This paper first appeared in the fourteenth print edition of the *Photovoltaics International* journal, published in November 2011.

Fab & Facilities
Materials
Cell Processing
Thin Film
PV Modules
Power Generation
Market Watch

Utility-scale PV power plants – investment costs and electricity price

Denis Lenardič, pvresources, Jesenice, Slovenia

ABSTRACT

It is essential to understand the investment and operating costs of photovoltaic power plants in terms of economic parameter calculations such as levelized cost of electricity (LCoE). The dynamic behaviour of national and international markets requires a precise and detailed estimation of costs, and this knowledge is especially important to investors and policymakers. Only if the investment and operating costs of PV power plants are known can the price of electricity and the more detailed levelized cost of electricity be precisely calculated. High investment costs also require reliable investment policies and close cooperation between financial institutions (such as banks and investment funds) and power plant investors. Investment in large-scale PV power plants requires a detailed evaluation of solar radiation potential and grid availability, as well as a load analysis and a precise economic evaluation. When the investment cost based on the above-mentioned parameters is known, an estimation of the operating costs should be the next step. When all the costs of a PV power plant have been estimated, the price of electricity, or even a more detailed LCoE, can be calculated. This paper presents the trend of investment costs and some typical maintenance costs, and calculations of electricity price based on recent real data for large-scale PV power plants.

Investment costs

The average investment cost of large-scale photovoltaic power plants has decreased from about €6 million per MWp in 2008 to about €2 million per MWp in 2011. Data for recent years is presented in Figs. 1 and 2. Considering PV power plant size and investment costs over a short period of time (for example 1 year), investment costs increase fairly linearly, regardless of the installed PV power capacity.

> "The average investment cost of large-scale photovoltaic power plants has decreased from about €6 million per MWp in 2008 to about €2 million per MWp in 2011."

The analysis of investment costs presented in this paper is based on detailed investment-related data collected in recent years by the author's research [1] and taken from approximately 500 PV power plants that were commissioned between 2006 and 2011.

Only the average investment costs are considered, but overall investment cost for tracking PV power plants is slightly higher than for fixed-mounting ones. To express the calculations in €, US$ or other currencies, the mean exchange rates based on OECD Main Economic Indicators (MEI) can be used [2]. Note that the amount of data available varies each year.

As will be shown later, the investment cost is not the only criterion that should be considered during the planning phase of a PV power plant. Different technologies could have a significant impact on power plant investment costs, but they could have a significant impact on yield per area as well. It should be noted once again that only a detailed yield analysis can provide guidelines for making decisions regarding investment in new PV power plants. Detailed investment data is available for approximately 100 roof-mounted PV power plants: Fig. 2 presents the mean investment cost (€/MWp) for 2007–2010.

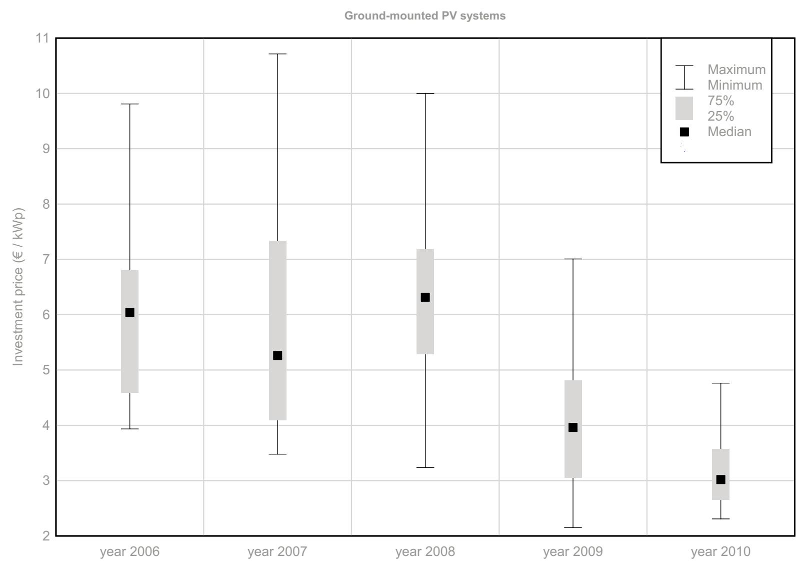


Figure 1. Investment costs (€/MWp) for ground-mounted PV power plants > 200kWp capacity during the period 2006–2010. After reaching a peak in 2008, prices have decreased significantly in subsequent years [1].

Based on the data from power plants commissioned in Italy, investment costs are estimated to lie within a similar range to that in Germany and Spain, with an average value of between €2.5 million and €3.5 million per MWp in 2010. A large amount of investment data are available for other countries, but Italy and the Czech Republic, in particular, are worth mentioning. In Europe the Czech Republic has offered some quite interesting financial conditions. The average investment value for crystalline PV power plants was at a similar level to the thin-film power plants in Germany in recent years. Basically, no significant difference between investment price (per kWp) for utility-scale and smaller PV power plants has been observed lately.

The largest part of the investment cost relates to the price of solar modules. For small-scale PV power plants, the proportion is slightly more than 50% of total investment costs; however, it is much higher for utility-scale PV power plants. The trend of solar module prices for PV power plants less than 100kWp power capacity in Germany [3] is shown in Fig. 3; further information on market prices can be found in the literature [4].

> "The largest part of the investment cost relates to the price of solar modules."

Additional costs that need to be considered in the investment calculation are those of the land required for PV power plants; these costs may be either for leasing or for purchasing the land. Some data is available in the literature, but no detailed land rental cost correlation regarding soil quality, GDP or population density has been found as yet [5]. Therefore, the global average land rental cost of US$100/hectare per year might help to calculate the land rental cost as proposed in the literature [5].

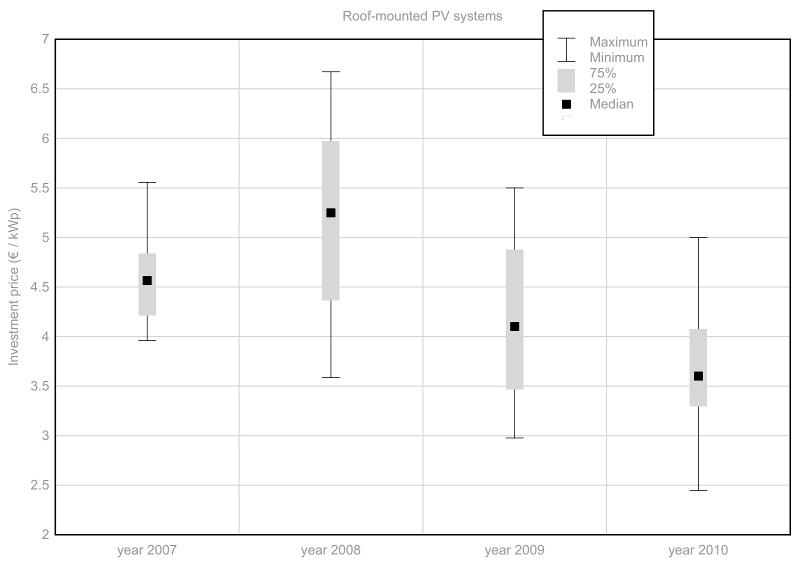


Figure 2. Investment costs (€/MWp) for roof-mounted PV power plants > 200kWp capacity during the period 2007–2010, sorted by year of construction [1].

Maintenance and operating costs

Only a few systematic studies of maintenance and operating costs have been published in the last few years. Some data based on maintenance cost analysis in the USA [6,7], Germany [8] and Italy [9] are available, for example. Total operating and maintenance costs (excluding land or roof rental cost) might vary from 1 to 5% of the total investment cost annually, as reported in literature [6,7]. A selection of data from a report issued by the Electric Power Research Institute (EPRI) [6] is given in Table 1.

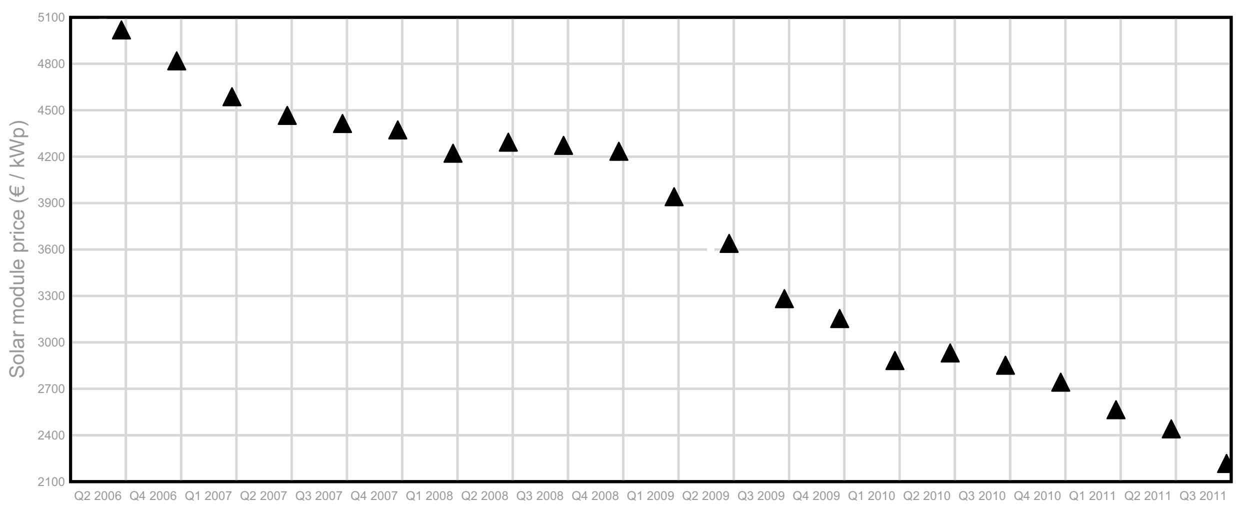
Breakdown of cost	sc-Si fixed tilt [US$/kW year]	c-Si single-axis tracking [US$/kW year]
Scheduled maintenance/cleaning	20	30
Unscheduled maintenance	2	5
Inverter replacement reserve	10	10
Insurance, property taxes, owner's costs	15	15
Total operating and maintenance costs	47	60

Source: Electric Power Research Institute (EPRI) [6]

Table 1. Utility-scale PV power plants: estimates of operating and maintenance costs (US$/kW year). (Additional, more detailed data may be found in EPRI's report [6].)

Levelized cost of electricity (LCoE)

Electricity price is based on the investment data of PV power plants as presented in this paper and on the predicted yield as announced by plant owners or plant planning/construction companies. Because simulation data of only limited precision is available, it should be emphasized that there will be some degree of uncertainty associated with these values and they should be used for information purposes only. The long-term value of the price of electricity is based on investment data and on different discount rates (see Table 2). Annual maintenance costs of 1% of investment costs are also taken into account. The present value (PV) can be



Source: BSW-Solar Photovoltaik-Preisindex, BSW-Solar 10/2011 [3]

Figure 3. Solar module prices (€/kWp) for PV power plants < 100kWp capacity in Germany (prices exclude VAT).

Discount rate (WACC)	Lifetime [years] 10	15	20	25	30
0.05	0.1295	0.0963	0.0802	0.0710	0.0651
0.06	0.1359	0.1030	0.0872	0.0782	0.0726
0.07	0.1424	0.1098	0.0944	0.0858	0.0806
0.08	0.1490	0.1168	0.1019	0.0937	0.0888

Table 2. Capital recovery factors for the most commonly used discount rates and lifetimes related to photovoltaic systems. Additionally, a 10% discount rate is often used, though only for off-grid systems and not for those connected to the grid.

calculated using the formula

$$PV = a\frac{(1+i)^n - 1}{i \cdot (1+i)^n} \qquad (1)$$

where PV = present value, a = annuity, n = time period and i = discount rate.

The discount rate i can be calculated by applying the weighted average cost of capital (WACC) given by the equation (see Breyer et al. [11])

$$i = WACC = \frac{E}{E+D} \cdot R_e + \frac{E}{E+D} \cdot R_d \cdot (1 - T_c) \qquad (2)$$

where E = market value of the firm's equity, D = market value of the firm's debt, R_e = cost of equity, R_d = cost of debt and T_c = corporate tax rate.

The costs of depreciation and interest are often expressed in terms of the capital recovery factor (CRF). The CRF is a ratio of the constant annuity to the present value

$$CRF = \frac{a}{PW} \qquad (3)$$

Figure 4. Electricity price for 5% discount rate and 20-year system lifetime for different yield rates.

where a = annuity and PV = present value.

Substituting the expression for PV from Equation 1 into Equation 3 yields the equation for the CRF

$$CRF = \frac{i \cdot (1+i)^n}{(1+i)^n - 1} \quad (4)$$

which may be evaluated using the values for different lifetimes and discount rates given in Table 2. (For a more detailed explanation of economic evaluation see Short et al. [10].)

The levelized cost of energy (LCoE) or levelized energy cost (LEC) is the constant unit cost (per unit of energy produced) of a payment stream that has the same present value as the

total life-cycle cost of a power plant. It is most relevant to energy providers such as electric utilities or PV power plant investors. The calculation methodology is explained in detail in the literature [12,13], as is the practical application of the LCoE method in terms of grid-parity calculations [11,14]. LCoE is given by the expression

$$LCoE = \frac{Total\ Life\ Cycle\ Cost}{Total\ Lifetime\ Electricity\ Production} \quad (5)$$

where the total life-cycle cost includes all costs, not just those of investment. Other costs – for example those associated with operation and maintenance, insurance, land rental and so on – should be taken into account as well. If a system is financed for a shorter period than a lifetime then residual value should also be considered. Costs can be calculated by

$$costs = \sum_{n=1}^{N} \frac{c_{annual}^{n}}{(1+i)^n} \cdot (1 - T_c) \quad (6)$$

where c_{annual} = total annual costs, N = lifetime (years), i = discount rate and T_c = corporate tax rate. (For details see Campbell [12].)

The weighted yield over the total lifetime (kWh/kWp) of the system is calculated by the equation (see Jordan et al. [15])

$$Yield_w = \sum_{n=1}^{N} \frac{Yield_i \cdot (1 - R_D)^n}{(1+i)^n} \quad (7)$$

where $Yield_w$ = weighted yield over the lifetime (kWh/kWp), $Yield_i$ = initial yield in the first year (kWh/kWp), N = lifetime (years), R_D = system degradation rate (% per year) and i = discount rate. It is important to note that the system degradation rate should be considered in order to obtain reliable estimates of the

Figure 5. Electricity price for 6% discount rate and 20-year system lifetime for different yield rates.

Figure 6. Electricity price for 7% discount rate and 20-year system lifetime for different yield rates.

Figure 7. Electricity price for 8% discount rate and 20-year system lifetime for different yield rates.

yield in the long term [15,16]. An average value of 0.7% per year has been reported in the literature [15] and can be used for detailed calculations for estimating costs.

Based on calculated values, the LCoE can be determined by using the equation (see Breyer et al. [11])

$$LCoE = \frac{CRF \cdot CAPEX + costs}{E_{total}} \quad (8)$$

where CRF = capital recovery factor, $costs$ = total costs calculated using Equation 6, $CAPEX$ = capital expenditure (investment costs) and E_{total} = total lifetime electricity production. In Equation 8, the value of the investment costs (CAPEX) is considered in the calculation of LCoE; alternatively, LCoE can be calculated using different equations, including (for example) a detailed calculation of the net present value (NPV) or depreciation [12,13,14].

"It is important to note that the system degradation rate should be considered in order to obtain reliable estimates of the yield in the long term."

Electricity prices

Electricity prices for systems with a planned 20-year lifetime, discount rates ranging from 5 to 8%, and typical annual yields of 900kWh/kWp, 1000kWh/kWp, 1500kWh/kWp and 2000kWh/kWp are shown in Figs. 4–7. (Additional information may be found in Baumgartner [17].) The yield range presented in these figures covers the typical annual yield (rough estimate) achievable in European countries. A yield of 900kWh/kWp can be achieved in northern Germany using fixed-mounting systems; up to 1500kWh/kWp is possible in Italy, Greece and Spain and around 2000kWh/kWp in these countries when using two-axis tracking systems. The range of investment costs covers typical investment costs in the period 2008–2011. Note that the values shown are based on rough estimates – for a detailed economic evaluation more accurate data is necessary. For these calculations, annual maintenance costs representing 1% of the investment are considered [6].

More detailed equations for electricity price calculations are also available in the literature [5,13]. Using these equations, more accurate calculations are possible, such as the calculation of electricity price as a function of solar module or balance of system (BoS) costs.

References

[1] pvresources.com, "PV power plants put into service till end of 2010", database [partially available online at www.sunenergysite.eu/en/top50pv.php].

[2] OECD, "Financial Indicators (MEI): Exchange rates (USD monthly averages)" [available online at http://stats.oecd.org].

[3] Bundesverband Solarwirtschaft e.V. 2011, "Statistische Zahlen der Deutschen Solarstrombranche (Photovoltaik)", October [available online at http://www.solarwirtschaft.de/fileadmin/content_files/BSW_Solar_Fakten_PV_1110.pdf].

[4] Solarbuzz, "Module pricing" [available online at http://solarbuzz.com/facts-and-figures/retail-price-environment/module-prices].

[5] Hoogwijk, M.M. 2004, "On the global and regional potential of renewable energy", Ph.D. dissertation, Utrecht University, The Netherlands.

[6] Electric Power Research Institute (EPRI) 2010, "Addressing solar photovoltaic operations and maintenance challenges: A survey of current knowledge and practices", White Paper, July.

[7] Orlandi, B., Zakaria, R. and Carraretto, C. 2011, "Large scale PV in Italy: Technical, financial and contractual challenges", *Proc. Renew. Energy World Europe 2011 Conf.*, Milan, Italy.

[8] Kost, C. and Schlegl, T. 2010, "Stromgestehungskosten Erneuerbare Energien", Studie, Fraunhofer-Institut für Solare Energiesysteme ISE, Freiburg, December.

[9] Hansen, T. et al. 2005, "Photovoltaic power plant experience at Tucson electric power", *Proc. ASME Internat. Mech. Eng. Congr.*, Orlando, Florida, USA.

[10] Short, W., Packey, D.J. and Holt, T. 1995, "A manual for the economic evaluation of energy efficiency and renewable energy technologies", NREL/TP-462-5173, National Renewable Energy Laboratory.

[11] Breyer, C. et al. 2009, "Grid-parity analysis for EU and US regions and market segments – dynamics of grid-parity and dependence on solar irradiance, local electricity prices and progress ratio", *Proc 24th EU PVSEC*, Hamburg, Germany.

[12] Campbell, M. 2009, "Minimizing utility-scale PV power plant levelized cost of energy using high capacity factor configurations", *Photovoltaics International*, 4th Edn.

[13] Whisnant, R.A. et al. 2006, "Economic analysis and environmental aspects of photovoltaic systems", in Luque, A. and Hegedus, S., Eds., *Handbook of Photovoltaic Science and Engineering*, New York: John Wiley & Sons, Inc.

[14] EPIA 2011, "Solar photovoltaics competing in the energy sector (2011): On a road to competitivness" [available online at http://www.epia.org/publications/].

[15] Jordan, D. et al. 2010, "Outdoor PV degradation comparison", *Proc. 35th IEEE PVSC*, Honolulu, Hawaii, USA.

[16] Jordan, D. 2010, "Degradation rates", NREL, February [available online at http://www1.eere.energy.gov/solar/pdfs/pvrw2010_jordan.pdf].

[17] Baumgartner, F. 2008, "Was kann der Solarstrom leisten?", Vortragsreihe ZHAW Energie Apero, June, Winterthur, Switzerland [available online at https://home.zhaw.ch/~bauf/pv/talks/080612_energie_apero_zhaw_baumgartner.pdf].

About the Author

Denis Lenardič received his degree in electrical engineering from the University of Ljubljana, Slovenia. From 2004 to 2008 he served as chairman of the Slovene national section of the IEC TC82 Technical Committee.

Enquiries

Cesta Revoucije 3
SI-4270 Jesenice
Slovenia
Email: contact@pvresources.com
Web: www.pvresources.com