

Solar Photovoltaic Toolkit

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Summary

This dataset compiles capital costs (CAPEX) and levelized cost of energy (LCOE) data for the solar photovoltaic (PV) technology by year and country and presents the data in an interactive manner. Although, the dataset contains information that dates back to the 1980s, most of the information covers the past 10 years.

With the exception of a small set of entries, all costs are reported in nominal U.S. dollars. If the costs were provided in a different currency, the amount is converted to U.S. dollars. Because several assumptions/factors affect the CAPEX and LCOE, these are included if they are reported in the source. Also when a range is provided for the CAPEX or LCOE, the median is reported.

In addition to the interactive dataset, a raw dataset is also provided in Microsoft Office Excel should the user wish to perform their own post-processing. Alongside the raw and interactive data, an LCOE

Analyzing Tool accompanies this toolkit and is specifically tailored for the solar PV technology. The Analyzing Tool allows the user to attain the LCOE using the capacity factor or solar irradiation.

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We intend to update this dataset quarterly. If you would like to obtain more information about this dataset, contribute to its contents, suggest ways to enhance it, or bring to our attention any errors, please contact us at research@kapsarc.org and include 'Solar PV Toolkit' in the subject line.

Overview – What is the Solar PV Toolkit?

The solar industry has witnessed remarkable declines in costs during the past 25 years for a number of reasons including technological advancements and industry expansion. The benchmark component that is typically referred to when reporting cost trends is the solar module, and many institutions publish the global average selling price for the modules on a regular basis.

Indeed, the module price serves as a good indicator of developments in the solar industry and technology. However, the module price is unable to capture regional differences that arise when building solar PV systems. Variations in labor costs, legal costs, taxes and cost of capital between countries are some of the reasons why the same plant would have very different costs when built in different places. The same also applies to the levelized cost of energy; solar conditions as well as maintenance costs vary across countries, which result in different operational costs. The variations in capital expenditure and operational costs between countries become even more pronounced when considering the size of the installed system.

To capture regional differences in capital and generation costs, we have compiled a large collection of data across many geographies for the three typical system sizes (i.e. residential, commercial, and utility). The costs are provided and accompanied by the assumptions that were used to arrive at these actual costs including interest rates, solar irradiation, technology type, etc, where these assumptions are given in the source.

The dataset is interactive. Users can compare the costs in a variety of ways depending on the filters that are used (see page 11). Furthermore, a user may be interested in analysing how generation costs change if the financial assumptions are altered.

For this reason, the toolkit provides an excel-based Analyzing Tool to aid in experimenting and evaluating different scenarios. The raw data is also provided if a user is interested in performing further analysis. To summarize, this tool kits provides the following:

1. A spatial (map-based) interactive representation of CAPEX
2. A spatial (map-based) interactive representation of LCOE
3. A scatter chart interactive representation of CAPEX
4. A scatter chart interactive representation of LCOE
5. An interactive bar chart for annual global solar PV installations
6. An interactive bar chart for cumulative global solar PV installations
7. An LCOE Analyzer that attains the LCOE via capacity factor or solar irradiation
8. Raw data in Microsoft Excel format

Users – Who is the Toolkit Intended for?

The toolkit, and more particularly the dataset, is intended for any individual or institution interested in the solar PV industry and its cost trends. It is designed to cater for policymakers, investors, technologists, researchers, analysts, installers, companies and homeowners wishing to install PV systems, utilities, or any other stakeholder including interested citizens.

Dataset Description

The two focal metrics that are provided in this dataset are the time-series capital costs (CAPEX) and the time-series levelized cost of energy (LCOE); both these terms will be explained shortly. CAPEX and the LCOE can capture the regional differences in building and electricity generation costs respectively – something the module cost cannot do. Along with the reported CAPEX and LCOE at a specified year, additional information (both quantitative and qualitative) is included to enable the user to better understand and explain the observed cost values and trends through time.

To complement the CAPEX and LCOE information available, the dataset user may be interested in knowing the installed capacities of solar systems, both annual and cumulative, in a specific country or countries. Looking at all this information collectively better enables the observer to correlate policy effectiveness with cost trends.

Capital Costs (CAPEX)

Capital costs are all the costs needed to build and commission a solar system. It is often referred to as **overnight costs** or **turnkey costs**. In order to allow for a quick and more intuitive comparison, the capital costs are provided in the form of **nominal USD-per-watt**, i.e. **nominal \$/W** rather than the overall payment. For example, a 2-kW system that costs \$8,000 should not be deemed more expensive than a 3-kW system that costs \$12,000 because both systems cost 4 \$/W. In an extremely limited number of cases (i.e. Switzerland) the costs were kept in euros per watt.

Levelized Cost of Energy (LCOE)

With respect to power generation costs, the levelized cost of energy (also referred to sometimes as the levelized cost of electricity and abbreviated as LCOE), is probably the most widely accepted metric used to compare the performance of different generation technologies, renewable or otherwise. In essence, the LCOE is the price at which a plant should sell electricity to break-even. It is derived as the ratio of the present value of the total costs incurred throughout the lifetime of the plant to the overall energy generated by the system over the lifetime of the plant. The LCOE has received significant research attention and both its advantages and weaknesses are well documented.

Typically, the LCOE is calculated, assuming no financing or policy support, using the following expression:

$$LCOE = \frac{I + \sum_{i=1}^n \frac{O \& M}{(1+r)^i}}{\sum_{i=1}^n \frac{E_i}{(1+r)^i}}$$

where

| | |
|--------|---|
| I | is the initial investment (\$) |
| r | is the discount rate (%) |
| E | is the energy output (in kilowatt-hours, or kWh) |
| n | is the lifetime of the plant (year) |
| $O\&M$ | is the operation and maintenance costs (\$) |

Dataset Description

Throughout the dataset, **the LCOE is reported in nominal USD per kWh, i.e. nominal \$/kWh.** Inevitably, the expression of the LCOE can vary from one document to another and from one author to another (for example, dismantling costs, retirement costs and salvage value may be considered). However, it is fundamentally a ratio of costs incurred to energy generated. For more information about LCOE please refer to any of the numerous reports available in the literature.

What Does This Dataset Include?

For each geographical location or country, the following associated information is included within the same row of raw dataset Excel file: Scale, Year, Source, Source Details, Financial, Annual Panel Degradation, Technology, Module Efficiency, Capacity Factor or Solar Condition, and Comments. Each of these terms is explained in this section. It should be noted, however, that if no information is provided, this means that the reference did not contain that particular piece of information.

Location

The location, for the most part, refers to a **country**. However, it may also refer to a group of countries that share **geographic proximity** like 'Europe' for example and may also refer to a **group of countries** that share some characteristic(s) like the Organization for Economic Cooperation and Development (OECD) countries for example.

Scale

Typically, solar systems are broadly categorized according to their size as **residential** systems (2kW to 10kW), commercial systems (10kW to 100-250kW), **utility** systems (1MW and above).

As expected, the system size has cost implications on both the CAPEX and LCOE, and it is inaccurate to compare systems across countries irrespective of their size. The scale is included if it were provided in the reference; otherwise, the term 'Not Specified' would be used.

Year

In this dataset, the 'year' provided is the year to which the cost data apply, not the year in which the data was published or released. For example, a report may have been released in 2012 but actually compiles cost data for 2010. In such a case, 2010 would be the year entered.

Source

The source refers to the **organization or institution that had published the costs**. In interest of brevity, the acronym of the organization's name is used. For example, if the source of the data was a report published by the 'International Energy Agency', the source will be included as 'IEA'. If a user is interested in more information they can turn to **Source Details**, which includes the actual citation.

Source Details

The source details will include the **actual citation of the reference** including authors, title of report or article, volume number, page numbers, etc, in **Harvard Referencing Style**. When available, the online link is provided along with the date that the source was accessed.

Financial

This section of the dataset includes any **financial assumptions that are associated with capital costs or the LCOE as mentioned in the source**.

As expected, some sources do not provide any financial information and if so this field is kept blank.

For brevity, this section uses some abbreviations as follows:

- COC: Cost of Capital
- COD: Cost of Debt
- DR: Discount Rate
- IR: Interest Rate
- ITC: Investment Tax Credit
- ROI: Return-on-Investment

Technology

Most of the solar modules that are available in the market are made of **silicon or any of its variations**. In fact, silicon modules accounted for nearly 90% of the global solar module production capacity in the photovoltaic industry in 2014. The remaining market is dominated **by thin-film technology and its variations**. Akin to the previous section, some abbreviations have been used as follows:

- a-Si: Amorphous Silicon
- c-Si: Crystalline Silicon
- CdTe: Cadmium Telluride (a type of thin-film technology)
- CIGS: Copper Indium Gallium Selenide (a type of thin-film technology)
- mc-Si: Multi-crystalline Silicon
- sc-Si: Single-Crystalline Silicon

In addition to the type of modules, solar modules can be installed on **roof-tops** or on the **ground** (i.e. **ground-mount**), and can also be **fixed** or have a **tilting**, i.e. **tracking** capability to follow the sun's movement thereby increasing the energy output. The modules may also be installed on a **flat roof** or a **sloped roof**. Some modules can tolerate mechanical stresses and/or bending by being **flexible**. It is also possible for the modules to be integrated during the building of a structure. In that case, the solar system can be referred to as the **façade** or **building integrated photovoltaic (BIPV)**.

Module Efficiency

As the sun shines on the solar modules, solar energy is transformed into electrical energy. Ideally, all the incident energy from the sun should be transformed into electrical energy. Practically, however, energy is lost during transformation and **the loss** is measured **as a percentage**. For example, if the incident solar power is 100W and the module possesses an efficiency of 20%, then the output of the module will be 20W.

Annual Panel Degradation

Solar panels (a group of modules form a panel) can easily last for 25-30 years. However, they do not perform equally well throughout their lifetime. Rather, **the performance deteriorates annually by a certain percentage**. Although modules typically come with a 20-year warranty guaranteeing that the panels will generate at least 80% of their rated power after 20 years of usage (which translates to an annual degradation of about 1%), empirical studies for recent modules show that an annual degradation rate of 0.5% is more indicative of real scenarios.

Capacity Factor and/or Solar Conditions

The cost of generating electricity for PV systems depends directly on the prevailing solar conditions. When reporting LCOE figures for systems, the assumptions made regarding the capacity factor or the solar conditions are important.

The **capacity factor**, as defined by the US Energy Information Administration, **is the ratio of the electrical energy produced** by a generating unit for the period of time considered **to the electrical energy that could have been produced** at continuous full power operation during the same period. In other words, it is a ratio of the actual output of the energy system to the maximum potential output that could be generated had the system run continuously. The time period that is usually considered for calculating the capacity factor is one year. As an example, a generator rated at 1 MW can generate a maximum of 8,760 MWh if it were to be on for a full year (there are 8,760 hours in one year). If the generator produces 1,000 MWh, then the capacity factor can be calculated as $1,000 \text{ MWh} / 8,760 \text{ MWh} = 11.4\%$.

Alternatively, the energy generated per year can be calculated by knowing the solar irradiation conditions that exist in the geographical location where the PV system is built. **Irradiation, also commonly referred to as insolation, is the amount of solar energy received on a surface in a given time.** Irradiation data is widely available online through a number of institutions and is usually provided per year. For example, irradiation in Germany is in the range of 1,100 kWh/m², whereas a typical irradiation value for Saudi Arabia is 2,000 kWh/m². Irradiation can also be expressed in kWh/kW.

Comments

In some instances, specific and detailed information is associated with the reported costs and these are included in this section if need be. Examples of these comments include:

Costs converted to USD from a different currency: as mentioned, this dataset reports all costs in USD. If a source provides the costs in euros for example, then the euros are converted to USD to enable comparison. The abbreviations that were used for currencies were the ISO currency codes and are included herein for quick reference as follows (in alphabetical order):

- AUD: Australian Dollar
- BRL: Brazilian Real
- CAD: Canadian Dollar
- CHF: Swiss Franc
- CLP: Chilean Peso
- CNY: Chinese Yuan
- DKK: Danish Krone
- EUR: Euros
- GBP: British Pound
- JPY: Japanese Yen
- KRW: South Korean Won
- MXN: Mexican Peso
- MYR: Malaysian Ringgit
- NOK: Norwegian Krone
- SEK: Swedish Krona
- THB: Thai Baht

Reporting the costs for a region or a city within a country: Many countries are large enough to yield different generation costs due to different state regulations, solar conditions, or other factors. If the specific city or region is reported in the source, they are included in the dataset in this section.

Connection to the grid (i.e. on-grid or off-grid): If a PV system is to be connected to the national electricity grid, additional costs will be incurred.

Inclusion of storage: Some solar system owners who are not close to the grid may opt to integrate a storage system (i.e. batteries) to overcome the intermittency limitation or to have access to energy at night. Obviously, that will result in additional cost.

Detailed size of system: as mentioned above, solar systems can be categorized according to their size (i.e. scale) as residential, commercial, or utility. However, the range that defines commercial and utility scale systems are particularly broad. Because of this, many reports do indicate the actual size of the system.

Dataset Characteristics, Collection, and Processing

Users of this dataset are advised to note the following:

The data that is available in this toolkit was collected from a variety of sources including websites, reports, articles and business communications. It is important to mention that some of the sources of these data points may overlap with regard to a particular country or time span, i.e. the information from multiple sources is compiled together for the data set.

Most assuredly, **there are no systematic or institutional biases** in the process of collecting the data, i.e. no inclinations to favor any particular outcome. The data points were included as observed and no data censoring was exercised.

The costs that are provided in this dataset are in **nominal U.S. dollars**. Often, the cost could be provided in a different currency such as the

euro; when faced with such a situation, the costs are converted to U.S. dollars.

Some sources provide the data graphically without giving the actual numbers. To extract the numbers from a graph, **a commercial data extraction software (digitizer)** is used.

The resolution of the LCOE is restricted to three decimal places, while the resolution of the CAPEX is restricted to two decimal places. When a range is provided for LCOE or CAPEX values, a single number, i.e. **the median**, is used.

This dataset compiles data dating back to 1980s. However, most of the information is available for the past 10 years.

Although parts of Turkey are in Europe, it was decided that Turkey be included as an Asian country given that the latter comprises almost 95% of the total land area.

How to Use This Dataset

Using the Raw Data

The dataset was created in Microsoft Office Excel. Using the capabilities of Excel, the user is able to perform further processing or filtering as necessary. For example, the user can sort the costs from highest to lowest, sort costs by country, create pivot tables and so forth.

Using the Interactive Dataset

Using the interactive dataset interface is easy and intuitive. An example of how the dataset can be used is briefly described below with the aid of Figures 1 and 2. Figure 1 shows a representative

dataset: The data points are on the left and several 'filters' are present on the right.

As an example, assume that a user would like to compare the CAPEX of commercial scale systems in Denmark and Germany. Further, assume that the user is only interested in systems that have cost less than 8 \$/W during the period 2005 to 2015. Under these conditions, the user chooses 'Denmark' and 'Germany' from the **Country** filter, chooses 'Commercial' from the **Scale** filter, slides the upper limit of the CAPEX to '8' in the **CAPEX** slider-filter and slides the lower limit of the year to '2005' in the **Year** slider-filter. The result of this filtering is shown in Figure 2.

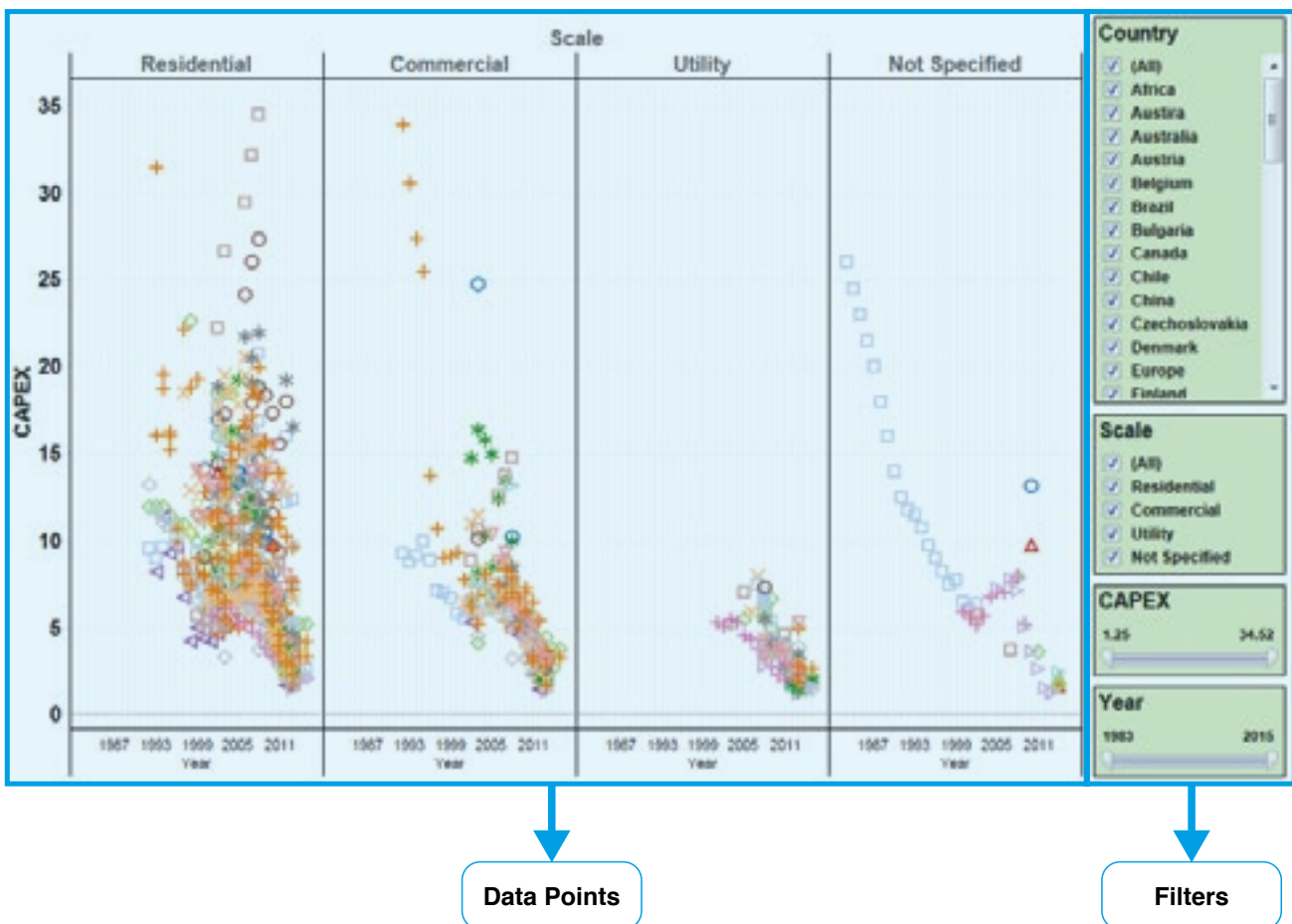


Figure 1. A representative dashboard of the interactive dataset. The data points appear on the left and the available filters are on the right.

How to Use This Dataset

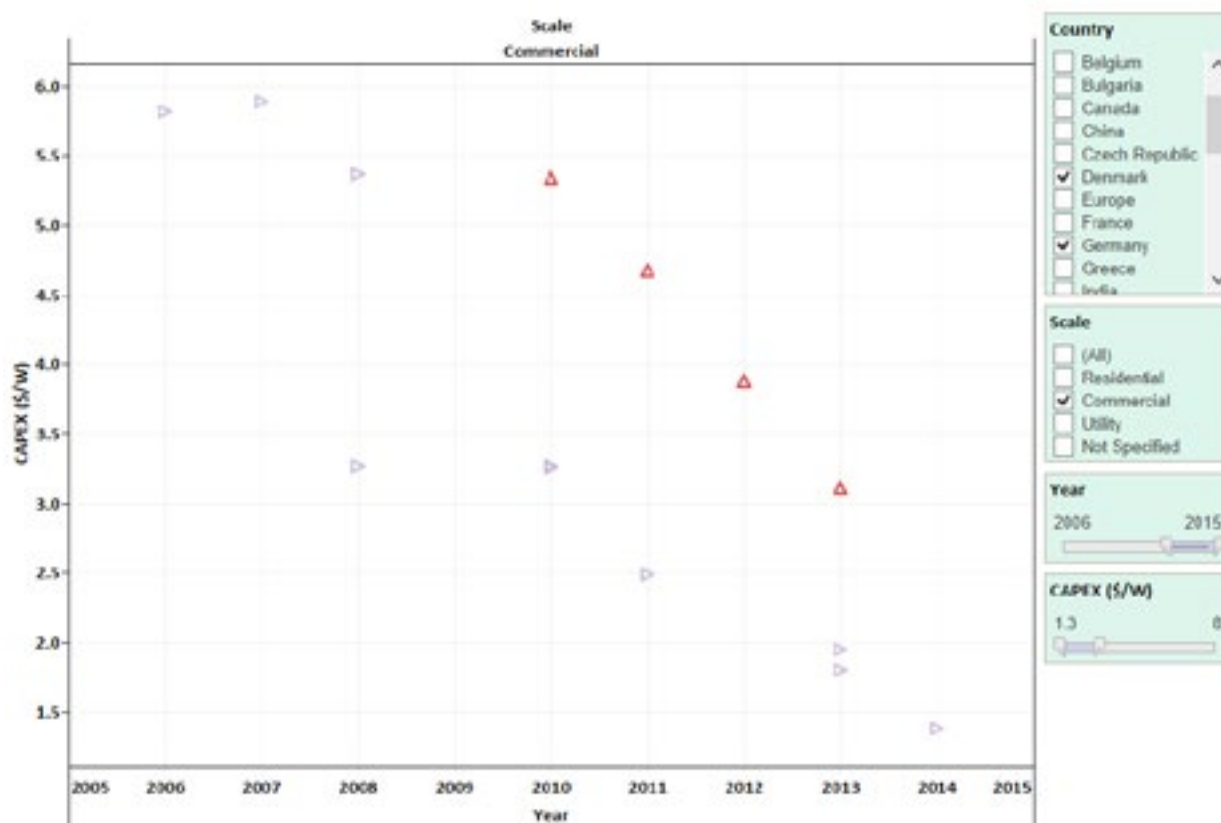


Figure 2. A representative example after the user has applied the filters of interest. In this case, the user wants to compare CAPEX of commercial systems in both Denmark and Germany, exclude results with a CAPEX higher than 8 \$/W and eliminate results prior to 2005. Note how the check-marks within the filters on the right represent what the user intends to study.

The user is also able to obtain more information on each data point that is present by simply hovering the mouse over the point of interest: a ‘tool-tip’, or a communication box will appear containing additional information on the point of interest. A sample of this is shown in Figure 3.

The illustration shows how to use the tabular/scatter representation of the dataset. As for the geospatial version, the user needs to click on the country of interest, and the corresponding data points will show under the map. Only countries that are ‘colored’ have data. Note that the spatial (map-based) representation of the data does not include all available data points – costs that represent regions like Europe or OECD countries for example are not shown in the spatial version. The scatter

representation, however, is comprehensive with respect to CAPEX and LCOE data.

The same methodology described above for filtering and visualizing the data also applies to the bar charts associated with annual and cumulative solar PV installations.

Using the LCOE Analyzing Tool

Often, when a source provides an LCOE along with some assumptions, the user may be interested in knowing how the LCOE would change if these assumptions were varied. To serve this purpose an LCOE Analyzing Tool was developed and is included in this solar toolkit.

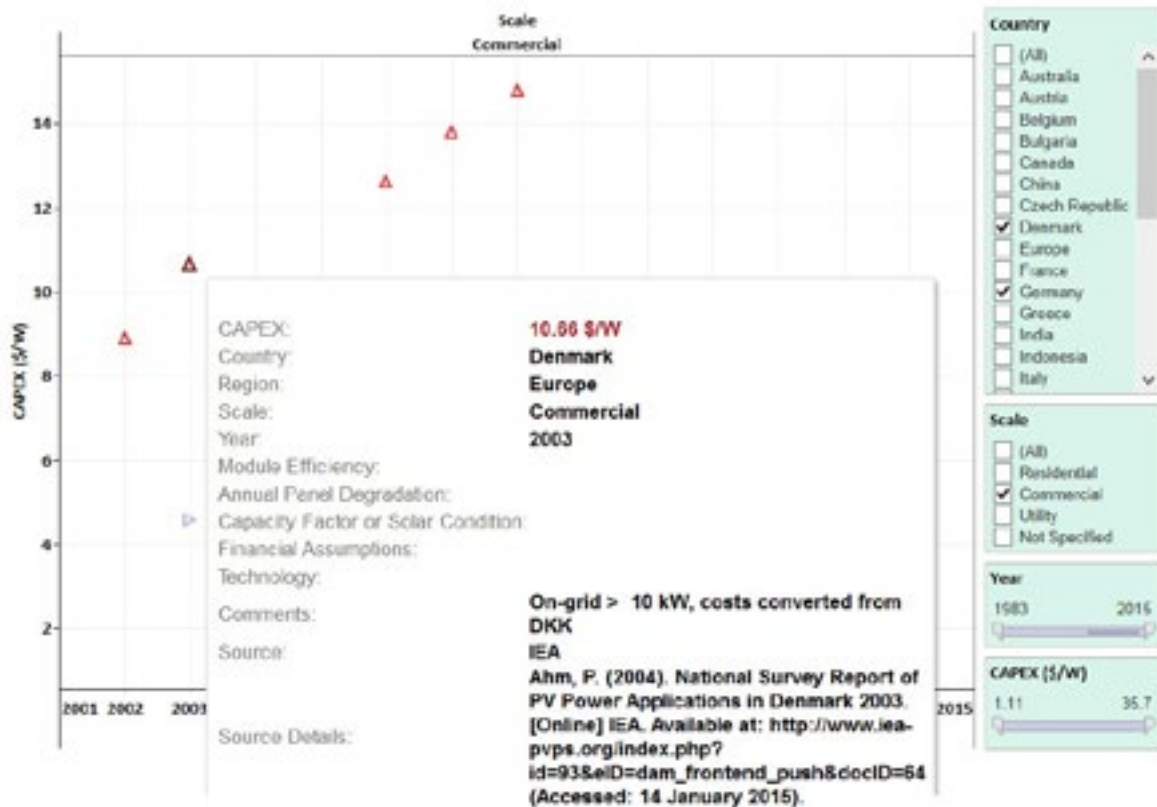


Figure 3. The ‘tool-tip’ that will appear when hovering over a specific data point. This tool-tip contains additional information about the data point as available in the source dataset file.

The LCOE Analyzing Tool was created using Excel and provides some advantages over existing calculators:

- It is specifically tailored for the solar PV technology.
- It allows the user several ‘levels of detail’ to enter parameters/costs.
- It allows the user to calculate the energy output through the ‘capacity factor’ or through ‘solar irradiation’.

- It allows the user to specify inverter replacements at non-equidistant periods and at different costs.

- It allows the user to perform a sensitivity analysis immediately.

- It strikes the right balance between being too complex and overly simplistic.

Details on how to use the Analyzing Tool are self-contained within the tool itself in the sheet under the ‘Housekeeping’ tab.

Data Sources and Citation

The dataset relies on a variety of sources including the National Renewable Energy Laboratory (NREL), International Energy Agency (IEA), Renewable Energy Network for the 21st Century (REN21) and others. In interest of brevity, an exhaustive list is not provided here and the user can refer to the excel file for details.

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About the Project

The solar toolkit compiles global time-series capital costs (CAPEX) and levelized cost of energy (LCOE) data for the solar photovoltaic (PV) industry. The data is presented in an interactive, yet intuitive, interface. Alongside the dataset, a generation cost analyzer is provided and is specifically tailored for the solar PV industry. Within a few minutes, cost and sensitivity analyses can be performed on any solar system irrespective of size, and consequently enabling the comparison of different solar projects based on an 'apples to apples' basis easily and effectively.



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