Technical-economic and environmental analysis of DHW systems in Spanish climate zones

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Abstract. There are many systems on the market for domestic hot water (DHW) production. Spanish legislation requires that 60% of the energy needed to produce DHW be of renewable origin. This work analyses the economic, energy and environmental viability of seven DHW production systems installed in six climatic zones of Spain. The systems combine the equipment: gas boiler, solar collectors, heat pump, photovoltaic and electric heater. The calculation tool used for the simulations has been EnergyPlus. Results show that the system that combines solar collectors with gas boiler is the one with the lowest energy consumption and the lowest amount of emissions in all climatic zones, although in areas with intermediate and cold climates, heat pump with photovoltaic system has a similar consumption and emission level. The system with the highest consumption and emissions is the electric boiler. The total life cost analysis includes the capital cost, the annual maintenance and the energy consumption for a 15-year period. In contrast to energy results, the most economical system for the life cycle is the gas boiler for all climatic zones, due to its low capital and maintenance cost. The heat pump system is the best economic alternative to reduce energy consumption and CO_2 equivalent emissions.

Keywords. DHW, heat pump, building efficiency, NetZero Buildings.
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1. Introduction

There are different systems for the production of DHW in single-family residential buildings. The choice of one system or another depends on different factors: cost of the system, accessibility to energy sources or even the space required for equipment. This study analyses the energy consumption, the environmental impact and the economic costs associated with the most common DHW systems in single-family homes. The study is carried out in six climatic zones of Spain.

The models of the different DHW systems have been defined and simulated in Energy Plus [1]. Seven systems have been studied: gas boiler, electric boiler with and without PV, solar thermal with gas and with electric boiler and heat pump with and without PV. Systems include different sources: electricity, natural gas and solar energy.

The second section of the paper shows the characteristics of the different climatic zones used in the analysis. Although these are Spanish cities, the most significant climate parameters are described and cities in other countries with similar climates are indicated. This section also details the characteristics of the seven DHW systems used.

The third section shows the results obtained divided into three topics: energy, CO2 equivalent emissions and economic analysis. Each topic includes an assessment and discussion about the results.

Finally, the fourth section presents the conclusion of the study.

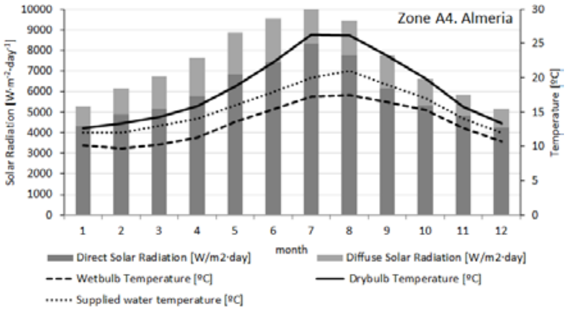
2. Methodology

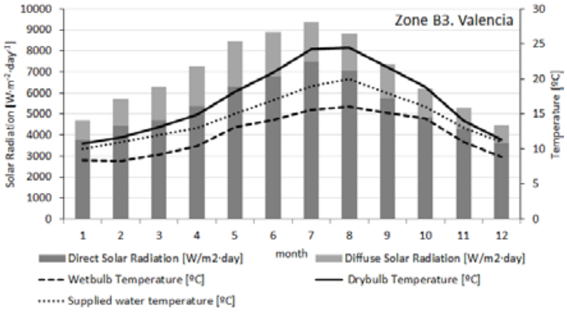
2.1 Climatic zones

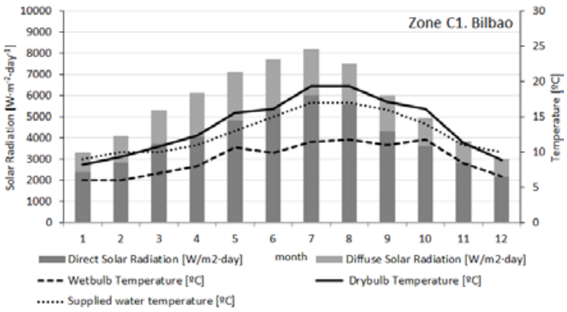
Spanish building regulations [2] divide Spain into 13 climate zones. A zone called alpha for the Canary Islands and twelve zones for the peninsula. Peninsular zones are named by a letter and a number. The letter represents the severity of winter weather and ranges from A (mild winters) to E (more severe winters). The numbers range from 1 to 4, from least to most severe in summer.

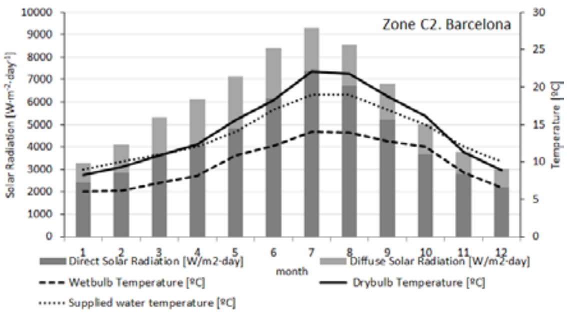
For this study six peninsular climates have been selected, from warmer to colder: A4 (Almería), B3 (Valencia), C2 (Barcelona), C1 (Bilbao) and E1 (León). According to the Spanish meteorological agency (AEMET) [3], the Köppen-Geiger classification of this climates and similar cities are: Almería-BWk: it is the only desert climate in Europe; Valencia-Csa: Naples (Italy); Barcelona-Csb: Toulouse (France); Bilbao-Cfb: Paris (France) and León-Csb: Porto (Portugal).

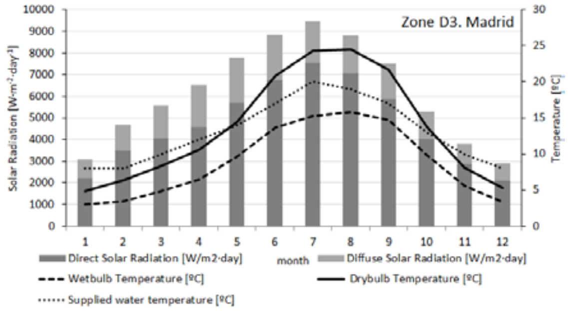
Fig. 1 shows the values of the most representative climatic variables in each area: monthly average outdoor temperature, monthly average wet bulb temperature, monthly average temperature of the tap water, direct radiation and diffuse radiation on horizontal surface.











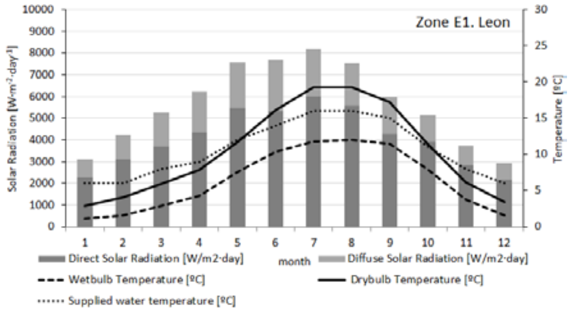


Fig. 1 – Weather data for each climatic zone

2.2 DHW demand

The DHW use profile and daily consumption used in the simulations have been calculated based on Spanish regulations [2] for a house with 4 people. The daily consumption is 165.5 litres of water at 45ºC, distributed as shown in Fig. 2. The highest consumptions are at 8 a.m. and 8 p.m. Simulations made with different profiles have showed similar results [4]. This usage profile is similar to those obtained by Widen for apartments and detached housed [5] on weekdays. There are studies that specify slightly higher daily values for DHW consumption, but do not indicate the water service temperature [6].

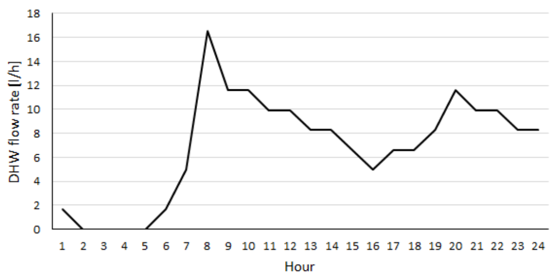


Fig. 2 – DHW demand daily profile.

2.3 DHW systems

The main features of the systems studied are indicated below.

System 1: Gas boiler. Instant production system without accumulation. The boiler has a constant efficiency of 90%. The maximum heating capacity is 20kW with modulating control. The water outlet temperature is 45ºC. The boiler fuel is natural gas.

System 2: Electric boiler. System made of electric heater inside a tank. The loss coefficient per unit area (UA) is 1 $W \cdot K^{-1}$. The electric efficiency is 100% and its capacity 2.4 kW. The tank volume is 0.2 m^3 and it is located outside. The maximum set point temperature of the tank is 50 ºC.

System 3: Thermal solar with gas boiler. The solar collector area in all zones is 4 m^2. The tilt angle of panels is equal to the site latitude: Zone A4 (Almeria) 36.8ºN, Zone B3 (Valencia) 39.5ºN, Zone C1 (Bilbao) 43.3ºN, Zone C2 (Barcelona) 41.4ºN, Zone D3 (Madrid) 40.3ºN and Zone E1 (Leon) 42.6ºN. The solar collectors are oriented to the south.

The solar tank volume is 0.2 m^3 and its maximum temperature is 80 ºC. The solar collector efficiency is shown in equation (1).

$$\eta = 0.757 - 3.994\frac{\Delta T}{I} - 0.009\frac{\Delta T^2}{I} \quad (1)$$

In equation (1), $I\left[\frac{W}{m^2}\right]$ is the inclined surface solar radiation and ΔT $[ºC]$ the temperature difference between water and outdoors, equation(2).

$$\Delta T = \frac{T_{w,in}+T_{w,out}}{2} - T_{outdoors} \quad (2)$$

The boiler is connected in series with the solar system and it turns on when the output temperature of the solar tank does not reach the DHW temperature of 45 ºC. The boiler maximum capacity is 20kW with modulating control.

System 4: Thermal solar with electric boiler. The solar system has the same characteristics as the previous case, but now the system is connected to the tank of system 2, Fig. 3. The specifications of this tank are the same as case 2.

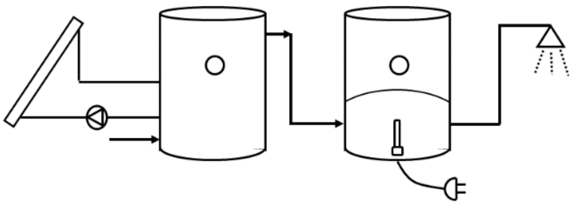


Fig. 3 – Diagram of the thermal solar system with electric boiler.

System 5: Heat pump. This system uses a heat pump as heat generator. For this, the condenser is inside the storage tank. The heating capacity of the condenser and the COP of the heating pump depends on the air and water temperatures. These relations are depicted in Fig. 4 and Fig. 5. The tank volume is 0.2 m^3 and it is located outside. The maximum set point temperature of the tank is 60 ºC.

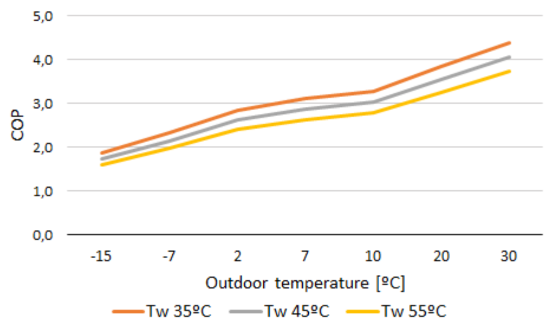


Fig. 4 – Heat pump COP.

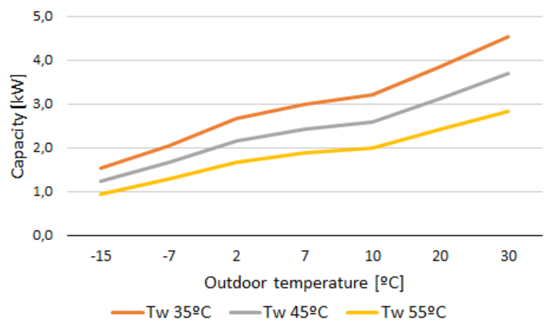


Fig. 5 – Heat pump capacity.

Heat pump reduces its capacity and performance noticeably when outdoor temperature drops below 5 ºC. The minimum outdoor operating temperature is -15 ºC and the maximum 45 ºC.

System 6: Photovoltaic with electric boiler. This system is the same as case 2 with the incorporation of a photovoltaic generator. The electric boiler uses electricity from the photovoltaic system if available. Otherwise, it is connected to the electrical network. The solar panels are oriented to the south and the tilt angle equal to the site latitude. The peak power of the photovoltaic array is 1.82 kW and the inverter efficiency is 0.96.

System 7: Photovoltaic with heat pump. This system is the same as case 5 with photovoltaic generator, Fig. 6. The solar system has the same specifications as the previous case.

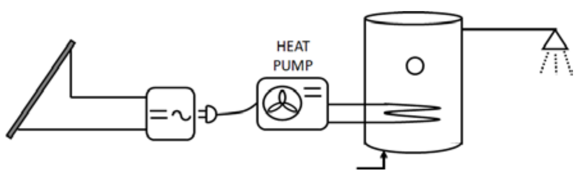


Fig. 6 – Diagram of the photovoltaic system with heat pump.

3. Results and Discussion

3.1 Energy analysis

Tab. 1 shows the energy consumption of each system in each climatic zone. It must be taken into account that systems 1 and 3 uses natural gas, while the rest electricity. Systems 1 and 2 are the most common in Spain and results show these have the highest consumption.

The most demanding systems are gas boiler and electric boiler. Scoccia [7] obtains a similar trend when comparing systems for DHW production and heating. The system with the lowest energy consumption in all climatic zones is the solar thermal system with gas boiler. The incorporation of solar energy reduces considerably the energy consumption. Comparing system 1 and 3, this reduction con reach 95% in the warmest zone and 69% in the coldest.

Comparing electrical systems 2 and 5 without any kind of solar support, the use of heat pumps reduces the electricity consumption between 65-52%. It is a significant reduction considering that systems require a similar installation. The incorporation of a PV system (systems 6 and 7) represents a reduction of 25-30% in system 2 and 40-50% in system 5. Although this energy reduction is important, it must be taken into account that the cost of the installation increases considerably and with current energy values it is not economically viable, Tab. 4.

Tab. 1 – Final energy in kWh per year.

DHW System	A4	B3	C1	C2	D3	E1
1	2050	2126	2255	2184	2236	2406
2	2306	2394	2552	2475	2534	2732
3	**90**	**176**	**554**	**513**	**539**	**748**
4	330	434	829	781	822	1051
5	791	850	993	955	1096	1306
6	1563	1630	1888	1818	1838	2034
7	397	440	**553**	**531**	641	796

3.2 Renewal percentage

Tab. 2 shows the renewable part of the total energy used for heating the water. This value is calculated with equation (3).

$$Ren(\%) = 100\left(1 - \frac{E_{final}}{E_{total}}\right) \quad (3)$$

The solar thermal systems have in general the greater use of energy from renewable sources. For climates C (template-cold), heat pump system with PV support has a renewable utilization value similar than the solar thermal system.

The use of heat pump (system 5) allows to reduce the consumption of electricity thanks to its high performance. In this system, the renewable energy is between 53-66%. Spanish regulations [2] require a value greater than 60% for newly built homes. This means that this system would comply with the regulations in zones A, B and C. The use of an integrated PV system increases this ratio and allows conforming with the minimum required by the regulations in all climatic zones.

Tab. 2 – Renewable percentage.

DHW System	A4	B3	C1	C2	D3	E1
1	0%	0%	0%	0%	0%	0%
2	0%	0%	0%	0%	0%	0%
3	**96%**	**93%**	**77%**	**79%**	**78%**	**71%**
4	87%	83%	70%	71%	70%	64%
5	66%	65%	62%	62%	57%	53%
6	32%	32%	26%	27%	27%	26%
7	83%	82%	**79%**	**79%**	75%	71%

3.3 CO_2 emissions

CO_2 emissions are related with the final energy consumption of each system and the kind of fuel used. The coefficients used for calculating the equivalent CO_2 emissions are the same used for the energy building certification [8]. The coefficient for electricity is 0.331 $kgCO_2/kWh$ and for natural gas is 0.252 $kgCO_2/kWh$.

This difference in the coefficients slightly favours the systems that uses natural gas (1 and 3). Thus, thermal solar with gas boiler (system 3) has the lowest environmental impact in all climates. Only in zones C, the heat pump and PV has a similar value of equivalent emissions.

These results will be different depending on the conversion coefficients used in each country [9]. In this case, the difference between natural gas and electricity coefficients is not so significant as to alter the existing relationship with the final energy consumption.

Tab. 3 – CO2 equivalent emissions in $kgCO_2$/year.

DHW System	A4	B3	C1	C2	D3	E1
1	517	536	568	550	564	606
2	763	793	845	819	839	904
3	**23**	**44**	**140**	**129**	**136**	**189**
4	109	144	274	259	272	348
5	199	214	250	241	276	329
6	517	540	625	602	608	673
7	100	111	**139**	**134**	162	201

3.4 Economic analysis

The economic analysis has been done taking into account current energy and system prices. Product inflation has not been considered. The subsidies and strategic incentive policies that exist have not been taken into account either (for example for PV installations in Spain). The average price of electricity is 0.17 €/kWh [10] and the price of natural gas 0.0553 €/kWh [11].

The capital price of the installation and the maintenance cost have been obtained by consulting different companies, Tab. 4. Be aware that these prices may fluctuate depending on the demand, the brand of the product and the company. The total cost of the installation has been analysed over a 15-year horizon. The cost includes the capital cost, annual maintenance and the operational cost, assuming a fixed cost of fuel throughout the indicated period.

Tab. 4 –Capital and maintenance cost of systems in €.

DHW System	Capital cost [€]	Annual maintenence [€]
1	380	95
2	330	30
3	**2920**	**285**
4	2870	220
5	1530	75
6	3180	350
7	4380	395

The results obtained for each system in each climatic zone are shown in Tab. 5. These results show the discrepancy between economic and environmental profitability. The simplest systems (with fewer components) are the cheapest in a 15-year life horizon (Systems 1 and 5). This is due to the fact that the low cost of installation and maintenance compensate for the energy inefficiency. Remember that inflation on the price of energy has not been considered, but the difference with respect to the results of the other systems gives a wide margin for this trend to continue. The low price of gas compared to electricity and the simplicity of the gas boiler system make it the most economical, despite having one of the greatest environmental impacts.

Solar systems increase the cost of installation between 750-850% (systems 1,2 vs systems 3,4) and have higher maintenance costs due to the greater number of elements and their exposure to the outside conditions. These drawbacks mean that their current cost does not compensate for the savings caused by reducing energy consumption (in economic terms).

For systems with PV contribution, two scenarios have been considered: the worst (system 6 pess. and 7 pess.), in which the solar system is only used for the DHW system; and the optimal case, (system 6 opt. and 7opt.) in which it is considered that all the energy that is not used in the DHW system is consumed by the building in other uses. Clearly, a PV system dedicated solely to the production of DHW is not economically viable without any type of government incentive. PV support for the heat pump be profitable only in climates with great amount of radiation, taking into account that all the energy produced is consumed in the home (self-consumption).

The cost of annual operation and maintenance of the gas boiler and the heat pump with the current prices of their fuels is very similar. The parameter that makes the cost of the heat pump more expensive is currently its capital cost, which is 4 times higher than the boiler. A decrease in the price of this type of equipment, a government incentive or a decrease in the price difference between gas and electricity would favour the use of the heat pump over the gas boiler and would allow the reduction of equivalent CO2 emissions.

Tab. 5 – Total life cost in k€.

DHW System	A4	B3	C1	C2	D3	E1
1	**3,44**	**3,50**	**3,61**	**3,55**	**3,59**	**3,73**
2	6,56	6,76	7,14	6,96	7,09	7,65
3	7,27	7,34	7,64	7,61	7,63	7,79
4	6,96	7,23	8,22	8,11	8,21	8,78
5	**4,61**	**4,77**	**5,11**	**5,02**	**5,34**	**5,85**
6 pess.	12,20	12,36	13,00	12,85	12,86	13,44
6 opt.	6,51	7,13	8,69	8,36	8,23	9,19
7 pess.	11,20	11,31	11,56	11,51	11,74	12,11
7 opt.	**3,55**	**4,10**	**5,57**	**5,36**	**5,34**	**6,15**

4. Conclusions

The article analyses seven DHW systems for single-family homes: gas boiler, electric boiler with and without PV, solar thermal with gas boiler or electric boiler and heat pump with and without PV. The study includes energy, environmental and economic analysis in six climatic zones: A4, B3, C1, C2, D3 and E1 from the warmest to the coldest.

In energy terms, the incorporation of solar thermal energy implies a reduction in consumption of 69-95% in the gas boiler system, while the incorporation of PV implies a reduction of 40-50% in the heat pump system and 25-30% in the electric boiler. This represents a use of energy from renewable sources of approximately 70-95% in solar thermal systems and 70-83% in PV system with heat pump.

Despite this reduction in energy consumption and with current market conditions, these values are not sufficient to make solar systems economically profitable due to its high capital cost.

The heat pump system seems to be the best economic alternative to the gas boiler to achieve a reduction in the environmental impact of the DHW installations in the residential sector, although economic incentives are still necessary to improve their profitability. In addition, in an optimal scenario, the incorporation of PV would allow a saving of around 50% of energy in the warmest climates and it slightly reduce the total life cost of the system.

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