European Commission

JRC SCIENTIFIC AND POLICY REPORTS

# Cost Maps for Unsubsidised Photovoltaic Electricity

T. Huld, A. Jäger Waldau, H. Ossenbrink, S. Szabo, E. Dunlop, N. Taylor

**2014**

Report JRC 91937

Joint Research Centre

**European Commission**
Joint Research Centre
*Institute for Energy and Transport*

**Contact information**
Nigel Taylor
Address: Joint Research Centre, Via Enrico Fermi 2749, TP 450, 21027 Ispra (VA), Italy
E-mail: nigel.taylor@ec.europa.eu

http://www.jrc.ec.europa.eu/
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This publication is a Scientific and Policy Report by the Joint Research Centre of the European Commission.



JRC 91937



*Printed in Italy*

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September 2014

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# 1. Introduction

The PV industry has experienced a compound annual growth rate of over 50% over the last 10 years, accompanied by a four-fold reduction of costs [1, 2]. The unsubsidised cost of electricity generated by PV systems has correspondingly seen substantial reductions, making it increasingly competitive with retail electricity prices and opening the way for a range of market opportunities.

To demonstrate this potential, the JRC has produced a series of PV electricity price maps, which combine a standard model for levelised cost of electricity (LCOE) with the geographically dependent PV performance data from its PVGIS software system [3, 4]. The calculated LCOE values are then compared with the retail electricity prices in the Member States. For those locations where the LCOE is lower than the prevailing retail price, unsubsidised PV may already offer an economic source of electricity to complement that available from the grid. The actual economic viability of a given system is dependent on a range of factors such as level of self-consumption, net metering arrangements, price of the sale of surplus electricity.

The first version of the PV cost maps was presented at the EUPVSEC conference in 2012 [5]. Given the dynamic nature of PV system prices and of the electricity market, the analysis is now being updated on a regular basis. JRC Technical Note on "Cost Maps for Unsubsidised Photovoltaic Electricity" was released in autumn 2013 [6].

The present report updates the system price input and other factors in the LCOE model, as well as using the latest available Eurostat data on retail electricity prices (2nd semester 2013).

# 2. Levelised Cost of Electricity for Photovoltaic Systems

## 2.1 Method and Model Parameters

The "Levelized Cost of Energy" (LCOE) is the price at which electricity must be generated from a specific source to break even over the lifetime of the project. It is an economic assessment of the cost of the energy-generating system including all the costs over its lifetime: initial investment, operations and maintenance, cost of fuel and cost of capital. It can be calculated in a single formula as:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

Where $I_t$ = Investment expenditures in year t , $M_t$ = operations and maintenance expenditures in year t , $F_t$ = fuel expenditures in year t, which is zero for photovoltaic electricity, $E_t$ = electricity generation in the year t, r = discount rate and n = investment period considered in years. The calculations were made with the algorithm used by the National Renewable Energy Laboratory (NREL) [1] and are fully consistent with the JRC SETIS LCOE calculator and the BNEF method[2].

[1] ,http://www.nrel.gov/analysis/tech_lcoe_documentation.html

[2] Bloomberg New Energy Finance, Levelised cost of electricity update: Q2 2013

**Table 1: Parameter values used in the LCOE model**

| **Parameter** | **Values** | | |
|---|---|---|---|
| | **2012** | **2013** | **2014** |
| $I_t$, PV system price (rooftop, < 25 kW), EUR/kWp. | 2300 | 1700 | 1400 |
| r, discount rate (cost of capital) | 5% | 5% | 5% |
| n, Investment period, years | 20 | 20 | 20 |
| $M_t$, annual O&M costs (as % of initial capital investment) | 1.0% | 1.5% | 2.0% |
| Et, annual electricity generation (specific to plant location) | From PV-GIS | From PV-GIS | From PV-GIS |

Table 1 summarizes the parameter values used in the 2012, 2013 and present analyses. The following points are noted:

- The system price (for a rooftop system of less than 25 kWp) is decreased to 1400 EUR/kWp. For the period July-August 2014 the the PVinsights web site gives the European average price of a residential system as 1.27 €/Wp[3] (low 1.15 €/Wp, high 1.68 €/Wp). This includes installation, but not fees, permitting or connection costs. We assume that these can be covered by a surcharge of 0.13 €/Wp, leading to a system cost of 1400 €/kWp. This is in line with the PV price index[4] published by the photovoltaic guide for Germany where the average price for PV systems smaller 100kWp in August 2014 is quoted with 1310 €/kWp, down from the 1 450 €/kWp in March 2014. Similar prices are reported by Solar Choice for Australia[5]

- A sales tax (VAT)[6] is applied on the system purchase price at the applicable rate foreseen in each Member State, as detailed in Table 2.

- 5% cost of capital (discount rate in the formula above): this value is chosen arbitrarily to be at the upper end of the long term interest rate data (secondary market yields of government bonds with maturities of close to ten years), which in July 2014 ranged from 1.1% to 6.1%) accordingly to the European Central Bank[7]. The spread relates to the risks of the respective government bonds, but analysis of this risk premium is beyond the scope of this study. Without the higher risk bonds, the European average is below 3%. Hence the 5% value is somewhat above what a private investor could currently expect from an investment of comparable duration in government bonds.

- The investment period is fixed at 20 years. This is intended to reflect the long term perspective of a private investor. Previously it also reflected the performance duration warranty offered by module manufacturers; however the industry standard is now 25 years, with 80% or better real power output.

[3] PVinsight, 18 July 2014, 29 August 2014, http://pvinsights.com/SolarSystem/SolarSystemPrice.php
[4] http://www.photovoltaik-guide.de/pv-preisindex
[5] http://www.solarchoice.net.au/blog/solar-power-system-prices-sydney-melbourne-perth-canberra-adelaide-july-2014
[6] VAT may not be applicable on the system price if the system is used to generate income, accordingly to Court of Justice of the European Union Judgment in Case C-219/12: see http://curia.europa.eu/jcms/upload/docs/application/pdf/2013-06/cp130075en.pdf Without detailed information on fiscal arrangements in each MS, the impact of this ruling could not be considered here.
[7] https://www.ecb.europa.eu/stats/money/long/html/index.en.html

- O&M costs are increased to 2% of the capital costs, up from 1% and 1.5% in the previous analyses. This is to keep the absolute level of O&M costs at about the same level.

- The annual energy yield (kWh per kWp installed) is provided using the JRC's PVGIS on-line tool, using the CMSAF database, for each 5 km x 5 km grid-cell (the resolution of the insolation database).

It is stressed that this model calculates an LCOE for a given generator up to the point when the electricity enters the grid. It therefore does not describe costs associated with distribution, transmission, profile costs (including flexibility and utilisation effects), balancing costs and other grid costs. In an overall system these categories are applicable of all electricity generators, whether conventional or renewable energy sources, and leads to a "system LCOE" for each generator. This issue is further discussed in the JRC's 2014 PV Status Report [2].

**Table 2: Sales tax (VAT) rates applicable to the purchase of a PV system.**

| Member States | Code | VAT rate [%] |
|---|---|---|
| Belgium | BE | 6* |
| Bulgaria | BG | 20 |
| Czech Republic | CZ | 21 |
| Denmark | DK | 25 |
| Germany | DE | 19 |
| Estonia | EE | 20 |
| Greece | EL | 23 |
| Spain | ES | 21 |
| France | FR | 10** |
| Croatia | HR | 25 |
| Ireland | IE | 23 |
| Italy | IT` | 10* |
| Cyprus | CY | 19 |
| Latvia | LV | 21 |
| Lithuania | LT | 21 |
| Luxembourg | LU | 15 |
| Hungary | HU | 27 |
| Malta | MT | 18 |
| Netherlands | NL | 21 |
| Austria | AT | 20 |
| Poland | PL | 23 |
| Portugal | PT | 23 |
| Romania | RO | 24 |
| Slovenia | SI | 22 |
| Slovakia | SK | 20 |
| Finland | FI | 24 |
| Sweden | SE | 25 |
| United Kingdom | UK | 5*** |

*) reduced rate applicable

**) in France reduced for houses more than 2 years old

***) UK rate for existing houses (0% for new build).

## 2.2 Results

Using the approach described above, LCOE values can be mapped over all of Europe, as shown in Fig. 1. The values range from a minimum of 9 EURcts/kWh in the southern Mediterranean to 22-23EURcts/kWh in the most northern regions. This variation mostly reflects the geographical differences in annual insolation. Differences in national sales tax (VAT) rates also have an impact. For instance, comparing areas of northern England and Ireland at the same latitude, the former has a notably lower LCOE, benefiting from the UK VAT rate of 5% compared to 23% in Ireland. A similar situation exists *vis a vis* northern France and Germany.

It is stressed that the LCOE value is independent of the size of the system or how the electricity generated is actually used. Typically a residential PV system is sized so as to generate the same amount of electricity as that consumed over a year. In such cases, without optimisation of consumption patterns or storage, only about 30% of the PV electricity is used directly at the time of use (the remainder is supplied to grid). Higher levels of self-consumption (up to 100%) may arise if the system is sub-sized with respect to the annual energy consumption due, for instance, to space or structural limitations, shading, unfavourable orientation etc) or through use of battery storage, heat pumps, domestic water heating, EV charging etc..

The contribution of the various elements to the LCOE can also be analysed. As an example, we consider a location with an annual PV productivity of 1000 kWh/kWp and an assumed VAT rate of 20%. This leads to the cost breakdown shown in Table 3. Financing is the largest single cost factor, and together with fees and permitting costs, contributes one third of the electricity generation costs from such a PV system over the financing period of 20 years (Fig. 2). Omitting these (reducing the discount rate to r=0% in the LCOE calculation) would reduce the LCOE by 25% from 0.16 to 0.12 EUR/kWh. Such a scenario is increasingly relevant given the modest capital cost of small system systems compared to that associated with purchasing a car or with home furnishing and improvements, which are often financed directly from savings. The operation, maintenance and replacement costs (O&M) are the second largest contributors, followed closely by the modules themselves. These data underline the need to target both technological and non-technological items to achieve further significant cost reductions and maintain the industry's high growth rate. The PV Status Report [2] provides more detail on the cost elements in the calculation.

A detailed sensitivity analysis is considered outside the scope of this study, which aims to provide a simple illustration of the competitiveness of small PV systems for residential applications. However 2013 PV Status Report includes calculations of the sensitivity of LCOE to the return on investment (ROI) value.

Finally it worth noting that in the post-financing period, the PV system will continue to produce electricity and the LCOE model can also be applied. In this situation there are only O&M costs and these therefore take on a decisive significance. A complete analysis would require detailed information on degradation rates of key components and replacement costs. This is an area of current research and beyond the scope of this study. However to provide indicative values, if one adds a conservative "safety" margin of 0.012 EUR/kWh on top of the 0.028 EUR/kWh used over the financing period, a highly attractive electricity price of 0.04 EUR/kWh is obtained.

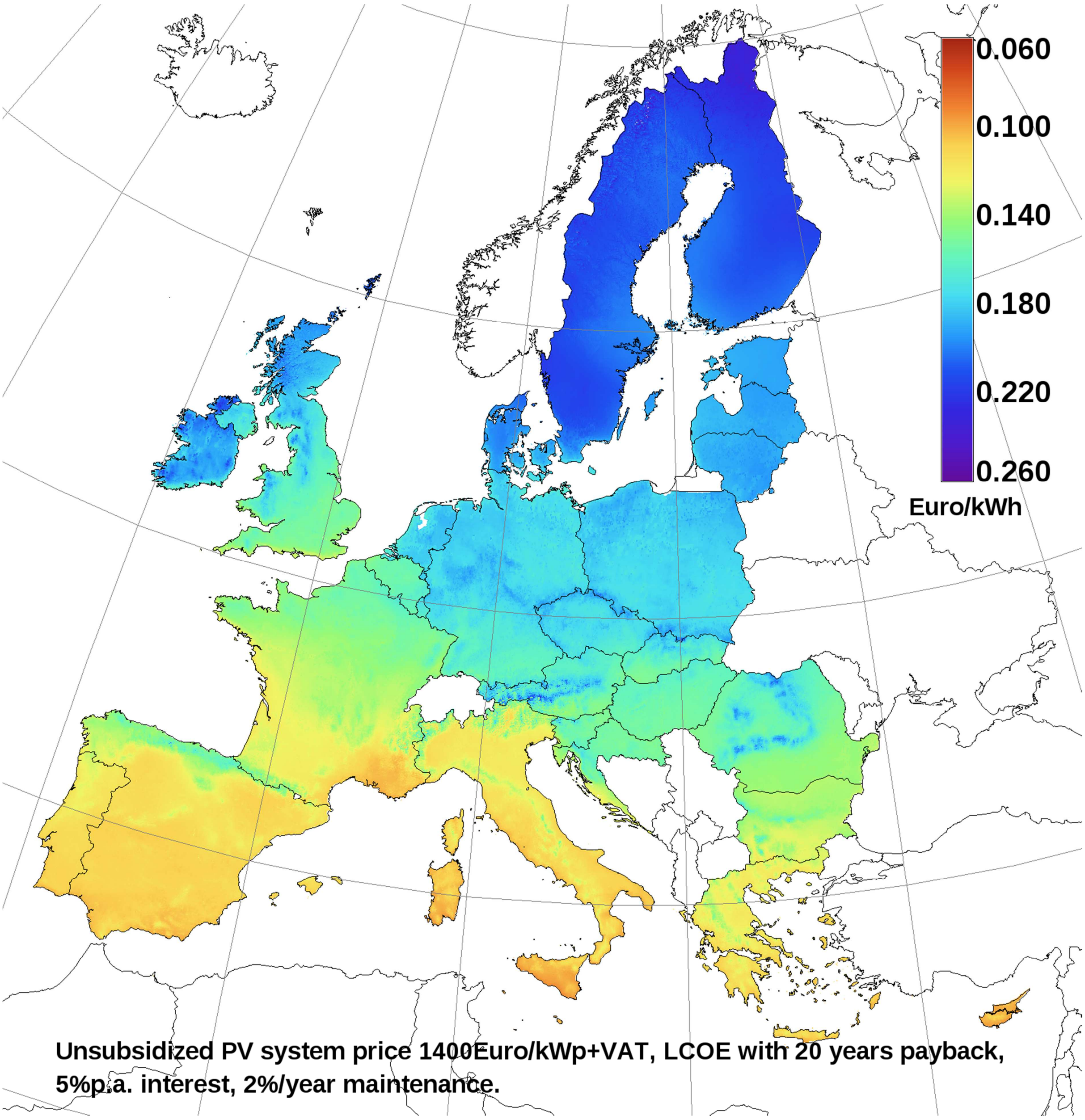



***Fig. 1 Distribution of the levelised cost of PV electricity in Europe.***

**Table 3: LCOE of PV generated electricity for residential systems with a system price of 1400 EUR/kWp +20% VAT, 2% operation & maintenance (O&M) costs, an annual generation of 1000 kWh/kWp/y installed and financial investment period of 20 years.**

| Item | Cost | Contributions to LCOE | | | | LCOE |
|---|---|---|---|---|---|---|
| | | Item | 20% VAT | Capital for ROI 5% | O&M 2% | Total |
| | [EUR/kWp] | [EURct/kWh] | [EURct/kWh | [EURct/kWh] | [EURct/kWh] | [EURct/kWh] |
| PV Module | 560 | 2.80 | 0.56 | 1.78 | 1.34 | 6.48 |
| Inverter | 140 | 0.70 | 0.14 | 0.44 | 0.34 | 1.62 |
| Balance of Systems | 270 | 1.35 | 0.27 | 0.86 | 0.64 | 3.12 |
| Engineering Procurement & Construction | 300 | 1.50 | 0.30 | 0.95 | 0.72 | 3.47 |
| Other (fees, permitting, Insurance.) | 130 | 0.65 | 0.13 | 0.41 | 0.31 | 1.50 |
| Total | 1,400 | 7.00 | 1.40 | 4.44 | 3.36 | 16.20 |

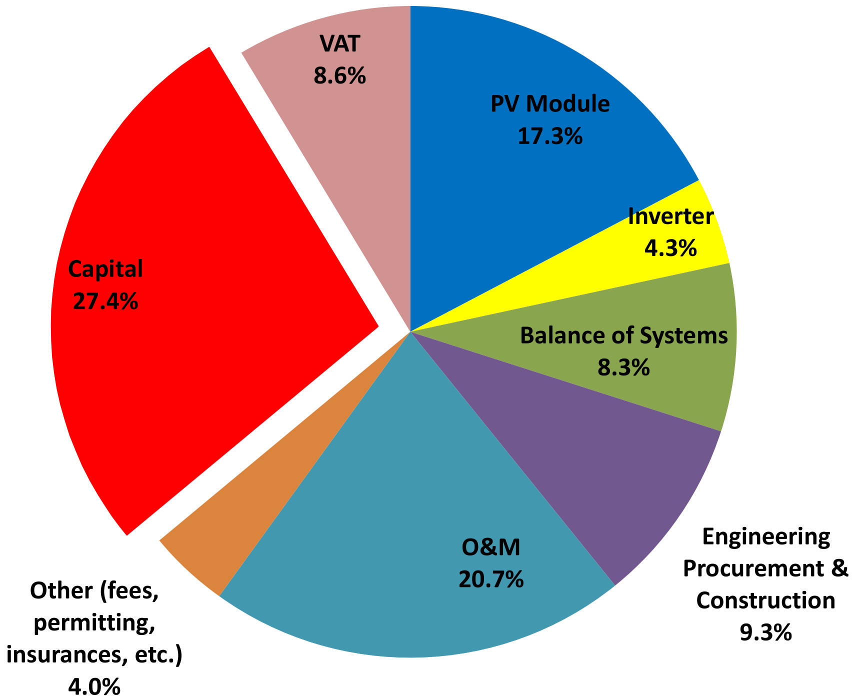



**Fig. 2: LCOE cost breakdown for a residential system costing 1 400 EUR/kWp +20%. VAT, 2% operation, maintenance and repair (O&M) cost, an annual generation of 1 000 kWh/kWp/y and financial lifetime of 20 years**

# 3. Assessment of PV LCOE Relative to Electricity Prices

## *3.1. Retail Electricity Prices in the EU MS*

This study uses the present retail electricity price as a benchmark for assessing the competiveness of residential/small-scale PV systems. The data is from EUROSTAT, which provides electricity prices in the EU member states each semester, for industrial and residential users, and with and without taxes. Table 5 shows the latest available data (2nd semester 2013) for residential users, together with values used in the previous 2012 and 2013 analyses. There are significant differences between the Member States (Bulgaria: 0.088 EUR/kWh to Denmark: 0.294 EUR/kWh), as well as variations from year to year. For a discussion of these the reader is referred to Commission's communication on energy prices and costs from earlier this year [7].

## *3.2. Price Competitiveness*

The analysis is based on a direct comparison between the PV LCOE value for each 5 km x 5 km grid-cell in Europe (as described above) and the residential electricity price in that Member State (see Table 4). It is stressed that:

a) The comparison does **not include any incentive or subsidy scheme** for the PV system.
b) Cost-free exchange with the grid is assumed i.e. net metering, whereby the electricity meter runs "backwards" during sunny hours, and forward while consuming electricity during bad weather and at night-time. Such schemes are not generally available to residential consumers in the EU[8].
c) The retail electricity price is fixed at the 2013 2nd semester value, and no account is taken of inflation or other possible price variations over the investment period.
d) The PV system price represents what a turn-key residential system can cost in the EU's most competitive markets. Actual prices at a given location may be higher.

Fig. 3 maps the results of subtracting the PV LCOE from the retail electricity price for the 2nd semester 2013. As an example, in Vienna the electricity retail price in 2nd semester 2013 for households was 0.202 EUR/kWh, while the LCOE for a PV system costing 1400€/kWp (including VAT) is 0.153 EUR/kWh, resulting in a difference of -0.049 EUR/kWh. Fig. 4 shows the corresponding maps from the 2012 and 2013 analyses. In all case the colour scale is the cost difference in Euro: red and yellow colours indicate that the PV LCOE is less than current residential electricity and blue the reverse. In favoured locations, with colours from yellow to red, the price difference could be used to invest into local battery storage or other means to allow the PV owner to increase self-consumption at a net cost below the retail electricity price.

At this system price level of EUR 1400/kWp, the PV LCOE is still above the retail electricity price in FI, EE, LT, LI, PL, HU, HR, RO and BU, as well as for some less sunny (but sparsely populated) parts of UK and SE. In the other Member States the population benefit from a situation where the PV LCOE is at or below the residential electricity price. As shown in Table 6, this amounts to 79.5% of EU citizens and illustrates the potential for PV electricity use in the residential sector under favourable circumstances. This value is considerably increased from that in the 2013 analysis (57%) despite the inclusion of VAT on the system price. In particular France and the UK can now be included for the majority of the population, thanks in part of favourable VAT rates for this type of investment.

In the situation where the financing costs are omitted (discount rate r=0 in the LCOE calculation), the PV LCOE is currently lower than the retail electricity price in all Member States except Bulgaria.

[8] An exception is the Netherlands, which currently allows full net metering for systems up to 5 KWp.

**Table 4 EUROSTAT data for retail electricity prices (including taxes and levies).**

| EU Member State | 2011 H2 | 2012 H2 | 2013 H2 |
|---|---|---|---|
| AT:Austria | 0.196 | 0.202 | 0.202 |
| BE:Belgium | 0.212 | 0.222 | 0.222 |
| BG:Bulgaria | 0.087 | 0.096 | 0.088 |
| CY:Cyprus | 0.241 | 0.291 | 0.248 |
| CZ:Czech Republic | 0.147 | 0.150 | 0.149 |
| DE:Germany | 0.253 | 0.268 | 0.292 |
| DK:Denmark | 0.296 | 0.297 | 0.294 |
| EE:Estonia | 0.104 | 0.112 | 0.137 |
| EL:Greece | 0.124 | 0.142 | 0.170 |
| ES:Spain | 0.209 | 0.228 | 0.227 |
| FI:Finland | 0.137 | 0.156 | 0.156 |
| FR:France | 0.142 | 0.145 | 0.159 |
| HR:Croatia | 0.115 | 0.138 | 0.135 |
| HU:Hungary | 0.155 | 0.156 | 0.133 |
| IE:Ireland | 0.209 | 0.229 | 0.241 |
| IT:Italy | 0.206 | 0.230 | 0.232 |
| LT:Lithuania | 0.122 | 0.127 | 0.139 |
| LU:Luxembourg | 0.156 | 0.171 | 0.165 |
| LV:Latvia | 0.134 | 0.137 | 0.136 |
| MT:Malta | 0.17 | 0.170 | 0.170 |
| NL:Netherlands | 0.177 | 0.190 | 0.192 |
| PL:Poland | 0.135 | 0.153 | 0.144 |
| PT:Portugal | 0.185 | 0.206 | 0.213 |
| RO:Romania | 0.108 | 0.108 | 0.128 |
| SE:Sweden | 0.204 | 0.208 | 0.205 |
| SI:Slovenia | 0.171 | 0.154 | 0.166 |
| SK:Slovakia | 0.149 | 0.172 | 0.168 |
| UK:United Kingdom | 0.158 | 0.179 | 0.180 |

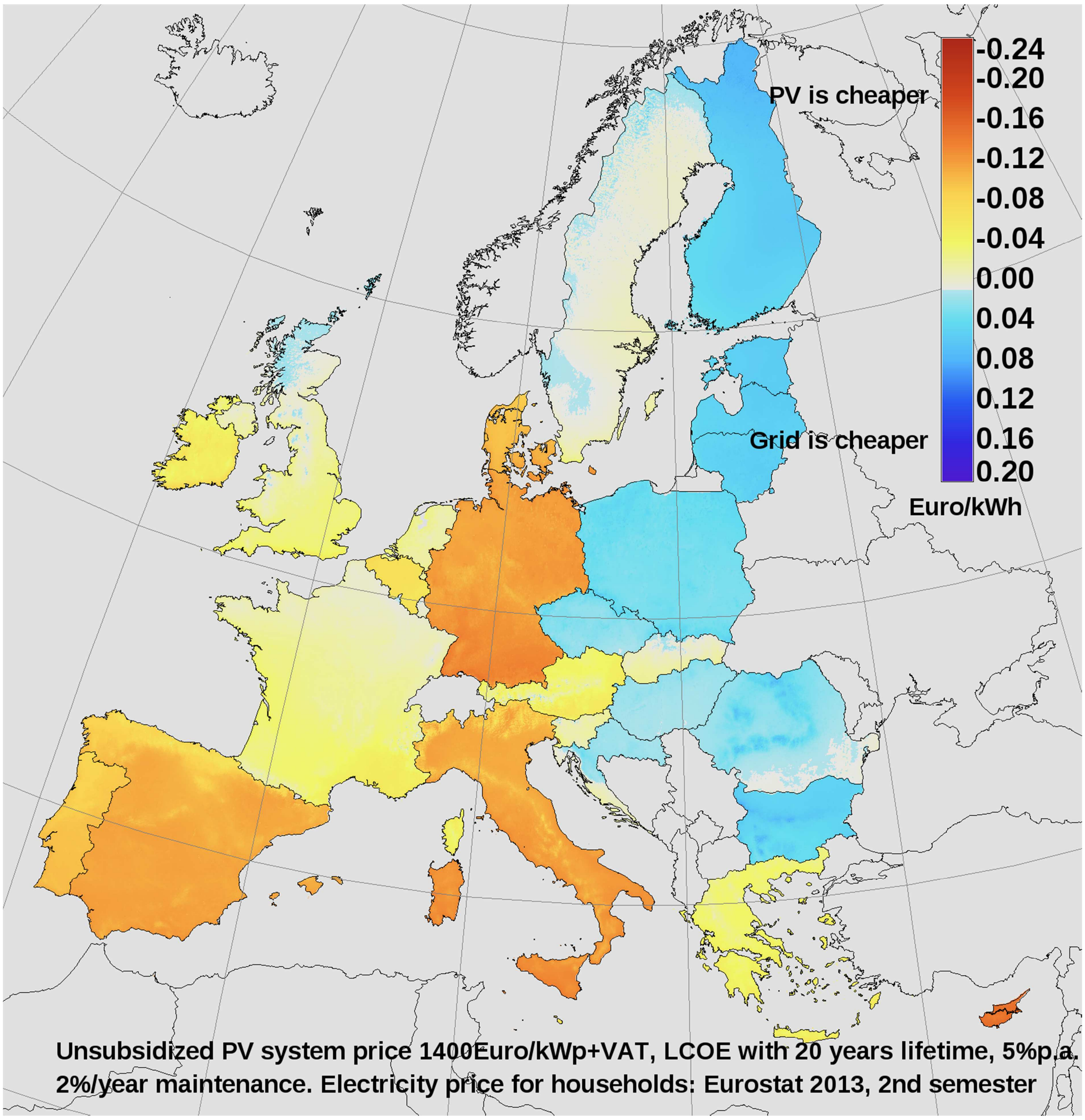
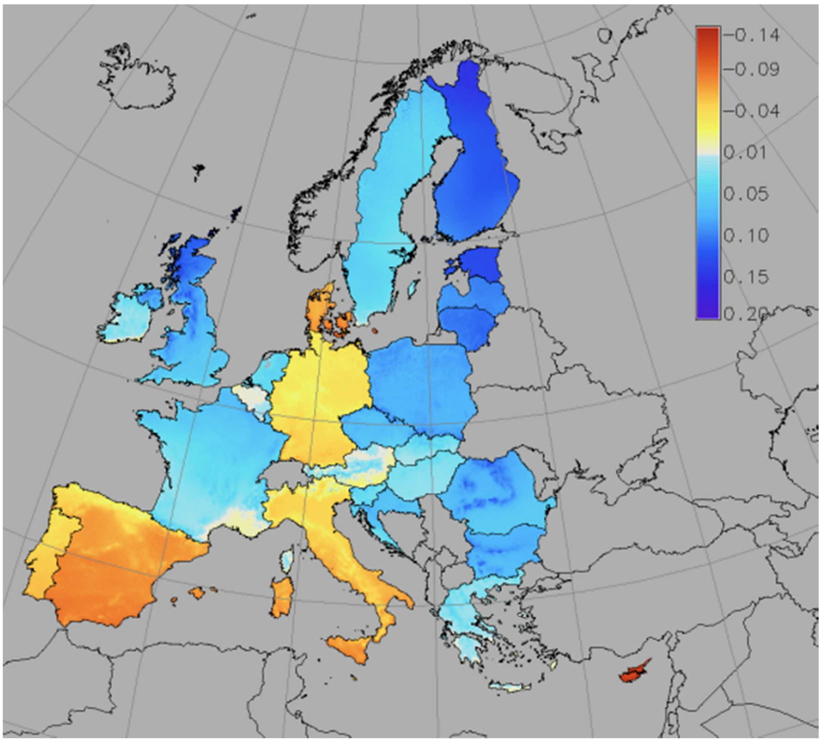
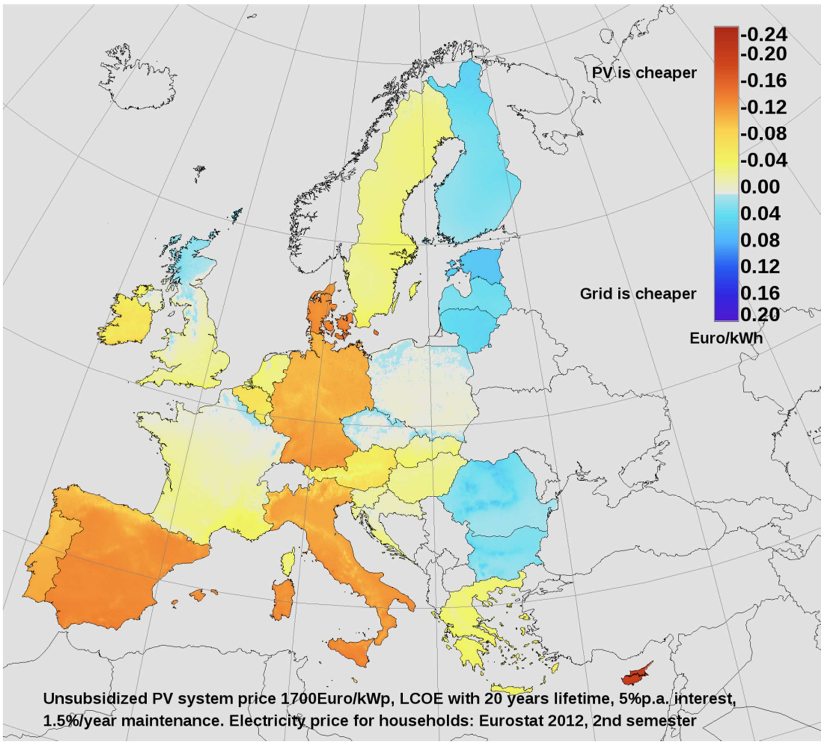



**Fig. 3 Price comparison map 2014.**



(a)



(b)

**Fig. 4 Price comparison maps for a) the 2012 and b) the 2013 analyses N.B. the absolute value in the colour scales differ**.

**Table 6 Country-by-country analysis of PV LCOE competitiveness**

| EU Member State | Population | PV LCOE < electricity price (see Fig. 2) | Population with PV LCOE < electricity price |
|---|---|---|---|
| AT:Austria | 8,443,018 | Y | 8,443,018 |
| BE:Belgium | 11,094,850 | Y | 11,094,850 |
| BG:Bulgaria | 7,327,224 | N | 0 |
| CY:Cyprus | 862,011 | Y | 862,011 |
| CZ:Czech Republic | 10,505,445 | N | 0 |
| DE:Germany | 81,843,743 | Y | 81,843,743 |
| DK:Denmark | 5,573,894 | Y | 5,573,894 |
| EE:Estonia | 1,294,486 | N | 0 |
| EL:Greece | 11,290,067 | Y | 11,290,067 |
| ES:Spain | 46,196,276 | Y | 46,196,276 |
| FI:Finland | 5,401,267 | N | 0 |
| FR:France | 65,327,724 | Y | 65,327,724 |
| HR:Croatia | 4,398,150 | N | 0 |
| HU:Hungary | 9,932,000 | N | 0 |
| IE:Ireland | 4,582,707 | Y | 4,582,707 |
| IT:Italy | 59,394,207 | Y | 59,394,207 |
| LT:Lithuania | 3,003,641 | N | 0 |
| LU:Luxembourg | 524,853 | Y | 524,853 |
| LV:Latvia | 2,041,763 | N | 0 |
| MT:Malta | 417,546 | Y | 417,546 |
| NL:Netherlands | 16,730,348 | Y | 16,730,348 |
| PL:Poland | 38,538,447 | N | 0 |
| PT:Portugal | 10,542,398 | Y | 10,542,398 |
| RO:Romania | 21,355,849 | N | 0 |
| SE:Sweden | 9,482,855 | Y | 9,482,855 |
| SI:Slovenia | 2,055,496 | Y | 2,055,496 |
| SK:Slovakia | 5,404,322 | Y | 5,404,322 |
| UK:United Kingdom | 63,456,584 | Y | 63,456,584 |
| Total | 507,021,171 | | 403,222,899 |
| | | | 79.5% |

# 4. Conclusions

- Updated maps have been generated comparing the levelised cost of PV electricity with residential prices in European countries. The analysis assumes that full and free net metering but does not include any feed-in tariff or subsidy scheme. The results highlight the increasing competitiveness of PV. On this basis the PV LCOE can be equal to or less than residential electricity prices for 79.5% of Europe's population.

- A system price of EUR 1400/kWp is used, which is considered representative of that in a mature and competitive market. VAT is added at the rate applicable in each Member State.

- The LCOE model also highlights how a PV system can produce extremely competitive electricity in the post-amortisation period (here 20 years). In this phase only operating, maintenance and replacement costs are incurred. Even with conservative assumptions, for these parameters, electricity costs of 0.04 EUR/kWh appear achievable. To better quantify this, detailed asset management strategies need to be put in place, underpinned by models of the degradation processes for key components. This latter area remains underdeveloped as yet for PV technologies and should be a research priority.

The results are of relevance to several aspects of EU energy policy:

a) With approximately 80 GW of installations by the end of 2013, PV already provides already about 2.8% of Europe's electricity needs. The scope for further growth of this important low carbon energy source will be driven largely by economic factors, such as the cost/price differentials identified here.
b) The economics of small PV systems suitable for buildings in the residential, institutional and service sectors play an important role in implementing energy efficient policies, where they form an important element in overall energy management systems.
c) In the longer term, PV systems will provide a very low cost electricity source once the initial investment has been amortised, leaving just the costs related to operation maintenance and component replacement,

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Title: Cost Maps for Unsubsidised Photovoltaic Electricity
Author(s): H. Ossenbrink, T. Huld, A. Jäger-Waldau, N. Taylor

2014 – 22 pp. – 21.0 x 29.7 cm

**Abstract**
The study assesses the generation costs for residential photovoltaic systems and prices for household electricity. The results are presented as maps comparing the levelised cost of PV electricity with residential prices in European countries. The analysis assumes net metering but does not include any feed-in tariff or subsidy scheme. On this basis the PV LCOE is now below the residential electricity price for more than 79% of Europe's population. These results have several implications for the further development of the photovoltaic solar electricity.

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