COST-EFFECTIVENESS ANALYSIS OF ALTERNATIVE WATER HEATER SYSTEMS OPERATING WITH UNRELIABLE WATER SUPPLIES

Arif Yurtsev

Eastern Mediterranean University, North Cyprus
arifyurtsev@gmail.com

Glenn P. Jenkins

Queen's University, Canada
and Eastern Mediterranean University, North Cyprus
jenkins@econ.queensu.ca

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ABSTRACT

This paper reports on a cost-effectiveness analysis of four types of water heating systems operating in a situation where there is an unreliable water supply. These systems are electric water heating, a solar water heating system (SWHS) with electricity back-up, the SWHS with an LPG water heater, and an LPG water heater alone. It is found that in the conditions of North Cyprus, that an SWHS with an LPG heater back-up is the most cost-effective, most convenient and most environmentally friendly system. The last three systems all have a cost per m3 of hot water that is approximately 50% of the cost of heating water by electricity. When a pressurized supply of water is available, the cost of heating water is reduced by 20% for the SWHS with LPG back-up and for the heating of water by the LPG heater alone.

Highlights

- **A cost-effective analysis is made of four different household water heating systems.**
- **Effects of reliability of supply and quality of water are integrated into analysis.**
- **Analysis is for area where solar radiation is plentiful but there is winter season.**
- **A solar water heating system with LPG backup is the most cost effective system.**
- **In terms of GHG emissions the SWHS with LPG is also the preferred option.**

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1. Introduction

The objective of this paper is to report on the cost-effectiveness analysis of a set of alternative water heating systems in an economy where tax and subsidy distortions on the supplies of energy are minimal, but the quality of public utility services are deficient.

The analysis integrates the problems associated with both unreliable water and electricity supplies and the absence of natural gas supplies into a cost-effectiveness analysis of these water heating systems. Previous studies have not taken into consideration the impact of the lack of reliability of electricity and/or water supplies when evaluating the financial competitiveness of alternative water heating systems, including solar water heating systems (SWHSs). The analysis is carried out for such situations, which are those found in North Cyprus.

This set of problems is not unique to North Cyprus, but is a chronic set of issues faced by households across many developing countries. This is particularly the case for many African countries that have equal or better solar radiation levels than Cyprus, but where households suffer from intermittent supplies of electricity and water, and natural gas supplies are not available. However, as in the case of North Cyprus and many developing countries, bottled liquefied petroleum gas (LPG) is readily available.

The results of this analysis are highly relevant to the design of energy policies for water heating in most developing countries. In particular, some countries such as Israel and Spain have legislated on the requirement to install SWHSs but have not considered LPG as a source of energy to serve as a back-up to such a system (Roulleau and Lloyd, 2008). Kenya has more recently made it mandatory to use SWHSs for heating water. The design of energy policies that are consistent with the financial incentives facing households are much more likely to succeed than those requiring subsidies that by their nature are subject to political risk.

This study first undertakes a financial cost-effective analysis of the alternative water heater systems in use: electrical heater, gas (LPG) heater, and the combinations of an SWHS with electricity back-up and SWHS with a gas heater back-up for winter use for situations in which there is unreliability of water supply. Second, we investigate how a reliable (continuously pressurized) potable water supply would affect the relative cost-effectiveness of the alternative water heating systems. The policy implications of the results of this analysis are then considered.

1.1. Background

Cyprus is the third largest island in the Mediterranean. Its climate is characterized by hot, dry, summers and mild winters. The average daily sunshine is 12.5 hours during the summer months and 5.5 hours during the winter months. Over the year the average daily solar radiation is 5.4 kWh per m^2 (Kalogirou, 1997). However, the island has a chronic shortage of surface water and groundwater as a result of inadequate rainfall.[1] In addition, many areas of North Cyprus have low-quality water in terms of salinity and scaling.[2] Therefore, the water utilities cannot supply reliable potable water to their customers. Another problem faced by residents is that North Cyprus experiences frequent electricity outages.

Most households have undertaken multiple investments to provide a reliable supply of water in order to overcome the problems of unreliable water and electricity supplies. First, in order to

[1] It is estimated that the groundwater level has decreased by over 90% from the 1960s to the present (Secretariat-General of The National Security Council, Republic of Turkey).
[2] Quality of water is an important factor that influences on the performance of SWHSs (Raisul Islam et al., 2013).

cope with intermittent water supply, residents install water tanks with an average size of 2 m^3 at the ground level of their house or apartment building. This allows them to maintain a continuous supply of water for household consumption, even when there are frequent interruptions in the supply of water from the utility. Second, they also install water tanks with an average size of 1 m^3 on the roof of their house or apartment building. These rooftop tanks address both of these problems. They provide additional water storage, and at the same time provide water through gravity to the house in the case of electricity outages when a water pump would not operate.[3] Third, a water pump of about 1 hp is used to pump water into the tank on the roof. This pump is needed because of the lack of water pressure from the supply of water by the water utility. The various storage tanks are not pressurized. Fourth, if the household is heating its water with an SWHS, a hot water tank equipped with an electric heater at 3-kW rating with capacity in the range of 120–200 liters is installed below the storage tank on the roof.

Solar thermal collectors (solar panels) have largely replaced the use of electricity in water heating. According to the national census (2006), 71% of households have solar panels in order to benefit from the use of solar energy for water heating.[4] The location of such panels on the roof of the building in tandem with the hot and cold water storage tank allows residents to use hot water on sunny days, even if there is an electricity outage or if there is no municipal water supply at that time.

To summarize, residents have perceived these investments as averting expenditures against unreliable supplies of both water and electricity. When solar panels are used, the system both

[3] The Northern Cyprus Water Supply Project was implemented in order to address chronic water shortages. It will transport water for household consumption and irrigation from southern Turkey to North Cyprus via pipelines under the Mediterranean. Construction of the project started in March 2011 and is expected to be completed in 2015 (Secretariat-General of The National Security Council, Republic of Turkey).

[4] This proportion is lower than that of South Cyprus, which is the world's leader on a per capita basis (REN21, 2013) and where 93% of houses have solar panels (Kalogirou, 2009b).

conserves electricity and protects the consumer from the problem of unreliable electricity supply by heating water for a significant part of the year.

1.2. SWHS configuration in North Cyprus

Thermosyphon or natural circulation solar water heaters consisting of flat plate collectors, a hot water tank fitted with an auxiliary electric heater and connecting pipes are the most widely used systems. They heat water and use natural circulation to transport it from the collector to the tank. Natural circulation occurs because the density of the water decreases as the temperature increases. Therefore, when the solar collector array absorbs solar radiation, the water in the collector is heated, and thus expands and rises through the collector header into the top of the hot water tank. The cooler water in the tank sinks to the bottom and flows down to the collector. This circulation continues until sunset.

The SWHSs available on the market are either locally manufactured or imported from Turkey. Local SWHSs are manufactured with lower-quality materials and using less-advanced manufacturing techniques than imported SWHSs.[5] However, they consist of two flat plate collectors with total net absorber area in the range 3.2–4.0 m^2, while imported SWHS consist of one collector with net absorber area in the range 1.6–2.2 m^2. Locally manufactured systems dominate the market as they can be purchased at lower prices than systems imported from abroad.[6] Although the local manufacturers receive no tariff protection from imports, they have been quite successful in competing with imports and capturing the local market. The development of this industry is a good example of the potential for linkages between efficient

[5] The panels of imported SHWSs are more durable against hard water, and hence their lifetimes are longer compared with locally manufactured panels (Atikol et al., 2013).

[6] Retail prices of the panels are correlated with the types of materials used. Panels made of copper cost almost twice as much as panels made of steel; however, they have higher thermal conductivity. This study considers the copper panels.

and competitive local enterprises and the demand for equipment designed to produce energy from renewable sources. In this study, we evaluate the financial feasibility of locally manufactured SWHSs.

2. Method

2.1. Literature Review

Atikol et al. (2013) investigated solar energy applications consisting of photovoltaic (PV) electricity generation, hot water production, space heating and passive cooling for a housing project developed in North Cyprus. They found that SWHSs are more financially viable than 3-kW electric heaters for hot water production.[7] Kalogirou (2009b) found that SWHSs are economic in South Cyprus: the lifecycle savings of households are potentially more than 2000 euro, while SWHSs with electricity back-up costs only 500 euro. Ozsabuncuoglu (1995) and Kablan (2004) evaluated the financial viability of SWHSs versus conventional water heaters in Turkey and Jordan, both of which have identical solar radiation levels to those in Cyprus. They found that SWHSs could be competitive with other types of water heating systems. Diakoulaki et al. (2001) and Kaldellis et al. (2005) carried out a cost–benefit analysis to compare SWHSs with conventional technologies in Greece. They found that although replacing electrical or diesel water heaters with SWHSs resulted in a considerable net social benefit, the use of natural gas for water heating gave greater economic net benefits owing to its lower cost.

[7] Atikol et al. (2013) calculated annual energy obtained from solar panels, taking into account average daily solar radiation data and assuming it is equivalent to annual energy savings by the household. They concluded that SWHSs are financially viable for water heating. However, Kalogirou (2009b) found that hot water supplied by SWHSs exceeds the hot water demand in summer in South Cyprus. Therefore, losses in summer as well as disregarded tank losses lead to energy savings being overestimated. In this study we take into consideration the coincidence of the hourly demand for hot water and the hot water supplied by SWHSs.

In addition, a number of recent studies have evaluated the financial analysis of SWHSs (Cassard et al., 2011; Giglio et al., 2014; Naspolini and Rüther, 2012; Raisul Islam et al., 2013). As a result of increased concern about the environmental impacts of energy consumption, a number of studies have also examined the environmental benefits of SWHSs (Allen et al., 2010; Fraisse et al., 2009; Han et al., 2010; Hang et al., 2012; Li et al., 2011).

2.2. Cost-effectiveness Analysis

In this study a cost-effectiveness analysis of the alternative water heating technologies is undertaken, taking into consideration lifecycle costs, namely capital costs, and maintenance and operation costs. In the case of SWHSs, the benefits in terms of energy saving need to be estimated in order to find out the most financially attractive system for water heating from the perspective of consumers. We use the levelized cost of energy (LCOE) criteria to compare the cost per cubic meter of hot water consumption of these technologies (Short et al., 2005). The LCOE for a given technology is a constant price (in real terms) that would equate the net present value of lifecycle cost with net present value of lifetime energy (hot water) production.

$$\sum_{n=0}^{N} q_n \frac{LCOE}{(1+r)^n} = \sum_{n=0}^{N} \frac{C_n + O_n + M_n}{(1+r)^n} \quad <=> \quad LCOE = \frac{\sum_{n=0}^{N} \frac{C_n + O_n + M_n}{(1+r)^n}}{\sum_{n=0}^{N} \frac{q_n}{(1+r)^n}}$$

where q_n is annual energy production, C_n is capital cost in year *n*, O_n is operation cost in year *n*, M_n is maintenance cost in year *n*, *r* is the real discount rate, *n* represents *n* year lifecycle and *N* represents the lifespan of the analysis.

2.2.1. Method of estimating quantity of energy saved by SWHSs

The proportion of the annual load met by SWHSs depends on daily hot water consumption, size of hot water storage tank, size and efficiency of solar panels, and climatic conditions (Allen et al., 2010; Tsilingiridis and Martinopoulos, 2010).

Although dynamic simulation software programs such as TRNSYS, WATSUN, and Polysun have in recent years been replacing design methods for estimating solar savings, design methods are still useful as they are less demanding in terms of data requirements (Kalogirou, 2009a; Koroneos and Nanaki, 2012; Martinopoulos et al., 2013; Raisul Islam et al., 2013; Tsilingiridis and Martinopoulos, 2010).

The benefit in terms of the quantity of energy saved by SWHSs is estimated using the f-chart method (Beckman et al., 1977; Duffie and Beckman, 2006). This design method is easy to use and provides adequate estimates of long-term thermal performance. It correlates the results of large numbers of thermal performance simulations of solar heating systems. The resulting correlations give the proportion of the monthly heating load covered by solar energy, $f_{i,}$ as a function of two dimensionless parameters, X and Y, as:

$$f_i = 1.029Y - 0.065X - 0.245Y^2 + 0.0018X^2 + 0.0215Y^3 \quad (1)$$

X is related to the ratio of collector losses to heating loads,

$$X = \frac{A_c F_R' U_L (T_{ref} - T_a) \Delta t}{L} \quad (2)$$

and Y is related to the ratio of absorbed solar radiation to heating loads,

$$Y = \frac{A_c F_R' (\mathrm{T}\alpha) H_T N}{L} \quad (3)$$

where A_c is collector net absorber area (m^2), F_R' is collector heat exchanger efficiency factor, U_L is collector overall loss coefficient (W/m^2 °C), T_{ref} is the empirically derived reference temperature (100 °C), T_a is the monthly average ambient temperature (°C), Δt is the total number of seconds in a month, L is the total monthly heating load for hot water (*J*), (Tα) is the monthly average transmittance-absorbance product, H_T is the monthly average daily radiation incident on the collector surface per unit area (*J*/m^2), and *N* is number of days in the month.

X and Y can be rewritten as:

$$X = F_R U_L * \frac{F_R'}{F_R} * \left(T_{ref} - T_a\right) * \Delta t * \frac{A_c}{L} \quad (4)$$

$$Y = F_R (T\alpha)_n * \frac{F_R'}{F_R} * \frac{(T\alpha)}{(T\alpha)_n} * H_T * N * \frac{A_c}{L} \quad (5)$$

where $F_R U_L$ and $F_R(T\alpha)_n$ are obtained from collector test results, $\frac{F_R'}{F_R}$ is equal to 1 as there is no heat exchanger in the hot water tanks in North Cyprus, and $\frac{(T\alpha)}{(T\alpha)_n}$ can be taken to be constant at 0.96 over a year (Duffie and Beckman, 2006).

The monthly total energy load, L, to heat water to the desired temperature is calculated by

$$L = mC_p(T_d - T_m) \quad (6)$$

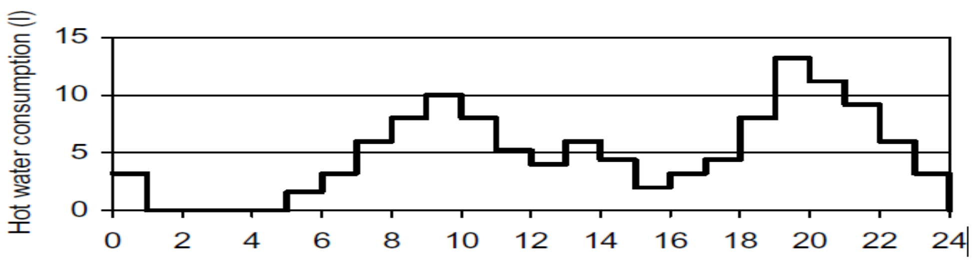
where m is monthly hot water consumption (liters)[8], C_p is the specific heat of water (*J*/liter °C), 4190 *J*/liter °C, T_d is the desired hot water temperature, set at 50 °C and T_m is the average

[8] Average monthly water consumption per capita is 4 m^3 in North Cyprus (information obtained from various municipal water supply departments in the country). Based on the RETScreen software assumption of hot water consumption, this is assumed to be one third of total water consumption (daily hot water consumption is 40 liters/person). RETScreen is free-of-charge Excel-based software developed by the Government of Canada to analyze technical and economic viabilities of renewable energy projects, including SWHSs.

temperature of water in the tank. It is important to point out that L should also include losses from the hot water tank and the connecting pipes.

The f-chart method uses the repetitive normalized profile of hourly hot water consumption adopted by Mutch (1974). The adjusted normalized profile with respect to daily hot water withdrawal of 120 liters for a household size of three is illustrated in Figure 1.[9]

Fig. 1. Daily hot water consumption profile (Kalogirou, 2009b)



After the proportion of the monthly heating load, f_i is determined, the proportion of the annual heating load supplied by an SWHS, Ƒ, can be obtained as follows:

$$Ƒ = \frac{\sum f_i L_i}{\sum L_i} \quad (7)$$

2.3. Data and Assumptions

2.3.1. Technical information for SWHSs

Cassard et al. (2011) and Fraisse et al. (2009) found that the absorber area of the collector is one of the most significant variables in estimating energy savings. It has been the normal manufacturing practice in North Cyprus to make the total absorber area of the locally manufactured collectors almost twice that of the imported SWHSs. Although the efficiency of the locally made collectors is lower than the imported solar collectors for same area, the overall

[9] It is difficult to estimate residents' daily hot water consumption profile, particularly in developing countries. Kalogirou (2009b) used this hot water consumption profile for residents of South Cyprus when evaluating the financial viability of SWHSs.

supply of hot water from the local SWHS is very similar to that of the imported system.[10] Technical information for the types of SWHS that are imported is readily available and is used in the current analysis because such data is not available for the locally manufactured SWHS.[11]

Studies have often conducted a financial analysis of SWHSs on the basis of a typical family size. However, energy saving estimations may vary significantly with the number of family members in a household, as this will affect the daily load volume (Cassard et al., 2011; Gillingham, 2009; Lin et al., 2015). For this reason, we estimate separately the energy savings for families with two to five members, while at the same time adjusting the size of the corresponding SWHS.[12] To do this, we assume that households behave rationally while buying their SWHS so that they consider both their daily projected water consumption and the system's hot water tank capacity. The correct sizing of the tank capacity for the household's daily water consumption is critical for the efficient utilization of the solar energy in the spring and fall. It is also critical in winter when solar radiation is low, if the required heating load during winter is being met largely by electrical energy. In this respect, we assume that households with two, three, and either four or five members have system A, system B, and system C, respectively. Technical efficiency parameters and system sizes of the SWHSs analyzed are presented in Table 1.

[10] Atikol et al. (2013), when evaluating the financial viability of both imported and local SWHSs, estimated similar energy savings for both systems.
[11] Imported SWHSs are certified by the Solar Rating & Certification Corporation (SRCC), which administers certification, rating and labeling programs for solar thermal collectors and complete SWHSs. The SRCC provides specific information on the collectors and systems certified under the various SRCC certification and ratings. For more information see: http://solar-rating.org.
[12] 85% of households in North Cyprus with SWHSs have two to five members (State Planning Organization (SPO)).

Table 1. Characteristics of the SWHSs under evaluation

System	A	B	C
Family size	2 people	3 people	4 or 5 people
F_RU_L	4.00	3.79	3.64
$F_R(\tau\alpha)_n$	0.711	0.73	0.705
Tank capacity	120 liters	150 liters	200 liters
Net absorber area	1.62 m^2	2.11 m^2	2.23 m^2

Source: SRCC website: https://secure.solar-rating.org/Certification/Ratings/RatingsSummaryPage.aspx.

2.3.2. Benefit of SWHSs

Once meteorological data and technical parameters of SWHSs have been gathered and the required monthly heating load determined, the proportion of the monthly load, and hence the proportion of the annual load, supplied by SWHSs is estimated using the *ƒ*-chart method. The energy savings for a typical household size of three based on daily average hot water consumption per person are presented in Table 2.

Table 2. Monthly and annual solar saving estimates for a typical household size of three

Month	H_T,MJ/m^{2*}	$T_a{}^*$	$T_m{}^*$	L, MJ	X	Y	*ƒ*	*ƒ*L,MJ	*ƒ*L,kWh**
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
(1) Jan	8.9	12.2	14.8	801	2.58	0.52	0.32	255	71
(2) Feb	12.4	11.9	14.9	724	2.61	0.72	0.47	337	94
(3) Mar	17.4	13.9	16.9	757	2.84	1.07	0.68	514	142
(4) Apr	21.5	17.5	20.7	652	3.39	1.49	0.86	562	156
(5) May	26.1	21.6	25.4	573	4.30	2.13	1.00ᵼ	573	159
(6) June	29.2	25.9	29.8	460	5.48	2.87	1.00ᵼ	460	128
(7) July	28.5	29.3	33.3	398	6.84	3.35	1.00ᵼ	398	110
(8) Aug	25.5	29.4	33.4	396	6.89	2.99	1.00ᵼ	396	110
(9) Sep	21.2	26.8	30.6	442	5.75	2.17	0.99	435	121
(10) Oct	15.3	22.7	25.8	559	4.37	1.28	0.71	398	110
(11) Nov	10.3	17.7	20.3	656	3.30	0.71	0.42	276	77
(12) Dec	7.9	13.7	16.3	767	2.75	0.48	0.28	212	59
(13)Total				7189				4821	1335

* Meteorological data for Nicosia, Cyprus's capital, is used in the analysis. It is assumed that the cold water temperature, T_m, is equal to earth temperature (Kalogirou, 2003). Source: Stackhouse and Whitelock (2008).

** 1 MJ = 0.277 kWh

ᵼ There is excess supply in the range 5–15% during the period May–August. Therefore, corresponding monthly proportions are corrected in order to avoid exaggerated outcomes.

Based on estimates from Table 2, all required heating load for water heating can be provided by an SWHS for the months May–September for a typical household size of three (see column 7). The total required heating load in winter is almost twice that of the total load in the summer, owing to considerably colder mains water temperature and higher tank losses during winter (see column 4). In addition, owing to low solar radiation levels in winter (see column 1), the proportion of the annual heating load met by solar energy is estimated to be 67%.[13]

Percentages of heating load met by SWHSs for a household size of two to five by month are shown in Figure 2.

Fig. 2. Proportion of heating load supplied by an SWHS for a household size of two to five

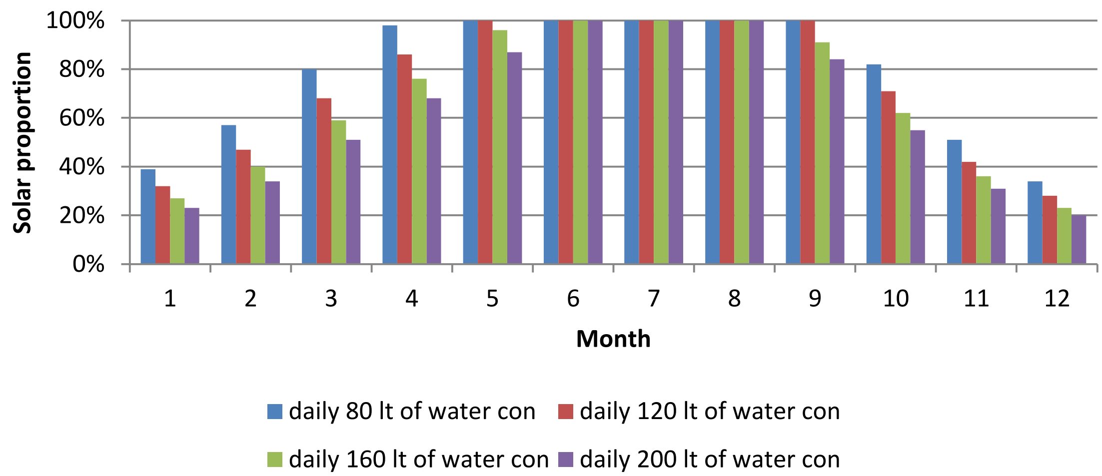


Figure 2 shows that in the summer months, even families with four or five members consuming 160 or 200 liters of hot water per day can have their hot water needs met completely through SWHSs, while in May and September over 80% of their needs are met. Furthermore, SWHSs can potentially contribute up to 50% of the heating load, even in the winter months where a back-up system is needed.

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[13] The proportion of the load met by SWHSs is estimated using equation (7): Ƒ = 4821/7189=0.67 (see row 13).

2.3.3. Cost and parameter values for alternative water heating systems

In order to carry out a financial analysis of the water heaters, the capital cost and the maintenance cost data are obtained by undertaking of a survey of five different local equipment suppliers and maintenance providers in the cities of Nicosia, Famagusta, and Kyrenia.[14] Because prices vary slightly across different suppliers and maintenance providers, we use the average cost of such equipment and maintenance.

None of the equipment or heavy fuel oil (HFO) for electricity generation nor the LPG for the water heating is subject to excise taxes or tariffs, whether imported or domestically produced. The only tax levied on the equipment and fuels is the valued added tax (VAT) that is generally applied. Furthermore, there are no subsidies for the purchase of either equipment or fuel.

For many years in the past the cost of electricity generation was partially subsidized by the state. This was no doubt a factor that caused many people either to heat water using electricity or to use electricity as a back-up to an SWHS. In recent years, however, electricity prices have been maintained very close to, and perhaps slightly above, the long-run cost of electricity generation and delivery. The following analysis is carried out without needing to consider such fiscal distortions.

Average capital and maintenance costs of the water heating systems under evaluation are shown in Table 3.

[14] North Cyprus consists of five districts: Nicosia, Famagusta, Kyrenia, Iskele, and Guzelyurt. According to the national census, 81.6% of the total population lived in Nicosia, Famagusta, and Kyrenia in 2011 (SPO).

Table 3. Average capital and maintenance costs of the water heating systems

Type of water heater	Electrical heater	SWHS with electricity back-up	Gas heater
Capital cost	700 TL	1400 - 1750 TL	450 TL
Electrical element cost	100 TL	100 TL	-
Hydrophore cost	-	-	150 TL
Installment cost	50 TL	50 TL	250 TL
Maintenance cost	-	-	100 TL

TL refers to Turkish Lira. Average exchange rate is 1 US$=2.20 TL as of November 2014.

According to the maintenance providers interviewed, the lifetime of the electrical heating element in the hot water tank is shortened as a result of the low water quality. From their experience, the lifetime varies between one and five years depending on water quality supplied by the water utility and the usage of electricity for water heating.

A major inefficiency with having an electric water heater on the roof is the waste of hot water from cooling in the pipes from the roof to the places where hot water is needed within the house. This distance is often 10–25 m, particularly in apartment buildings. This is not a significant problem in the summer months with an SWHS, as there is an abundance of hot water. A major problem arises in the winter months with an SWHS that uses electricity for winter back-up. Because the electrical element is built into the SWHS tank it must be located some distance from where the hot water is being used. In the estimations carried out here, we assume that if an all-season electrical heating system is installed, it will be located close to the place where the water is being used. Likewise, LPG water heaters are a separate appliance that can be located close to hot water intake into the house, either when they are the sole provider of energy or when they are used as the winter source of energy, coupled with an SWHS.

The lifetime of the analysis is taken as 20 years, which is the estimated lifetime of the SWHS equipment.[15] A real rate of 10% is used as the private discount rate for North Cypriot residents.

2.3.4. Electrical heaters

It is estimated that the efficiency rate of the electric heater in the hot water tank is 85% (Personal Communication, Department of Mechanical Engineering, Eastern Mediterranean University). The length of life of the heating element for residents using only electricity is one year in the base case scenario. It should be noted that the electricity price is set at 0.605 TL/kWh, including 10% VAT, as a base case because an average resident pays at the second block tariff rate (Ozbafli, 2011).[16] We assume that the electricity price (in real terms) would be constant throughout 20 years as a base scenario. Other electricity and fuel price scenarios are addressed in the sensitivity analysis.

2.3.5. Gas heaters[17]

Some households use gas heaters that use LPG as a heat source for water heating owing to their lower initial capital costs. Households using gas heaters alone do not need to install a hot water tank under the cold water tank on the roof.[18] Owing to the low water pressure a hydrophore unit needs to be installed to pump the water into the gas heater. The lifetime of the gas heaters and hydrophore unit are seven and five years, respectively, if used as the exclusive supplier of hot

[15] The lifetime of the hot water tank under consideration is estimated to be 20 years, while the lifetime of the solar panels is estimated to be 10 years owing to the low water quality causing scale formation in the collector system.

[16] An increasing block tariff structure is used for the pricing of electricity for the residential sector in North Cyprus. As of November 2014, residential consumers pay 0.45 TL/kWh for the first 250 kWh, 0.55 TL/kWh for consumption of 251–500 kWh, 0.67 TL/kWh for consumption of 501–750 kWh, and 0.84 TL/kWh for consumption above 750 kWh excluding 10% VAT (Cyprus Turkish Electricity Authority, Kib-Tek website: http://kibtek.com/Tarifeler/tarife18012014s.pdf).

[17] The estimated annual heating load for a gas heater is lower than that for an SWHS. The reason is that tank heat losses are included in the heating load in the case of SWHS usage. Moreover, desired hot water temperature is assumed to be lower (set at 45°C), as hot water is not stored.

[18] Gas heaters are connected to the cold water tank because hot water flowing through the hot water tank potentially harms the heater's thermal performance and also shortens its life.

water. The efficiency rate of gas heaters is 80% (Personal Communication, Department of Mechanical Engineering, Eastern Mediterranean University). In addition, gas heaters need to be regularly serviced once a year. To estimate the electricity cost of operating the hydrophore unit, a standardized time for showering for a person is considered.[19]

2.3.6. SWHS with electricity back-up

Unlike for gas heaters, there is no maintenance service for solar panels. However, households that have the panels should clean them periodically, as soiling due to dust, dirt and particularly bird droppings reduces their efficiency. The life expectancy of the heating element when residents use an SWHS with electricity back-up is assumed to be three years.[20]

In order to take into account the standby heat loss through pipes in the case of an SWHS with electricity back-up, we assume that a daily average of 10 liters of water and its heat per capita would be wasted during a six-month period when electricity as a source of energy is used to heat water.

2.3.7. SWHS with gas heater back-up

SWHSs combined with gas heaters as back-up have the highest capital costs. Households with such systems invest in both an SWHS and a gas heater. However, this has a convenience factor in that the system supplies hot water on demand in the winter months. One does not have to remember to turn on the electrical element to heat the water or wait to drain the cold water out of

[19] A standardized six-minute showering time for a person is used in order to estimate daily operation duration of the hydrophore unit (Sezai et al., 2005).

[20] The lifetime of the electrical element may be highly variable from one region to another, depending on water quality. Residents using an SWHS with electricity back-up in Famagusta, which has the lowest water quality in the country, may potentially need to replace their element every year. In contrast, the lifetime of an element may be more than five years in Nicosia and Kyrenia, which have a relatively higher quality of water.

the pipes before receiving usable hot water. Gas heaters are mainly used in the period November–February, when the contribution of SHWSs to the total required heating load is low. The gas heaters completely replace SWHSs during these months. Electricity may be used to supplement the heating of the water instead of LPG in the spring and fall. The lifetime of the heating element is assumed to be five years as a base scenario in this case. The experience in North Cyprus is that gas heaters last 10 years when they are used as a back-up to SWHSs during the winter season.

3. Results and Discussion

3.1. Financial attractiveness of SWHS

Taking the efficiency factor of the electrical water heater to be 85%, households with solar panels connected to their hot water tanks are able to save electrical energy of 1340–1910 kWh per annum depending on family size. This is equivalent to at least 670 TL (US$ 305) and 950 TL (US$ 430) savings on electricity bills annually for families with two and five members, respectively. Hence, the payback period of an SWHS compared with that for heating all the water using electricity is estimated to be about two years. To put it differently, the levelized cost per unit energy saving is estimated to be in the range of 0.11–0.14 TL/kWh, depending on the family size, while the cost of electricity is at least 0.495 TL/kWh and the cost of LPG is 0.34 TL/kWh. To conclude, the SWHS is relatively financially very attractive in North Cyprus as a replacement for the energy obtained from electricity or LPG. However, while the SWHS may be the most cost-effective producer of energy for use in water heating, the question remains as to which water heating system, including both equipment and energy costs, is the most cost-effective in providing a year-round supply of hot water to households, given the seasonal nature of the weather in Cyprus.

3.2. SWHSs with electricity back-up versus alternative water heaters on the base case

The results are expressed as the levelized cost of hot water consumption per cubic meter for the four systems being studied and are presented in Table 4.

Table 4. Levelized costs of hot water consumption (TL/m^3) under base case

Daily water consumption (liters)		Levelized cost per cubic meter (TL/m^3)			
		Electricity only (1)	Gas heater only (2)	SWHS with electricity back-up* (3)	SWHS with gas heater back-up (4)
(1)	80	43.4	21.9	21.9	21.5
(2)	120	36.3	18.1	20.0	17.6
(3)	160	32.8	16.9	19.6	16.1
(4)	200	30.6	16.1	19.3	15.2

* To estimate cost of heat loss through pipes, we use average variable cost of electricity used to heat water per cubic meter.

Based on the estimations presented above, electricity usage for the daily purpose of water heating is very costly. The cost of hot water per cubic meter of 30.6–43.4 TL/m^3 (US$ 13.90–19.70/m^3) is approximately double the cost of heating water by LPG gas alone or with an SWHS with gas back-up. Gas heaters and SWHSs with either electricity or gas back-up are competitive for households with daily water consumption of 80 liters (see row 1). However, SWHSs with gas heater back-up become more economical as the daily demand for hot water rises, even though households need to invest in a gas heater in addition to the equipment needed for the SWHS.

3.3. Sensitivity Analysis

The results from empirical estimations are expected to be sensitive to the parameters including the real prices of fuel oil and LPG, the real discount rate used, the marginal electricity tariff rates paid by households in winter when electricity is used as a back-up, and the lifetime of the electrical element. The last two of these variables potentially affect the viability of the SWHS with electricity back-up. The levelized cost estimations for a system that only uses electricity to heat water are omitted in the following sections because they are far from being competitive in any situation, as compared to the other systems.

3.3.1. Sensitivity analysis with respect to changes in the real price of fuels

North Cyprus is an oil-importing country and its energy mix relies entirely on imported HFO to produce electricity and LPG for heating and cooking. Hence, the marginal cost of electricity generation is highly correlated with fuel oil prices. Although forecasting energy prices is uncertain, energy prices will undoubtedly change. To assess the effect of this on our estimations, we consider alternative average energy prices (in real terms) over 20 years compared to the base price projections, rather than assuming a specific annual price escalation rate. It is assumed that the movements in HFO and LPG prices are perfectly correlated. In this respect, the sensitivity results shown in Table 5 are based on average changes in the level of prices over the life of the analysis in the range of −10% to 10% of the base prices.

Table 5. Sensitivity analysis of levelized cost of hot water (TL/m^3) with respect to average real prices of fuels over 20 years

		Gas heater			SWHS with electricity back-up			SWHS with gas heater back-up		
Average real price of fuels (TL)		10% less (1)	Base cost (2)	10% more (3)	10% less (4)	Base cost (5)	10% more (6)	10% less (7)	Base cost (8)	10% more (9)
Daily water consumption (liters)										
(1)	80	20.5	21.9	23.2	20.4	21.9	23.3	20.8	21.5	22.2
(2)	120	16.8	18.1	19.3	18.6	20.0	21.5	16.9	17.6	18.4
(3)	160	15.6	16.9	18.1	18.1	19.6	21.1	15.3	16.1	16.9
(4)	200	14.9	16.1	17.4	17.7	19.3	20.9	14.3	15.2	16.1

Changing the average real prices of electricity and LPG for the 20 years of the analysis results in insignificant changes in the costs of hot water so that the relative costs of the three alternatives are changed only in minor ways. The most significant change is that for heavy users of water the relative advantage of SWHSs with gas back-up is increased over heating with gas alone if the energy prices increase (see row 4, columns 3 and 9). In this situation the high cost of electricity makes SWHSs using electricity as a back-up less competitive than either using a gas heater alone or using a SWHS with a gas heater back-up. Furthermore, SWHSs with gas heater back-up would still be competitive with gas heaters for all households even if the energy prices decline by 10% (see columns 1 and 7).

3.3.2. Sensitivity analysis with respect to real discount rate

The size of the real rate of discount has a significant impact on calculating the present values and thereby the levelized costs. One might loosely relate the discount rate to the level of income of families. Families with low incomes and those with consumer loans are likely to have a higher opportunity cost of funds, and hence, a higher discount rate. The opposite could be the case for high-income families who are net savers and have a lower return on their invested funds. The effects of this key parameter for values between 5% and 15% are reported in Table 6.

Table 6. Sensitivity analysis of levelized cost of hot water (TL/m^3) with respect to the real rate of discount

		Gas heater			SWHS with electricity back-up			SWHS with gas heater back-up		
Real discount rate		5% (1)	10% (2)	15% (3)	5% (4)	10% (5)	15% (6)	5% (7)	10% (8)	15% (9)
Daily water consumption (liters)										
(1)	80	21.3	21.9	22.4	20.6	21.9	23.2	19.6	21.5	23.5
(2)	120	17.7	18.1	18.4	19.1	20.0	21.0	16.2	17.6	19.0
(3)	160	16.6	16.9	17.1	18.8	19.6	20.4	15.0	16.1	17.2
(4)	200	15.9	16.1	16.3	18.7	19.3	19.9	14.3	15.2	16.1

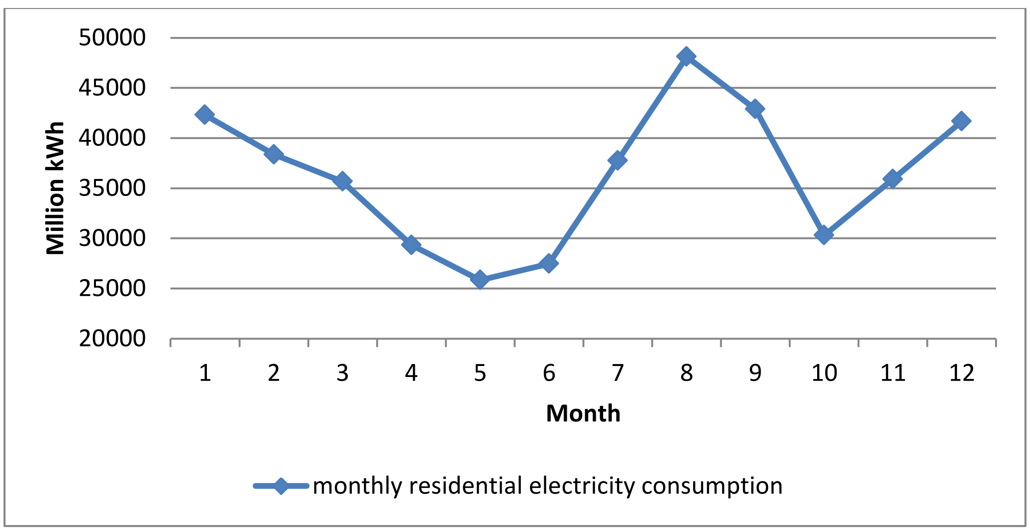
As can be seen from Table 6, the levelized cost of the gas heater is less responsive to variations in the discount rate because gas heaters have lower capital costs but higher operation costs than

SWHSs (see any row and columns 1–9). Gas heaters become most cost-effective compared to SWHSs with either electricity or gas heater back-up for households with discount rates of 15%. Conversely, for people with low discount rates the SWHS with a gas heater back-up becomes more attractive than gas heaters for all levels of hot water consumption (see columns 1 and 7).

3.3.3. Sensitivity analysis with respect to households' marginal electricity tariff rates in winter

The contribution of SWHSs to the total required heating load is around one third in the period November–February. In other words, households with SWHSs with electricity back-up use mainly electricity as the source of energy for water heating in this period. Total household consumption of electricity is highest during the winter months of December, January and February, except for the summer peak, as shown in Figure 3.

Fig. 3. Monthly total residential electricity consumption as of 2012 (Kib-Tek)



Many households when using electricity to heat water will be paying at the third block price of 0.737 TL/kWh during these months. As a result, SWHSs that use an electrical element become more costly compared with alternative water heaters for these households, as shown in Table 7.

Table 7. Sensitivity analysis of levelized cost of hot water (TL/m^3) with respect to households' marginal electricity tariff rates in winter

		Gas heater[Ŧ]		SWHS with electricity back-up			SWHS with gas heater back-up[Ŧ]	
Electricity tariff rate (TL/kWh)		0.495 (1)	0.605 (2)	0.495 (3)	0.605 (4)	0.737 (5)	0.495 (6)	0.605 (7)
Daily water consumption (liters)								
(1)	80	21.3	21.9	20.6	21.9	23.2	19.6	21.5
(2)	120	17.7	18.1	19.1	20.0	21.0	16.2	17.6
(3)	160	16.6	16.9	18.8	19.6	20.4	15.0	16.1
(4)	200	15.9	16.1	18.7	19.3	19.9	14.3	15.2

Ŧ The values based on first-second block tariff rates as gas heaters are used for water heating.

It is important to note that these estimations show that prices of alternative supplementary energy sources for SWHSs have a significant impact. On the one hand, for households consuming 80 liters of hot water per day and using less than electricity of 250 kWh monthly in winter, the SWHS with electrical back-up becomes the most economical system (see row 1, columns 1, 3 and 6). On the other hand, the cost of the SWHS with electricity becomes 50% more expensive than that of the SWHS with gas heater back-up for households consuming 200 liters of hot water per day and paying at the third block price tariff in winter (see row 4 and columns 5 and 7).

3.3.4. Sensitivity analysis with respect to lifetime of electrical element

The lifetime of the electrical heating element is highly critical when evaluating the cost-effectiveness of an SWHS with electricity back-up. Therefore, it is necessary to conduct a sensitivity analysis on this parameter. We analyze how the SWHS with electricity back-up cost estimations change as the lifetime of the heating element varies between one and five years. No adjustment is made for the case of SWHSs with gas heater back-up as the electrical element is rarely used. The results are presented in Table 8.

Table 8. Sensitivity analysis of levelized cost of hot water (TL/m^3) with respect to lifetime of the electrical element

		Gas heater	SWHS with electricity back-up			SWHS with gas heater back-up
Lifetime of the element (years)		no element (1)	1 (2)	3 (3)	5 (4)	5 (5)
Daily water Consumption (liters)						
(1)	80	21.9	20.6	21.9	23.2	21.5
(2)	120	18.1	19.1	20.0	21.0	17.6
(3)	160	16.9	18.8	19.6	20.4	16.1
(4)	200	16.1	18.7	19.3	19.9	15.2

The results reported in Table 8 show that the SWHS with electricity back-up loses its competitiveness with alternative water heaters for households using 80 liters of water per day when the element is required to be replaced each year (see row 1).

To draw a general conclusion from these sensitivity analyses, gas heaters alone may become the most cost-effective alternative for households with higher discount rates who heat relatively small amounts of low-quality water. For these households the additional upfront costs of investing in SWHSs might not be worthwhile. This conclusion is also consistent with the observed preferences of residents of North Cyprus on water heating systems. In Famagusta, which has lowest quality of water in the country, the proportion of households using SWHSs is 65%, while the usage is 75% in Nicosia and Kyrenia, which have a higher-quality water supply (SPO).

3.4. SWHS with electricity back-up versus alternative water heaters with pressurized potable water supply

If the water utility were to supply pressurized potable water, households using gas heaters (either alone or as a back-up with an SWHS) would not have to buy a hydrophore unit to pressurize the water supply.[21] Furthermore, a high level of water quality would increase the lifetime of solar panels and electrical elements. In this respect, the lifetime of the element in the case of the SWHS with electricity back-up would be five years and in the case of the SWHS with gas heater back-up it would be 10 years. The lifetime of the solar panels would increase to 20 years.[22] Based on these parameter values, we estimate the levelized costs of the water heaters.[23] We find that real prices of electricity and LPG throughout the lifetime of the project have a minor effect on the estimations, although the findings are sensitive to the real rate of discount used. The results for discount rates in the range 5–15% are presented in Table 9.

Table 9. Levelized costs of hot water consumption (TL/m^3) with pressurized potable water supply

		Gas heater			SWHS with electricity back-up[Ŧ]			SWHS with gas heater back-up		
Real discount rate		5% (1)	10% (2)	15% (3)	5% (4)	10% (5)	15% (6)	5% (7)	10% (8)	15% (9)
Daily water consumption (liters)										
(1)	80	17.4	17.8	18.2	18.8	20.2	21.8	15.8	17.8	19.9
(2)	120	15.1	15.4	15.6	17.8	18.8	20.0	13.6	15.1	16.6
(3)	160	13.9	14.1	14.3	17.7	18.6	19.6	12.7	13.9	15.1
(4)	200	13.2	13.4	13.6	17.8	18.5	19.3	12.3	13.2	14.2

[Ŧ] The estimations based on second block electricity price of 0.605 TL/kWh.

Based on the estimations in Table 9, the continuous supply of pressurized potable water by the water utility makes SWHSs with electricity as a back-up less competitive than using either gas heaters alone or SWHSs with gas heater back-up. The SWHS with gas heater back-up would potentially be the best choice for water heating for all households having the discount rate of 5–

[21] Households with gas heaters (alone or as a back-up with SWHS) would provide reliable hot water on demand.
[22] We obtained information from maintenance providers interviewed from Nicosia and Kyrenia on the lifetime of the electrical element, and solar panels under different conditions.
[23] It is important to note that residents will not need to install cold water tanks or replace their old tanks on the roof once there is a reliable pressurized supply of water. Therefore, our estimations in the case of SWHSs presented in Table 9 would rise slightly for the residents of houses that will be constructed, owing to the additional cost of connecting an SWHS on the roof to the mains.

10%. However, gas heaters would be the most cost-effective option for families with the discount rate of 15% owing to their further lower capital costs and operation costs (see columns 3, 6 and 9).

3.5. Relative greenhouse gas (GHG) emissions

Here we make an approximate comparison of GHG emissions of LPG with those of electricity generation when they are used as a back-up to SWHSs. To do this, we need to take into consideration the efficiency of both the water heaters and the electricity generating power plants as well as their CO_2 emission factors per unit of energy. The power plants in North Cyprus are operated with thermal efficiency using HFO of 33% (Atikol et al., 2013). There are also transmission and distribution loses of about 10% in the delivery of the electricity to the households (Kib-Tek).

The efficiency of converting the energy content of LPG into hot water is 0.80. Therefore, the required supplementary energy should multiply by a factor of 1.25 in the case of LPG. In other words the volume of LPG required is 1.25 times as much as if a 100% efficient gas heater system were available. When using electricity the efficiency of the water heating element is 0.85, hence the adjustment factor is 3.96 of electrical energy needed.[24] This means that 3.96 times as much HFO is required to operate the electricity hot water heating system than would be needed by a 100% fuel efficient system. Furthermore, LPG releases less CO_2 per unit of energy than the HFO which is used in the power plants (U.S. EPA, 2014).

In conclusion, the much smaller volume of LPG used as a supplement to an SWHS will create less than a third as much GHG emissions as using electricity as a back-up source of energy for

[24] The factor for LPG is estimated as 1/0.80=1.25 and for electricity is estimated as 1/ (0.85*0.33*0.9) =3.96.

the SWHS.[25] Furthermore, if water heating is done all year round using an LPG heater, much less gas would be used during the summer months when the ambient water temperature is very high than during the winter months when the LPG water is used all of the time. Hence, we can safely say that the SWHS with electricity back-up will create more GHG emissions than would the use of an LPG gas water heater used throughout the entire year.

4. Conclusions

In almost all circumstances heating water using an SWHS combined with an LPG heater for winter usage is more cost-effective than heating water using electricity. In the vast majority of cases it is also superior to an SWHS that uses electricity as a supplement for winter water heating. In addition to the financial savings in the costs of the SWHS with LPG gas back-up, there is the added convenience of having almost instant hot water in the winter months, and also the advantage of almost eliminating the wastage of hot water through cooling in the distribution pipes that are located outside the building. Only in some special circumstances, and mainly if the public water supply system is modernized, will heating water with an LPG water heater alone be more cost-effective than the SWHS with LPG back-up.

Owing to the GHG emissions from thermal electricity generation, it would appear that the option of an SWHS with LPG back-up will also result in a substantially lower amount of GHG emissions than is the case for the SWHS with electricity back-up.

In the presence of a neutral set of tax and subsidy policies (where electricity, LPG and SWHS equipment are neither taxed differentially nor subsidized) in North Cyprus, the most cost-effective system also has the lowest GHG emissions. In other words, the financially attractive

[25] We did not take into account CO_2 emissions produced in transporting LPG cylinders to retail outlets. However, this fact is unlikely to reverse the conclusions.

option of having an SWHS using LPG as the winter back-up emerges from a relatively distortion-free environment.

North Cyprus is a good example of a situation in which local manufacturers, without any tariff protection from imports or subsidies from the EU budget, have been able to design and build SWHSs that are highly price competitive and meet the needs of the local circumstances. They have been so successful that they have almost wiped out the importation of SWHSs from abroad.

4.1. Policy Implications

The results of this study have a number of implications for the design of energy policies with regard to water heating. A major policy recommendation that emerges from this study is that in climates where solar water heaters are not able to deliver adequate energy throughout the year, it is very important to take into consideration what is to be used as the source of back-up energy along with the design constraints that the alternative back-up systems might impose. In most cases, electricity is assumed as the default supplier of the supplementary energy in an SWHS, particularly when natural gas is not readily available. In Cyprus, with its relative abundance of sunshine and mild (above freezing) winters, this is not the most cost-effective solution. The readily accessible LPG supplies combined with the relatively inexpensive and reliable gas water heaters is an option that needs to be considered.

When designing such energy policies it is important first to investigate what financial incentives exist in a relatively fiscally undistorted market environment. Sustainable solutions may well emerge to deal with real problems through the creativity of local entrepreneurs. In this case LPG gas is used across Cyprus for cooking, and hence there is already an efficient commercial distribution system operating without subsidy. The marginal cost of using LPG in water heating is lower because of the existing distribution system. Similarly, a manufacturing sector has emerged that produces competitive local solar panels for water heating that are designed to operate effectively in a situation with no water pressure and low-quality water.

Finally, policy makers should not assume that all private market solutions are going to be environmentally bad. The market solution of an SWHS with an LPG heater as back-up is both the most cost-effective and the most environmentally friendly.

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