16 dwellings	2,697,312	2,676,264	62.86%	21,048	0.67%

Moreover, Figure 2 shows that the electricity (39%) and biomass (39%) are the main sources that meet the energy demand for hot water in the rural areas.

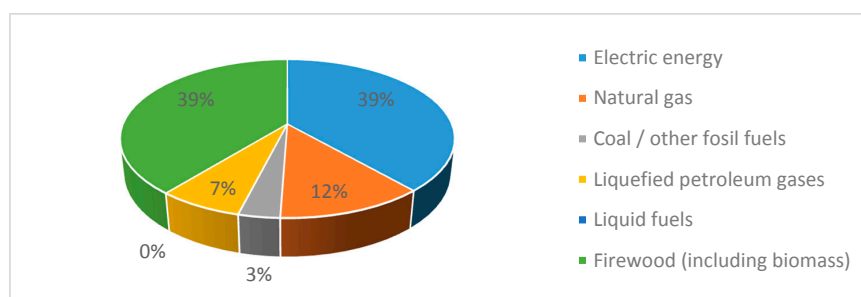


Figure 2. The structure of houses according to the energy source used for heating water in 2009.

All these above-mentioned factors combined show the great environmental, social and economic potential of transition to cleaner renewable energy sources that are locally available. The rural energy use is important because rural communities have a higher carbon footprint than their urban compatriots and thus are forced to choose high polluting energy sources, such as coal, diesel or wood.

3. Solar Potential Analysis in 52 Romanian Cities

3.1. Climatic Data

Solar energy is a clean source of energy and does not contribute to global warming. The performance of a SWH system is heavily dependent on climatic conditions. The monthly average values data used for simulation of solar water system in 52 locations in Romania were provided by Retscreen software [13]. The data required are the monthly average of the solar global radiation on horizontal surface, ambient temperature and wind speed.

The maximum radiation for the locations included in this analysis occurs in May and June. The timing of this peak roughly coincides with the June solstice when day lengths are maximum and solar heights are their greatest. However, the monthly temperature variations do not follow the changes in radiation exactly. The peak monthly temperatures occur about two months after the net radiation maximum in July and August. This lag is probably caused by the delayed movement of stored heat energy in the ground into the atmosphere. The minimum monthly temperatures occur in January and do not coincide with the lowest values of net radiation, which occur during the December solstice.

3.2. Solar Radiation on a Tilted Surface

In order to design and assess the efficiency of the solar collectors, it is necessary to know solar radiation intensity for that location. Thus, the data related to hourly, daily and monthly average solar radiation that reaches the horizontal and tilted surfaces are essential for designing the solar water heating equipment [50].

Solar radiation incident on the solar collector surface depends not only on the solar radiation intensity but also on the angle made by the collector and the sun [51]. When solar radiation is perpendicular on absorbing surface of the collector, the power on collector surface will be maximum and equal to that of solar radiation. Because the angle between fixed surface of collector and the sun is changing continuously, the power on fixed surface of the collector is lower than the incident radiation [52,53].

Because solar collectors are inclined at a certain angle to the horizontal is necessary to determine the solar radiation incident on their surface [54–57]. The tilted angle of the collector has a major impact on the solar radiation incident on its surface. The tilt angle of the collector was considered equal to the latitude of the location, in order to maximize the solar energy collected throughout the year [58–60]. Because the solar collector will be inclined at an angle of 45° (the latitude of the locations) from the horizontal, it was necessary to calculate the amount of solar radiation incident on a surface tilted at this angle.

Figure 3 shows the monthly variation of the power available on the tilted surface of the solar collector at a 45° angle calculated for the locations analysed.

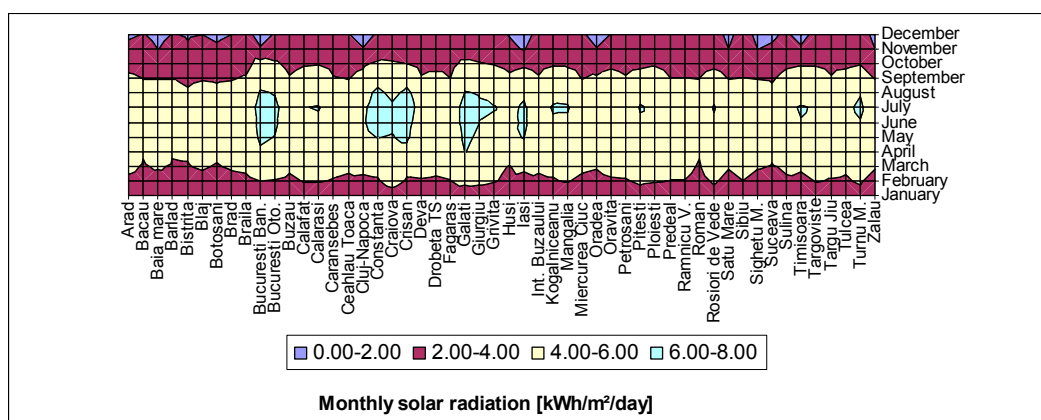


Figure 3. Monthly variation of global radiation on the surface of the solar collector tilted by an angle of 45° .

It can be observed that the available power on the solar collector surface for this tilt angle increases throughout the year, even in the cold period. Average daily solar radiation increases from $3.51 \text{ kWh/m}^2/\text{day}$ to $4.15 \text{ kWh/m}^2/\text{day}$.

Intermittency is one of the major critical characteristics of solar energy and consequently affects it so the solar thermal collector output varies throughout the day and through the seasons and is affected by dust, cloud cover, frost or snow. Thus, the solar energy source and the water heating demands of

a house, in general, do not match each other, the peak solar radiation occurs near noon, but the peak hot water demand is in the late evening or early morning when solar radiation is not available.

Many of these factors are fairly predictable, and thermal energy storage is generally required to couple the time-dependent hot water demands of a residential house with time-dependent solar energy source. The solar water heating system analysed in this study is a thermosiphon system (natural circulation) as the most common and simplest installation in the Romania, it converts energy of solar radiation to useful energy for sanitary water heating at a temperature of 50–60 °C. The main components of the system are the solar collector, the hot storage tank and the supporting structure. Table 3 presents the basic parameters of the analysed system.

Table 3. Parameters of the solar water system considered.

Parameter	Value
Average number of people per house [11]	3
Occupancy rate	100%
Daily hot water usage estimate (rural area) [61]	75 L/day
Hot water temperature	50 °C
Operating days per week	7
Solar water heater type	Glazed
Collector area [13]	2.2 m ²
Collector slope	45°
F_R ($\tau\alpha$) coefficient [13]	0.69
FRUL coefficient [13]	4.12 W/m ² /K
Auxiliary capacity	1.5 kW
Backup water heating	electric resistance
SHW initial & installation cost (offer was made by the company Cyclone) [62]	€765
Electricity rate [63]	0.126 €/kWh
Project life	25 years
Incentives and grants (per cent of initial cost)	0%
Annual O&M cost (per cent of initial installed cost) [64]	1.0%

These characteristics of the system were considered in the following calculations.

3.3. Calculation of the Monthly Energy Demand

Domestic hot water consumption depends on many factors, such as consumer habits, sanitation facilities of homes and the energy cost. Demand varies depending on time of day, days of the week and season [65]. According to the literature, per capita demand for domestic hot water, to an apartment with a centralized distribution system is between 40 and 80 L/day [66].

However, the use of hot water differs from one household to another and, thus, in most cases, there is a peak in energy consumption in the morning, late afternoon and evening. Within the consumption profile, 45% of the daily energy is used in the late afternoon and evening when occupants get back home from work.

In individual homes, where water is heated on kitchen stoves, the consumption of hot water for sanitary needs is much lower than in homes with centralized system. As the standard of living of these homes is improving, the total consumption of hot water and, thus, the energy demand will increase significantly. Most often the water for sanitary needs is heated using electricity, but a large percentage is still heated on kitchen stoves, with small efficiency, and involves the use of wood or agricultural waste.

For individual homes in rural areas without centralized distribution system, consumption of hot water between 20 and 25 L/day was considered with an average water temperature of 50 °C [61]. The estimated energy consumption for water heating is in the range of 2.66–3.09 GJ/year. Since there is no connection to the gas network of the rural sector, the solar collectors can be a viable solution for getting domestic hot water.

Very good results can be achieved, especially in locations in the southern of Romania, where the sunshine period is the highest during the year. Due to the low cost of installation and maintenance, the passive systems are thus much more cost-effective and, on winter, auxiliary electric heating solutions can be added if need be. Calculation of the monthly energy demand for preparation of domestic hot water is necessary for determining the collection surface and the storage volume. Effective energy demand is calculated as the energy needed to heat water at the specified temperature. The monthly energy required Q_{load} for heating water is determined as [67]:

$$Q_{load} = V_w \times \rho_w \times N_d \times c_{pw} \times (T_h - T_c), \quad (1)$$

where V_w is total volume of hot water used in building (L/day); ρ_w is specific mass of water (1 kg/L); N_d is number of days in the month; c_{pw} is specific heat of water (kWh/kg/K); T_h is the temperature required to the hot water (K); and T_c is the inlet temperature of cold water (K).

The groundwater supply temperature, which is the inlet temperature of cold water in the solar collector has simulated as proposed by Arias-Penas et al. (2015) [68].

Required load is proportional to the number of days per week in which the system is used. Regarding the thermal load, although the hot water demand varies from day to day and from one consumer to another, the total demand of heat energy was considered fairly constant throughout the year. This is not very fair during the summer, when consumption is slightly higher. However, at this time, the heat demand for hot water is about as high as in the winter due to the higher temperature of the feed water.

3.4. Solar Collectors Efficiency

Useful energy provided by the solar collector can be calculated with the following formula [57,69]:

$$Q_u = F_R A [(\tau\alpha) I_t - U_L (T_h - T_a)], \quad (2)$$

where F_R is the collector heat removal factor, A is the area of the collector (m^2), I_t is the solar radiation to the plane of the collector (W/m^2), $(\tau\alpha)$ is the product of transmittance and absorbance, T_a is the monthly ambient temperatures of the installation site (K) and U_L is the heat loss coefficient of the collector (W/m^2).

The efficiency of plane solar collector is:

$$\eta = F_R (\tau\alpha) - \frac{F_R U_L (T_h - T_a)}{I_t}, \quad (3)$$

Because solar energy is a time-dependent energy resource, the solar system requires a thermal energy storage.

The energy balance of the water tank storage is:

$$(mc_{pw}) T_h = Q_u - Q_{load} - (UA)_s (T_h - T_a), \quad (4)$$

where m is mass of water in the tank storage and Q_{load} is energy removed from the tank to the load.

Another indicator related to the performance of the solar water heating system is the solar fraction. The solar fraction is the stake of solar energy in the total load of conventional water heater. The greater is the solar fraction, the greater the solar contribution will be for water heating, which reduces the energy required for the auxiliary system. The solar fraction ranges between 0 and 1.

The solar fraction f is defined as the ratio of the useful solar energy supplied by the system and the energy required for heating water. Figure 4 presents the average annual solar fraction of SWH system for the locations analysed and considering a constant load profile. The average annual solar fraction for all the cities in Romania varies in the range of 64%–78% for a tilt angle of 45° .

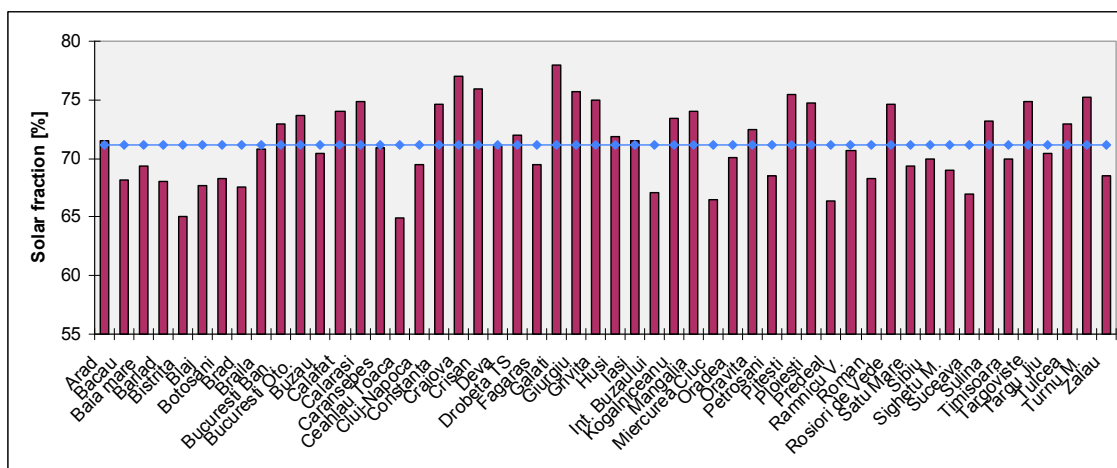


Figure 4. Predicted solar fraction of SWH system.

Figure 5 shows the monthly average variation in energy collected for analysed locations. The figure shows that the maximum energy is collected in July being of $4.36 \text{ kWh/m}^2/\text{day}$ and the average amount of annually collected energy will be of $2.64 \text{ kWh/m}^2/\text{day}$. It can be noticed that in December the incident solar radiation shows a decrease and therefore the energy collected will be reduced, this having a minimum of $0.88 \text{ kWh/m}^2/\text{day}$.

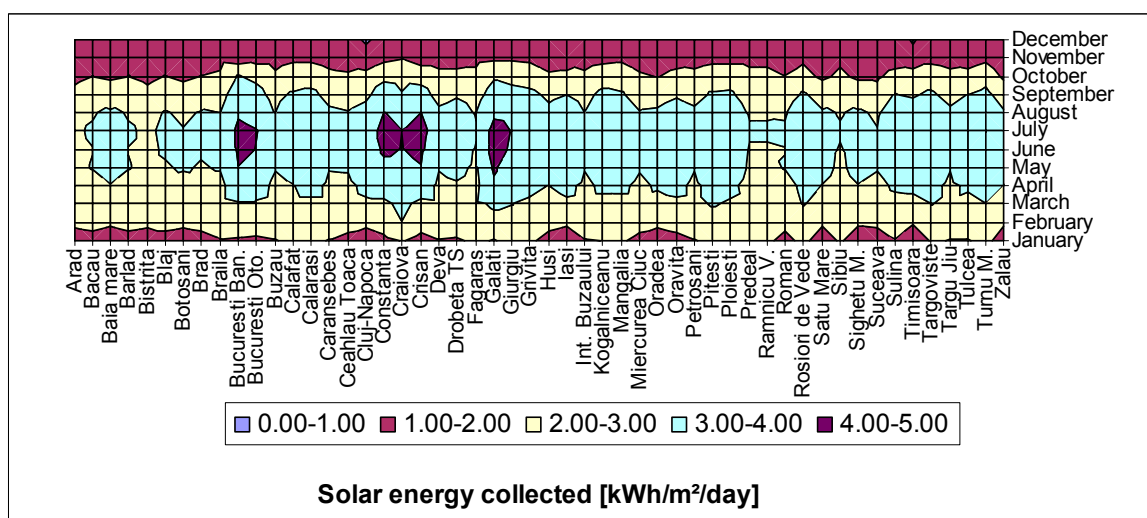


Figure 5. Variation of monthly solar energy collected for analysed locations.

Figure 6 shows that the maximum auxiliary electricity consumed during the year is approximately $2.43 \text{ kWh/m}^2/\text{day}$ in December.

The annual average solar fraction was determined as being 71%, lower in winter months and higher, reaching 100%, in the summer months. It is noted that by the use of solar systems for preparing domestic hot water through easy adjustment of consumption profile, contributions of 100% in the months from May to September, could be obtained, which actually happens in practice.

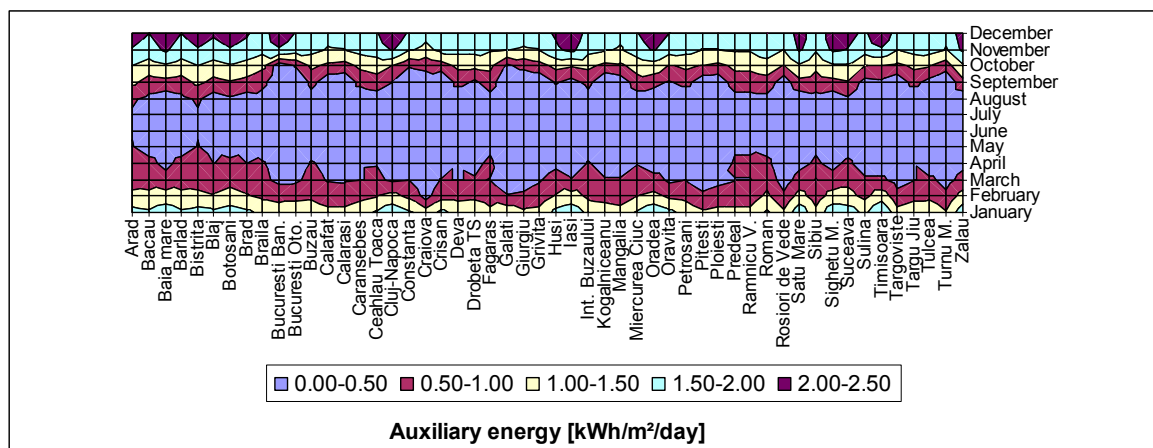


Figure 6. Variation of monthly auxiliary energy.

4. Economic and Environmental Impact Analysis

This study aims to determine whether residential solar systems are financially attractive investments for homeowners in the absence of governmental subsidies or other material support or in the presence of subsidies, on the basis of cash flows estimated as energy savings [30].

4.1. Economic Features

Typically, investors will consider making such investment only if it is profitable. The main objective of evaluation of this investment is to calculate the expected cash flows and the indicators of selecting investments in order to determine whether the investment will be suitable for the investor.

Treated as a financial investment, the attractiveness of residential solar energy systems depends on the following parameters: the initial cost of system, maintenance costs, the lifespan of the system, the amount and form of energy used, the concordance between solar energy captured and load, the cost of the energy consumed using conventional energy and awarded grants.

Investment valuation methods applied in this study include: net present value (NPV), savings to investment ratio (SIR), simple payback period (SPB)/discounted payback period (DPB)/modified discounted payback period (MDPB) and internal rate of return (IRR), in accordance with possible lifespan period of maximum 25 years.

The economic analysis includes the cost of SWH system of 765 Euro being offered by the company Cyclone and cash flows generated on the exploitation period of maximum 25 years [63]. In this study, it was considered that all cost of the SWH system was paid entirely at the beginning without taking out any loans. The total capital investment includes all costs incurred to purchase the equipment needed for the SWH system (purchased equipment costs), the costs of labour and materials for installing that equipment (direct installation costs) and some other costs (indirect installation costs) [70].

The cash flows represent the savings obtained by using SWH system comparing with the classic electric systems of heating water. These savings for each city are presented in Figure 7. The savings are referred to the costs of replaced energy (electricity), and were considered constant on the forecasting period that is the lifespan of the SWH system.

The annual energy savings associated with the SWH system is determined by subtracting the energy produced by the SWH system from the base case energy consumption. The calculation of monetary savings for the solar water heating system took into account a variety of factors, including climate, how much hot water is used at the location, conventional fuel costs (electricity), the water temperature required, and system performance.

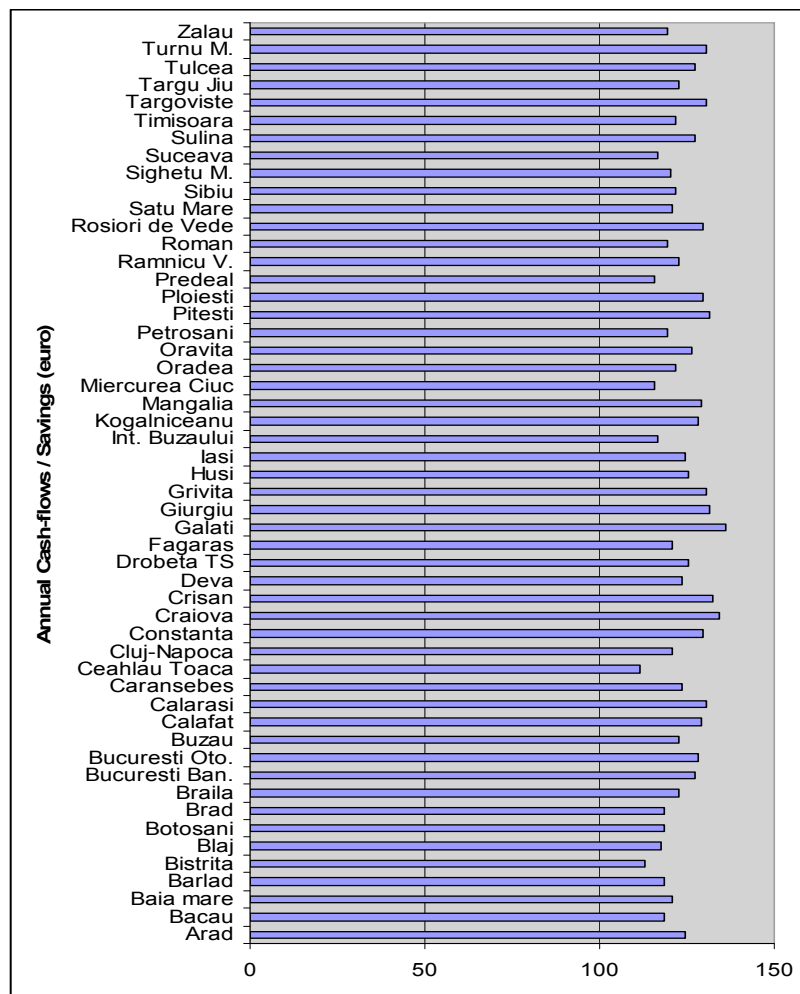


Figure 7. Annual savings.

4.1.1. Net Present Value and Savings to Investment Ratio

The net present value (NPV) of a stream of payments is defined as the sum of the discounted values of the individual terms in the stream, where each term is discounted to a common reference date [71]. NPV is the sum of all the future cash flows to determine the present value. Cash flows include the both inflows (investment cost) and outflows (savings generated on the exploitation period) that are discounted at a rate.

Assuming that our initial investment is I_0 and savings are net cash flows (CF_i) on exploitation period, where the forecasting period is $i = 1 \div n$, which corresponds to the lifespan of the SWH system, n being 25 years. Assuming that r is the social discount rate of 5% according to the Guide to Cost–Benefit Analysis of Investment Projects [72], the NPV of the introducing SWH system is determined by deduction of the present value of savings resulted by the exploitation of the initial investment value in SWH system:

$$NPV = -I_0 + \sum_{i=1}^n \frac{CF_i}{(1+r)^i}, \quad (5)$$

The investment is cost-effective if its $NPV > 0$.

Saving to investment ratio (SIR) is used when benefits occur primarily as cost reductions [73]. We can use here SIR because it is recommended for use when debt financing is not present [74]. The formula is:

$$SIR = \frac{NPV}{I_0}, \quad (6)$$

where

NPV is the present value of net savings of the activity; and

I_0 is the present value of the investment costs, without considering replacement costs and also salvage values.

Calculating NPV and SIR for a lifespan between 1 and 25 years, we found that NPV without subsidies (NPV-S0%) became positive earliest in Year 7 for Galati (21.81 Euro) where the yearly savings are the highest and the investment become profitable, SIR-S0% being of 0.0285, and at the latest in Year 9 for Ceahlau Toaca (21.81 Euro) where the yearly savings are the lowest, and SIR-S0% is only 0.0352. In addition, for an exploitation period of 20 years, the NPV-S0% and SIR-S0% varies between 623.46 Euro and 0.8150 (Ceahlau Toaca), respectively, and 929.58 Euro and 1.2151 (Galati), respectively, and, for a lifespan of 25 years, NPV-S0% and SIR-S0% range between 805.26 Euro and 1.0526, respectively, and 1151.46 Euro and 1.5052, respectively.

A SIR-S0% of 1.5052 registered for Galati, when the lifespan is 25 years, shows that the investment will save 1.5052 Euro on average for every 1 Euro invested, over and above the required rate of return reflected in the discount rate.

4.1.2. Simple Payback Period and Discounted Payback Period

Simple payback period (SPB) is a quick, simple way to compare alternative investments. Simple payback is the number of years necessary to recover the project cost of an investment under consideration [74]. One drawback to the SPB method is that it ignores the time value of money, i.e. the use of SPB implies that there are no opportunity costs to the investor and consequently the investor's discount rate is zero [75]. However, the simple payback method can be useful if there are uncertainties, such as uncertain tenure or life of the technology. When there is a high degree of uncertainty associated with future cash flows, SPB gives an indication of how long one's assumptions must hold to ensure that at least the principal is returned to the investor [74].

Simple payback periods are determined mainly by the solar radiation intensity in the analysed locations, they are being minimal for areas with high global solar radiation. The minimum value of simple payback period is 5.6 years for Galati and the maximum value of 6.9 years was found for Ceahlau Toaca when considering 0% subsidies. An average simple payback period in the other locations was determined to be approximately 6.2 years. The simple payback period for solar systems installed in Ceahlau Toaca is higher by 22% compared to that of Galati, and by 11% compared to the average SPB registered in all areas.

The discounted payback period (DPB) is the number of years that will pass before the investment cost is recovered; it is calculated while accounting for the time-value of money [70]. The DPB period works as a quick assessment of the time period during which an investor's capital is at risk [74]. The DPB period is determined by:

$$DPB = \frac{\ln\left(\frac{1}{1 - \frac{I_0 \times r}{CF}}\right)}{\ln(1 + r)}, \quad (7)$$

We apply DPB because we assumed that cash flows are considered constant during the analysed period. The minimum value of DPB is 6.8 years for Galati and the maximum value of 8.6 years was found for Ceahlau Toaca when considering 0% subsidies. An average DPB in the other locations was determined to be approximately 7.6 years. The discounted payback period for solar systems installed

in Ceahlau Toaca is higher by 27% compared to that of Galati, and by 14% compared to the average DPB registered in all areas.

This discounted payback period has some limits in the sense that does not take into account the post-payback period cash flows of investments. If we take into account all cash flows discounted on the lifespan period of SWH system, we can determine the modified discounted payback period (MDPB) as follows:

$$MDPB = \frac{I_0}{\sum_{i=1}^n \frac{CF_i}{(1+r)^i}}, \quad (8)$$

In this case, we will obtain different MDPB depending on the lifespan period considered in the analysis, between 1 and 25 years. Thus, the minimum value of MDPB is nine years for Galati and the maximum value of 11 years was found for Ceahlau Toaca when considering 0% subsidies and 20 years for lifespan. When the lifespan is considered 25 years, MDPB is 10 years to Galati and 12.2 years to Ceahlau Toaca. These values are higher than DPB because take into account all cash flows actualized until the end of lifespan considered.

4.1.3. Internal Rate of Return

The internal rate of return (IRR) approach determines the discounted rate at which the cumulative NPV of the investment costs would exactly equal the cumulative NPV of all investment benefits if both are discounted at the internal rate of return [76]. Therefore, the investment with an IRR greater than the cost of capital is approved [77]. The IRR is the rate that sets the NPV of the cash-flows equal to zero. The IRR is therefore expressed by:

$$NPV = 0, \quad \sum_{i=1}^n \frac{CF_i}{(1+IRR)^i} - I_0 = 0 \quad (9)$$

Calculating IRR for a lifespan period between 1 and 25 years, we found that IRR without any subsidies (IRR-S0%) for an exploitation period of 20 years varies between 13.44% (Ceahlau Toaca) and 17% (Galati), and, for a lifespan of 25 years, IRR-S0% ranges between 14% and 17.5%.

According to the results presented above, installing a SWH system without subsidies presents a payback period ranging between 6.8 and 8.6 years. From a financial standpoint, the installation of SHW will determine savings between 1570 Euro and 1916 Euro on a 25-year period.

4.2. Sensitivity Analysis of the Impact of Subsidies

In many developing countries, such as Romania, certain programs have been developed, aiming at improving air, water and soil quality by reducing pollution caused by the burning of wood and fossil fuels used to produce thermal energy for heating and domestic hot water. Thus, these programs stimulate the introduction of the systems that use renewable, non-polluting sources. Grants that have been given for residential solar systems also raise an issue of social justice, because these systems are typically purchased by high-income families. Moreover, because of eligibility conditions, low-income families cannot access these funds, even if subsidies would be 90% of eligible costs. Consequently, subsidies granted in developing countries aimed at encouraging low-income families to adopt these systems could not achieve their goal, as was the case in Romania [29].

During the sensitivity analysis, the inputs and outputs associated with the SWH system investment were analysed. The purpose of doing so was to consider those inputs that had the greatest likelihood of occurring, analyse them for potential changes, and investigate the impact that they would have on investment indicators. With all other inputs held constant, uncertainty was found with the granting of subsidies to homeowners by national funding programs. In our study we analysed the efficiency of SWH systems when the homeowners can benefit of subsidies of 15%, 30% and 50%.

4.2.1. Sensitivity Analysis of the Impact of Subsidies on NPV and SIR

Analysing the impact of changes in the investment cost as a result of grants, we can conclude:

(1) When the subsidies are 15%, NPV-S15% and SIR-S15% became positive earliest in Year 6 for Galati (39.93 Euro, 0.0614) and at the latest in Year 8 for Ceahlau Toaca (69.84 Euro, 0.1074). During a 20-year exploitation period, the NPV-S15% and SIR-S15% vary between 738.21 Euro and 1.1353 (Ceahlau Toaca) and 1044.33 Euro and 1.6060 (Galati), respectively, and, for a lifespan of 25 years, NPV-S15% and SIR-S15% range between 920.01 Euro and 1266.21 Euro, and between 1.4149 and 1.9473, respectively.

(2) When the subsidies are 30%, NPV-S30% and SIR-S30% became positive earliest in Year 5 for Galati (53.21 Euro, 0.0994) and at the latest in Year 6 for Ceahlau Toaca (30.00 Euro, 0.0560). For an exploitation period of 20 years, the NPV-S30% and SIR-S30% vary between 852.96 Euro and 1.5928 (Ceahlau Toaca) and 1159.08 Euro and 2.1645 (Galati), respectively, and, for a lifespan of 25 years, NPV-S30% and SIR-S30% range between 1034.76 Euro and 1380.96 Euro and between 1.9323 and 2.5788, respectively.

(3) When the subsidies are 50%, NPV-S50% became positive in Year 4 for all cities, while SIR-S50% is positive, with a minimum of 0.0329 in Ceahlau Toaca and maximum 0.2606 in Galati. For an exploitation period of 20 years, the NPV-S50% and SIR-S50% vary between 1005.96 Euro and 2.6300 (Ceahlau Toaca) and 1312.08 Euro and 3.4303 (Galati), respectively, and, for a lifespan of 25 years, NPV-S50% and SIR-S50% range between 1187.76 Euro and 3.1052 and 1533.96 Euro and 4.0103, respectively.

We can observe that, for Galati, which is the location with the highest intensity of solar radiation and thus offers the best conditions for SWH installation, NPV increases between 12% and 41% for a 20-year lifespan and between 10% and 33% for a 25-year lifespan, when subsidies increase from 0% to 50%. SIR increases with between 32% and 182%, for a 20-year lifespan and between 29% and 166% for a 25-year lifespan.

4.2.2. Sensitivity Analysis of the Impact of Subsidies on SPB, DPB and MDPB

Analysing the impact of reducing the investment cost as a result of subsidies granted, we found that:

(1) SPB decrease from 5.6 years to 4.8 years (S15%), 3.9 years (S30%) and 2.8 years (S50%) in the area with the highest intensity of solar radiation (Galati) and from 6.9 years to 5.8 years (S15%), 4.8 years (S30%) and 3.4 years (S50%) in the area with the lowest intensity of solar radiation (Ceahlau Toaca). The results show that a reduction of up to 50% in the investment cost determines a reduction of up to 50% in SPB.

(2) DPB decrease from 6.8 years to 5.6 years (S15%), 4.5 years (S30%) and 3.1 years (S50%) in Galati and from 8.6 years to 7.1 years (S15%), 5.6 years (S30%) and 3.9 years (S50%) in Ceahlau Toaca. The results show that a reduction of 50% in the investment cost determines a reduction of 54%–55% in the DPB, depending on the area of installation SWH system.

(3) MDPB was calculated for each strategy for a lifespan between 1 and 25 years in all areas. We also found a decreasing of MDPB when the subsidies increase.

For the area with the highest intensity of solar radiation, the MDPB decreases from nine years to 7.7 years (S15%), 6.3 years (S30%) and 4.5 years (S50%) for 20-year lifespan and from 10 years to 8.5 years (S15%), seven years (S30%) and five years (S50%) for 25-year lifespan, which shows that, when investment cost is reduced by 50% because of subsidies, the MDPB is also reduced by 50%. A similar evolution is registered for all areas included in this study.

We can observe that when the subsidies granted increases, the payback periods are reduced, but the spread between the maximum and minimum payback periods is maintained similar to the variant without subsidies.

4.2.3. Sensitivity Analysis of the Impact of Subsidies on IRR

Analysing the impact of subsidies awarded on IRR we found that:

(1) When the subsidies are 15%, IRR-S15% became positive earliest in Year 5 for Galati (0.0150) and at the latest in Year 6 for Ceahlau Toaca (0.0080). For an exploitation period of 20 years, the IRR-S15% varies between 0.1630 (Ceahlau Toaca) and 0.2040 (Galati) and, for a lifespan of 25 years, IRR-S15% is between 0.1678 and 0.2072, respectively.

(2) When the subsidies are 30%, IRR-S30% became positive earliest in Year 4 for Galati (0.0063) and at the latest in Year 5 for Ceahlau Toaca (0.0133). For an exploitation period of 20 years, the IRR-S30% varies between 0.2029 (Ceahlau Toaca) and 0.2510 (Galati) and, for a lifespan of 25 years, IRR-S30% is between 0.2061 and 0.2530, respectively.

(3) When the subsidies are 50%, IRR-S50% became positive earliest in Year 3 for Galati (0.0329) and at the latest in Year 4 for Ceahlau Toaca (0.0641). For an exploitation period of 20 years, the IRR-S50% varies between 0.2895 (Ceahlau Toaca) and 0.3547 (Galati) and, for a lifespan of 25 years, IRR-S50% is between 0.2908 and 0.3553, respectively.

We can conclude that when the investment costs are reduced by 50% due to governmental subsidies, the IRR increases with ratio between 107.4% and 116.4% for a lifespan between 20 and 25 years for the area where the intensity of solar radiation is the lowest, and between 103% and 109% for the area with the highest intensity. Based on economic indicators, Galati proved to be the best location for installing SWH systems. In all cases, simple payback period was less than seven years.

According to the results of the sensitive analysis, installing a SWH system with subsidies of up to 50% determines the reduction of simple payback period to 2.8–3.4 years. From a financial standpoint, the installation of SWH systems will determine savings between 1570 and 1916 Euro on a 25-year period and internal rate of return between 0.2908 and 0.3553, which shows that investing in SWH systems is cost-effective and feasible as long as the grant percentage increase.

The very high yields produced currently by solar installations have made the savings to investment ratio become more attractive to domestic users. Thus, the investment in a solar system for domestic water heating is recovered in a reasonable period of 6–8 years. Considering the lifetime exceeding 20 years, the implementation of such a system is cost-effective and if we consider the obvious probability in the future of price increase to fossil fuels, it will lead in the future to the increase the return on investment. As the payback period is reduced, the installation of SWH will be more attractive and the savings thus achieved will be higher over the life period of the project.

4.3. Greenhouse Gas Emission Analysis

Although solar energy is considered the cleanest energy source available, interaction with the environment occurs over the whole life cycle of a SWH system (materials, manufacturing, transportation, use and final disposal or recycling) [15,78]. These interactions can lead to depletion of natural sources, greenhouse effect, acidification, eutrophication, etc. [79].

We evaluate the environmental impacts associated with greenhouse gas emissions of a solar water heating system during its operation phase. The greenhouse gas (GHG) emissions for the manufacturing and dismantling of the solar water heating system were not included in this analysis. GHG emission reductions are calculated based on the fuel type mainly used at dwellings namely electricity. The GHG emissions are calculated using the GHG emission factor, which is the level of CO₂ emitted per unit input energy. The GHG emission factor depends on the type of fuel used and the efficiency of the energy conversion device used on-site.

In order to estimate emissions from power plants, specific emission factors for each type of pollutant, which depend on fuel characteristics and combustion technology, have been used. Carbon dioxide (CO₂) is a main product from the combustion of all fossil fuels. The CO₂ emission is directly related to the carbon content of fuels. Electricity is a significant source of carbon dioxide. Alongside carbon dioxide, methane (CH₄) and nitrous oxide (N₂O) are the most prevalent greenhouse gases

For the considered solar water heating system, the operating cost savings compared to an electric water heater is about 70%. The average annual solar contribution to the hot water needs of the household is 76%, while the maximum discounted payback period of system is 8.6 years, and the average savings on lifespan are 1151.46 Euro.

Financial analysis of SWH installation for a typical household indicates that such a system is always profitable, with a simple payback period on investment of 5.6 to 6.9 years without any government subsidy. The greenhouse gases emissions analysis indicates that such a SWH system will prevent the emission into the atmosphere of about 17 to 20 t CO₂ over its lifespan. When subsidies are granted to reduce the investment costs supported by households, then the payback period is reduced considerably and the net present value, savings to investment and internal rate of return increase substantially.

It seems that the only barrier that prevents the penetration of large scale of solar water heating systems in Romania is the lack of understanding among the population of the benefits they provide and financial unattractiveness to poor households. When the population understands all these technology advantages, they accept it easily. In the case of SWH systems, for a payback period of seven years, the benefits are not immediately visible; the energy bill will be reduced, but not fast enough in order to justify the cost of installation, so that governmental subsidies will be an important incentive for beneficiaries.

Economic indicators showed that Galati is the best location for the use of solar systems. From an environmental viewpoint, it was found that, on average, the emissions in local atmosphere of 0.7 tonnes CO₂ per year can be avoided and the average CO₂-equivalent payback period is 16 months. Although solar water heating systems have great potential for use with subsidies, many families believe that solar water heating systems are too expensive because of the high initial investment costs.

Author Contributions: Alexandru Șerban and Spiru Paraschiv analysed experiences in SWH systems in Europe and accomplished the solar potential analysis in 52 Romanian cities; Nicoleta Bărbuță-Mișu and Nicoleta Ciurescu performed the economic and sensitivity analysis; Simona Paraschiv analysed similar studies performed, realised the environmental impact analysis of SWH systems and had drawn the conclusions; Nicoleta Bărbuță-Mișu wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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