SE 2610 ARTICLE IN PRESS No. of Pages 7, Model 5+
18 November 2010; Disk Used

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ScienceDirect
Solar Energy xxx (2010) xxx–xxx
SOLAR ENERGY
www.elsevier.com/locate/solener

Brief Note

Roof-top solar energy potential under performance-based building energy codes: The case of spain

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Received 18 March 2010; received in revised form 17 August 2010; accepted 8 November 2010

Communicated by: Associate Editor C. Estrada-Gasca

Abstract

The quantification at regional level of the amount of energy (for thermal uses and for electricity) that can be generated by using solar systems in buildings is hindered by the availability of data for roof area estimation. In this note, we build on an existing geo-referenced method for determining available roof area for solar facilities in Spain to produce a quantitative picture of the likely limits of roof-top solar energy. The installation of solar hot water systems (SHWS) and photovoltaic systems (PV) is considered. After satisfying up to 70% (if possible) of the service hot water demand in every municipality, PV systems are installed in the remaining roof area. Results show that, applying this performance-based criterion, SHWS would contribute up to 1662 ktoe/y of primary energy (or 68.5% of the total thermal-energy demand for service hot water), while PV systems would provide 10 T W h/y of electricity (or 4.0% of the total electricity demand).

Keywords: Solar energy; SHWS; Renewable energy; Potential quantification; GIS

1. Introduction

The definition of clean energy policies at regional (*e.g.* national) level requires the quantification of renewable-energy potentials. An important effort has been made in the last years towards this estimation in several regions of the world [*e.g.*] (Šúri et al., 2007; Trieb, 2006; NASA, 2009; Domínguez Bravo et al., 2007). Among the available technologies, the quantification of the energy generated by solar systems in buildings (comprising SHWS, roof-top PV, building-integrated PV and passive solar energy saving) is one of the most complex to estimate because of the large amount of entities to be accounted for (typically, hundreds of thousands of buildings in a country). Despite of the complexity, this information is valuable for the development of efficient-building energy-codes. In a previous work by some of the present authors (Izquierdo et al., 2008), this problem is addressed by performing a stratified statistical sampling of roof availability as a function of building typologies. The geo-referenced datasets generated using this methodology include the available roof area for solar energy facilities in each municipality, and the irradiance arriving at each roof. The method was applied by the authors to peninsular Spain and the Balearic Islands, and thereafter partially reproduced for other regions in the world, as for example for Ontario (Canada) (Wiginton et al., in press).

The Spanish Technical Building Code (MVIV, 2009), as other European norms based on performance goals (EU, 2002), requires for new buildings to obtain a minimum of the energy needed for the service hot water from solar sources; such regulated minimum depends on the total hot water demand in the building and on the climate zone. In the case of Spain, except for the most challenged areas, this minimum is 70% of the total hot water demand. Once this requirement is fulfilled, the remaining roof area can be otherwise used, for example, for PV systems, in order to

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0038-092X/$ - see front matter © 2010 Published by Elsevier Ltd.
doi:10.1016/j.solener.2010.11.003

optimize the available area. Using this criterion we estimate the potential of roof-top solar energy in Spain.

2. Methodology

The methodology followed for computing the potential of the solar energy and the available roof area in Spain is described in Izquierdo et al. (2008). The irradiation was evaluated based on well-established procedures (Duffie and Beckman, 1991; Goswami et al., 1999; Lorenzo, 1994): first the extraterrestrial radiation was calculated from the Sun–Earth system geometry; then a clearness index was assessed for every municipality using measured meteorological data from a set of stations and kriging interpolation; these data were combined to obtain the daily average horizontal irradiation for a typical day in every month; finally, using previously computed data, direct and diffuse components of hourly irradiance were obtained; thus, the annual irradiation over the collector surface was calculated by integrating hourly irradiance values along the year. The available roof was computed by GIS sampling, using a vector database from the Spanish cadastre and satellite images. The available roof surface area was estimated using this method as 571 km^2, with an error of ±32% (Izquierdo et al., 2008).

The service hot water demand coverage is computed using the f-Chart method (Beckman et al., 1977), a procedure widely used in prefeasibility studies to estimate the amount of energy delivered by SHWS. The input data for the f-Chart method are the monthly values of incident solar radiation, ambient temperature and load.

Table 1
Assumptions for the evaluation of the SHWS demand coverage and payback.

Consumption of hot water at 60 °C	35 l/person/day
Installation costs	579 €/m^2 collector
Maintenance costs	10.4 €/m^2 collector/year
Alternative fossil fuel (gas) cost	4.5 c€/kW h
Heater efficiency	80%

Table 2
Assumptions for the evaluation of the PV cost–supply curves. T_{ref} is the reference temperature; NOCT is the normal operating cell temperature; and β_p is the power temperature coefficient of the module.

	Value
Technical parameter	
Performance at T_{ref}	14.7%
NOCT	47°C
β_p	0.5%/°C
Installation losses	18.5%
Availability	96%
Economic parameter	
Installation costs	855 €/m^2 collector
Maintenance costs	6.4 €/m^2 collector/year
Installation lifetime	25 years
Interest rate	9%

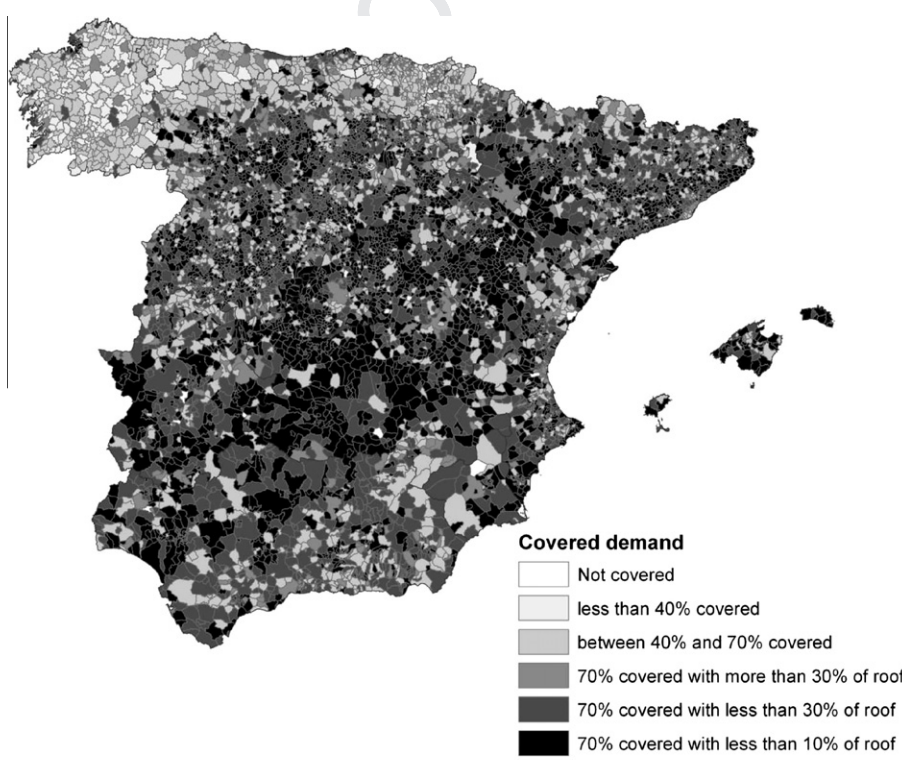

Fig. 1. Geographic distribution of the hot water demand coverage with solar systems.

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For the economic analysis of SHWS we estimate the local payback period of the system, which is calculated from the following expression:

$$Payback = \frac{\text{SHWS installation costs}}{\text{Cost of gas saved} - \text{SHWS maintenance costs}}. \quad (1)$$

A fossil-fuel heater is assumed to be installed in any case, and thus its installation and maintenance costs are not accounted for in the payback calculation. The assumptions made to evaluate the demand coverage and the SHWS payback are shown in Table 1.

For the economic analysis of PV electricity we use, more appropriately, cost–supply curves, which represent the generated electricity arranged in increasing costs. The corresponding assumptions for the computation of the PV cost–supply curves are collected in Table 2.

3. Results

3.1. Spatial coverage

Applying the methodology summarized in the previous section to each of the 8005 municipalities in Spain, we cal-

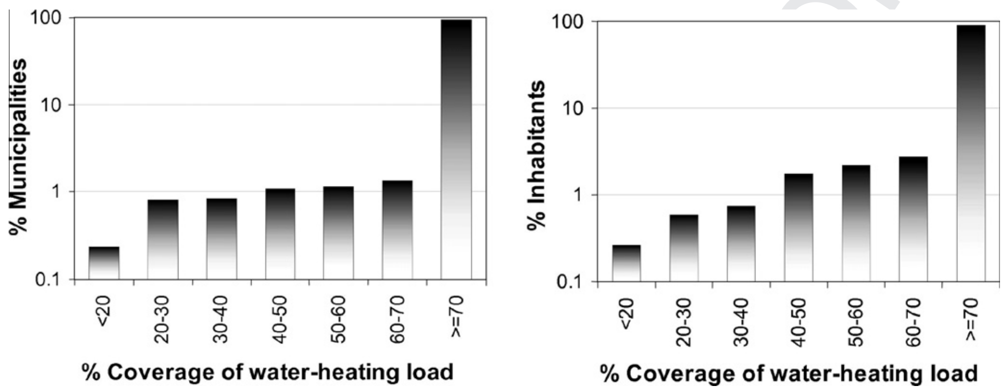

Fig. 2. Distribution of the hot water demand coverage.

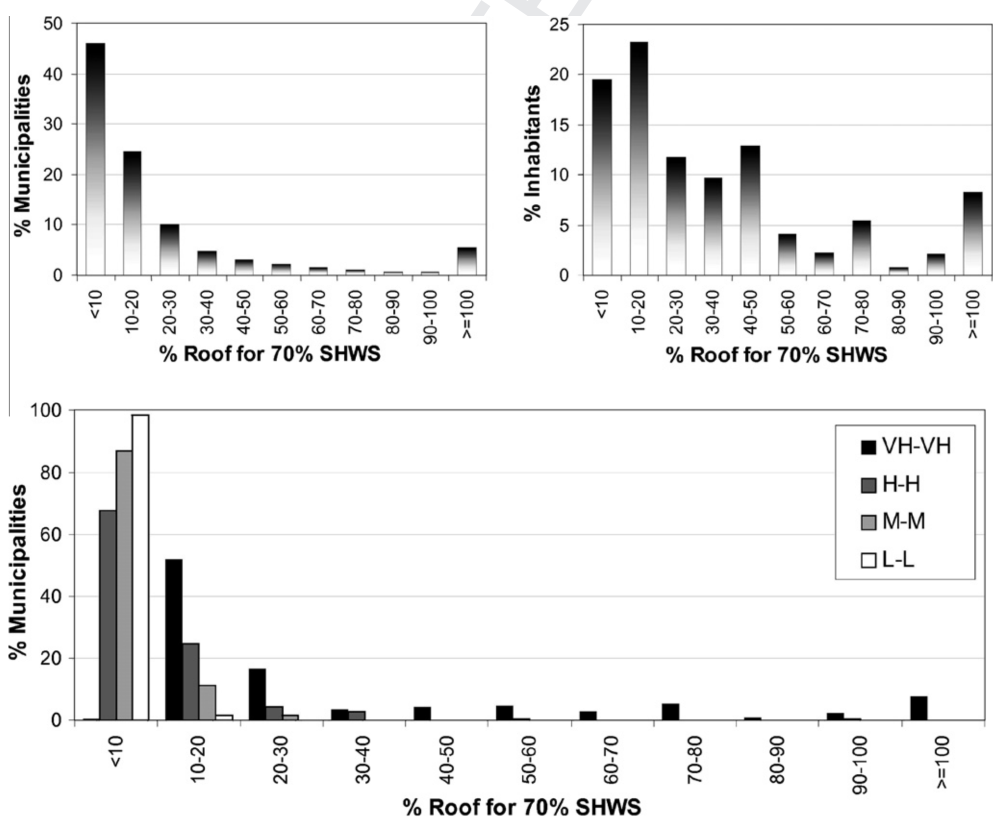

Fig. 3. Distribution of the roof needed to cover 70% of the hot water demand (top); disaggregation of the data for representative building typologies (bottom). VH–VH stands for *Very High* building density and *Very High* population density (H: *high*, M: *medium*, L: *low*) see Izquierdo et al. (2008) for further details.

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culate the demand coverage and the roof area necessary in order to cover 70% of the heat water demand (see the map in Fig. 1). It is found that in north-western Spain the demand is often not covered, due to insufficient irradiation, while in the rest of the country 70% of the demand is usually fulfilled with a relatively low percentage of the roof area. If these results are rearranged we can obtain the percentage of municipalities and inhabitants that can fulfill using solar energy a given fraction of the demand, as shown in Fig. 2. To complete this information, the distribution of the amount of the available roof area needed to cover 70% of the demand is also presented in Fig. 3.

Some consequences of the geographical mismatch between the distribution of the solar resource and the hot water demand is that in 5.5% of the municipalities (corresponding to 8.3% of the population) there is not enough roof surface to cover 70% of the hot water demand. This outcome is worth noting because it would not become apparent in a global analysis: considering the total amount of solar energy arriving to the total available roof area, it would be possible to generate five times the total demand. Other consequence of the mismatch is that around in 70% of the municipalities (encompassing 43% of the population) 70% of the hot water demand is covered with less than 20% of the roof area, thus leaving a substantial slack for PV applications.

Finally, in Fig. 3 (bottom) results are shown for some of the representative building typologies (RBT) described by Izquierdo et al. (2008). RBT's are an attempt to characterize the building typology at a location by using a pair of statistical, readily-available parameters: the population density and the building density. Thus, for instance, when both densities are very high the local building typology is the one pertaining to a densely populated down-town area, typical of many large cities in Spain. Conversely, when both are very low then rural housing prevails at the location. Thus, RBT's are closely related to both the amount of collecting surface required for solar hot water and the availability of roof area.

3.2. Economic analysis

With the assumptions made in the Section 2, the payback of SHWS for every municipality in Spain can be assessed. Aggregating the results we obtain the graphs in Fig. 4. A noteworthy implication of this analysis is that the SHWS installed in about 25% of the municipalities (corresponding to around 21% of the population) would

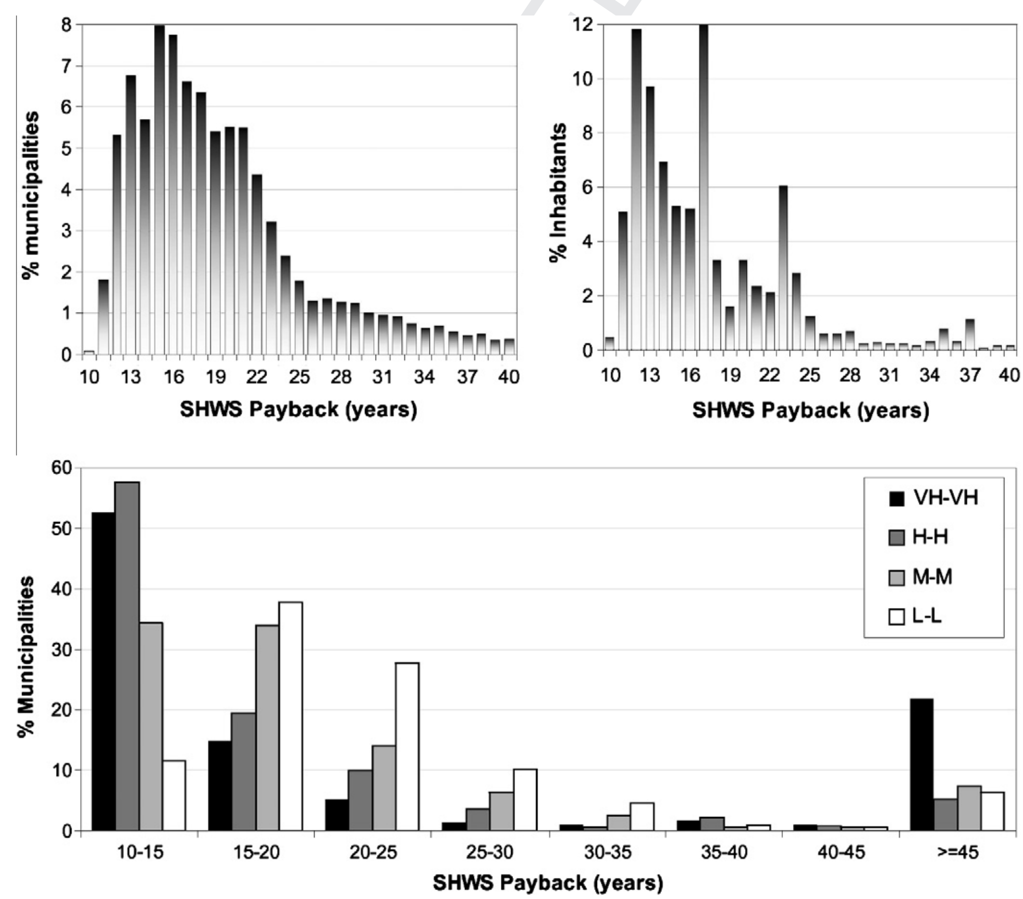

Fig. 4. Distribution of the payback of solar hot water systems (top); disaggregation of the data for representative building typologies (bottom). VH–VH stands for *Very High* building density and *Very High* population density (H: *high*, M: *medium*, L: *low*) see Izquierdo et al. (2008) for further details.

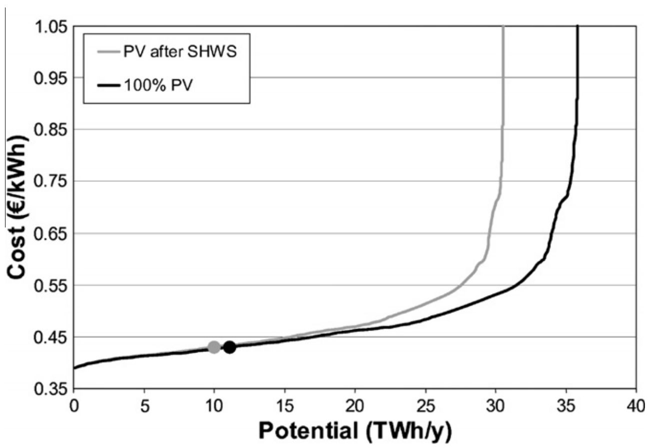

Fig. 5. Cumulative cost–supply curve for PV using the available roof surface area before and after satisfying 70% of the hot water demand, if possible. Dots indicate the representative cost (statistical mode of the cost) (Izquierdo et al., 2010).

have a payback period higher than the lifetime of the installation (assumed as 25 years).

The shape of the distribution for the demand coverage differs from the payback one because the former are strongly influenced by both the roof area available and the solar resource, while the latter depends mainly on the quality of the resource. Thus, a compact town may not have enough roof area to fulfill the hot water demand, but if the solar resource at the location is substantial, the fossil fuel savings result in reduced payback periods.

The cost of the fossil fuel considered is that for natural gas; however, diesel is often used in Spain as fuel for heating and hot water supply, especially in old or isolated areas; and, in that case, the payback periods are reduced to approximately half of the ones for natural gas.

The remaining available roof area (83% of the total) can be used for PV systems. With the assumptions made in Section 2, the cost–supply curve for the electricity generated in roof-top PV systems is obtained. In Fig. 5 this curve is shown before and after SHWS, in order to illustrate the influence that the requirement of covering 70% of the service hot water demand has on the electricity potential of roof-top PV systems. The total annual energy that can be generated after SHWS is 30.5 T W h/y. However, this is a technical limit that can be further restricted by economic criteria. Izquierdo et al. (2010) suggest the use of the statistical mode of the cost (*i.e.* the most frequent cost) as an indication of an intrinsic cost of the technology in a region; using this criterion, about 10.0 T W h/y of electricity can be generated at a cost smaller than the characteristic one of 43 c€/kW h. This represents 4% of the total annual demand in Spain (251.3 T W h/y in 2009) (REE, 2009).

4. Conclusions

Due to the spatial distribution of the solar energy resource, although the solar potential (about 12,000 ktoe/y) is several times the service hot water demand in Spain (2425 ktoe/y), around a 8% of the population cannot fulfill the quota of 70% of hot water demand from solar energy. Moreover, when competing with natural gas heaters, SHWS have a minimum payback of about 11 years, and in 25% of the municipalities the payback would be higher than the lifetime of the installation. The payback period can be reduced by more than a half if the fossil fuel is diesel, or more expensive ones.

The combined potential of roof-top solar energy systems is therefore: (i) 68.4% (1662 ktoe/y) of the energy for service hot water systems would be covered in an optimal implementation of the Spanish Technical Building Code (MVIV, 2009), using 17% of the available roof surface area; and (ii) using the remaining 83% of the available roof surface area it would be possible to produce 30.5 T W h/y of electricity from PV systems, albeit only 10 T W h/y can be generated at a cost below the representative one (most common one) of 43 c€/kW h.

It should be finally indicated that the results reported are likely to be sensitive to the input data (Tables 1 and 2) and to the method used to estimate the available roof surface area (Izquierdo et al., 2008). While space limitations in this paper preclude a thorough quantitative analysis, it is relevant to remark that the qualitative shape of the distribution functions shown in Figs. 2–5 is expected to show little sensitivity to such changes; this has been shown, for instance, by Izquierdo et al. (2010) for the case of the cost–supply curves of renewable energy on the large scale.

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