Large Scale PV Plants – Also in Denmark

54 MW PV Plant in Moura Portugal; Photo: PA Energy Ltd.

Project Report

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PA Energy Ltd. SiCon

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i. Colophon

The project ”Large Scale PV Plants – Also in Denmark” (LPV) is supported by the Energy Research and Demonstration Programme (EUDP) of the Danish Energy Agency under ref. no.: EUDP-II J. Nr.: 64009-263, and has been carried out in the period December 2009 to March 2011.

Large scale PV plants are increasingly established worldwide and in particular in the EU countries, but so far not in Denmark. The LPV project aims at describing the advantages and disadvantages of large scale PV plants in Denmark, investigation and analysis of the potential for same and recommendations for barrier removal, the target group being potential investors and developers as well as energy planning authorities and political decision makers.

The LPV project recognizes the valuable data and input provided by a wide range of PV experts and institutions, in particular thanks are due to the IEA PVPS Task 8 on “Very Large Scale PV Systems” (www.iea-pvps.org).

The LPV project further recognizes the valuable data provided via the www.pvresources.com, www.pvlegal.eu, PV Power Plants 2010 by RENI, EPIA, SEPA and others.

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The full project report will be made available for download from the homepage of the Danish Solar Cell Association: www.solcelle.org or by mail from both authors.

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iii. Summary

Large scale PV (LPV) power plants, i.e. plants with a capacity of more than 200 kW, has since 2007 constituted an increasing share of the global PV installations. In 2009 large scale PV plants with a cumulative power of more than 1.3 GW_p were connected to the grid. Market of the year was Germany with about 600 MW_p new LPV power capacity installed followed by Italy (about 200 MW_p), the USA and the Czech Republic. Some other EU countries (Belgium, France, Greece and Bulgaria) also increased cumulative power capacity. Among Asian countries it is worth to mention China with several large scale PV power plants put into service and Thailand with a 72 MW plant under construction. The recent Asian Solar Energy Initiative of the Asian Development Bank is expected to accelerate the deployment of LPV in Asia. Also in Latin America large scale PV plants are emerging, e.g. a 30 MW_p plant in the Dominican Republic.

However, towards the end of 2010 and beginning 2011 several countries such as Spain, France, Germany, the Czech Republic and Belgium introduced less favorable conditions for LPV, as politicians in these countries are now seem to prefer to support smaller PV systems on private houses. The market for LPV in 2010 is estimated at 2.5 GW_p, but may in 2011 be reduced to about 1.5 GW_p in spite of a growing LPV market in the USA and Canada; in 2010 Canada commissioned the so far largest LPV in the world in terms of the Sarnia plant at 80 MW_p.

LPV systems are increasingly regarded with interest by the utilities. This was highlighted at the Executive Conference "The Solar Power Utility" organized by the IEA PVPS mid 2010. LPV is regarded as both a coming business opportunity for the utilities as well as a generating technology with unique features. PV deployment have now reached a level that necessitates new grid codes, first on the medium voltage level but later also at the low voltage level, requiring the PV installations actively to support power quality and grid stability.

The very first ground placed PV installation in Denmark was announced late 2010 in terms of a ca. 70 kW_p single axis tracking system at the company Linak on the island of Als. Of the about 7 MW of installed PV capacity in Denmark by end of 2010 the major part is small scale residential "roof-top" installations and installations on the roof of institutional facilities. The reason for this is the fact that the current VE-energy tariff payment level is not sufficient to support LPV investments and the LPV plants do not qualify for the otherwise quite attractive "net-metering" scheme, which by early 2011 puts the value of PV generated electricity around €c 30/kWh (DKK 2.1/kWh) for private households.

The necessary design data for LPV plants in Denmark are available or can be found, although irradiance data could be improved. There seems to be very few institutional barriers for LPV projects, but as we so far have not seen any LPV projects realized in Denmark, these findings have to be regarded as preliminary. The fast growing number of very large scale solar thermal plants for district heating applications support however support the these findings regarding the few administrative barriers.

It has further been investigated, how to optimize the lay-out of LPV plants. Under the Danish irradiance conditions with several winter months with very low solar height, PV installations on flat surfaces will have to balance the requirements of physical space – and associated land cost – with the loss of electricity production due to shadowing effects.

The potential for LPV plants in Denmark are found in three main categories: PV installations on flat roof of large commercial buildings, PV installations on other large scale infrastructure such as noise barriers and ground mounted PV installations. The technical potential for all three categories is found to be significant and in the range of 50 – 250 km^2. In terms of solar energy harvest PV plants will under Danish conditions exhibit an overall efficiency of about 10 % in conversion of the energy content of the light compared to about 0.3 % for biomass. The theoretical ground area needed to produce the present total annual electricity consumption of Denmark (around 33-35 TWh) is about 300 km^2.

Compared to other electricity generating alternatives LPV plants can easily be integrated into the surrounding landscape by putting a “shield” of bushes or threes, and the operation of the LPV plant is completely silent in contrast to wind turbines.

The Danish power grid system covers the country in a fine mesh allowing for relative cheap grid connection, and PV generated electricity fits well with the daily demand curve and complements the wind generation of electricity. The Danish grid codes and the electricity safety regulations do not address the LPV option, but it’s expected that LPV power plants will have to be treated similarly to big wind turbines.

A number of LPV plant scenarios have been investigated in detail based on actual commercial offers and the associated levelized cost of electricity (LCOE) has been found to be in the range of DKK 1 – 1.16 per kWh. With the present wind turbine tariff at around DKK 0.60/kWh the economics in isolation present a bleak picture for LPV. However, over the last four decades the learning curve of the PV technology exhibits a cost reduction of about 20 % for every doubling of the accumulated installed power, and there is nothing to indicate that this learning curve trend will not continue in the coming two decades. The global production volume of PV cells increased from about 13 GW in 2009 to about 27 GW in 2010 – an annual increase of more than 100 %. In 2011 the production volume is estimated to increase by 80-90 % compared to 2010. This will lead to fast decreasing prices. The German solar industry association (BSW) has indicated, that they expect the cost of PV technology to be at least halved by 2020 compared to 2010, and the European Photovoltaic Industry Association (EPIA) has publicized similar forecasts. If these price reductions materialize the LCOE of LPV plants in Denmark will be reduced from presently DKK 1-1.15/kWh to less than DKK 0.50/kWh.

The scenario for Denmark is consequently, that with an unchanged RE price guaranteed at DKK 0.60/kWh, LPV power plants will become an attractive investment opportunity in the coming years. It is therefore recommended, that framework conditions are created, which will allow Danish market actors to establish LPV power plants already now, to ensure that experience and know-how in this field can be developed, in order to ensure that such Danish market actors are able to benefit and contribute to the development and implementation of this – for Denmark – new source of renewable energy in the Danish energy system.

1 International Trends in the PV and Large Scale PV Markets

1.1. The PV Market

The development in PV cell/module manufacturing is illustrated in Figure 1 [PV Status Report 2010]. Since 2000 the total PV production has increased more than 30 fold with annual increases between 40 % and 80 %. Production volume is estimated to reach about 16-17 GW in 2010.

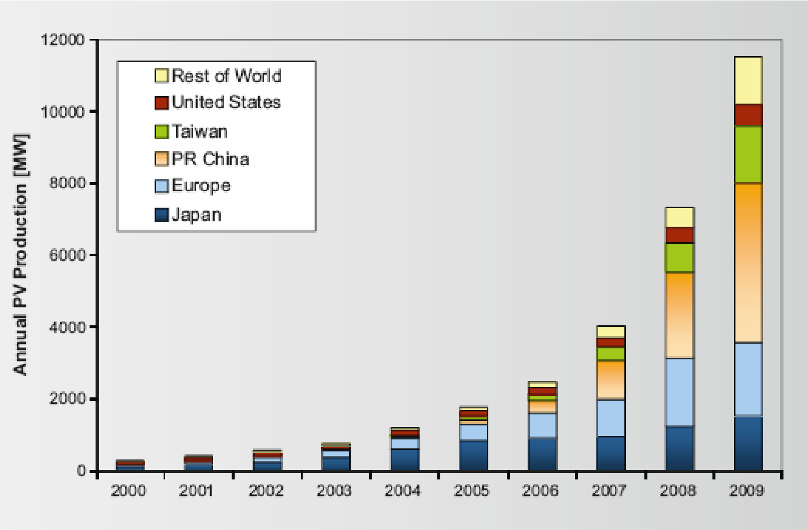

Figure 1: The development in PV cell/module manufacturing until 2009.

It is evident, that the manufacturing volume in the Peoples Republic of China and in Taiwan is growing very fast reaching about 50 % of the worldwide manufacturing volume in 2009 and estimated to reach about 56 % in 2010.

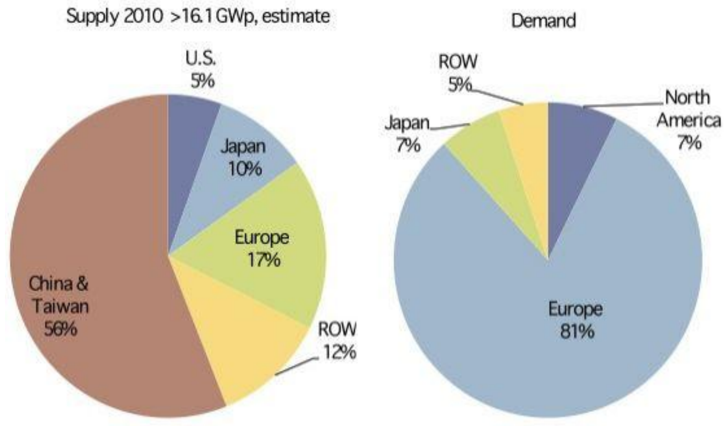

Figure 2: Supply and demand by region.

The supply and demand by regions is illustrated in Figure 2 [Navigant Consulting]. There was a huge discrepancy between the production volume at 17 % and market volume at 81 % in Europe in 2010. As the market to a large extent is driven by public incentives this situation is increasingly found politically untenable in several European countries.

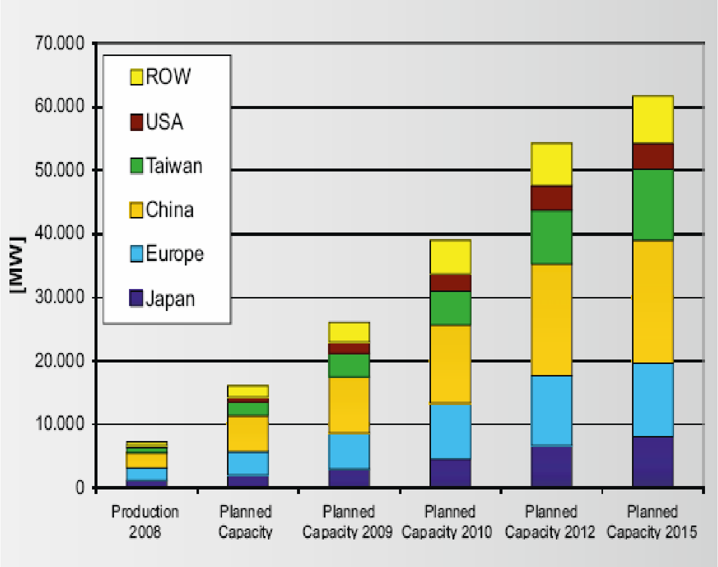

Figure 3: Expected growth in production capacity by country until 2015.

In 2009 about 80 % of the production volume was crystalline technology with the remaining 20 % encompassing various thin film technologies. However in 2010 the thin film marked share was down to 12 %, and the expectations for the future market share of thin film technologies demonstrate a large variation from 12 % to 30 % by 2015.

The announced/expected growth rate in manufacturing capacity is even more dramatic as shown in Figure 3 [PV Status Report 2010]; note the difference in units of the vertical axis as compared to Figure 1.

With an estimated realized production volume in 2009 of about 11.5 GW the announced production capacity[1] was about the double leading to a quite low utilization factor for the PV cell/module industry as a whole. If this low utilization factor is constant or growing the inevitable result will be decreasing prices.

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[1] Estimated/planned production capacity is based on figures announced by the industry. When it comes to announced plans for capacity expansion, experiences tell that these will not all be implemented.

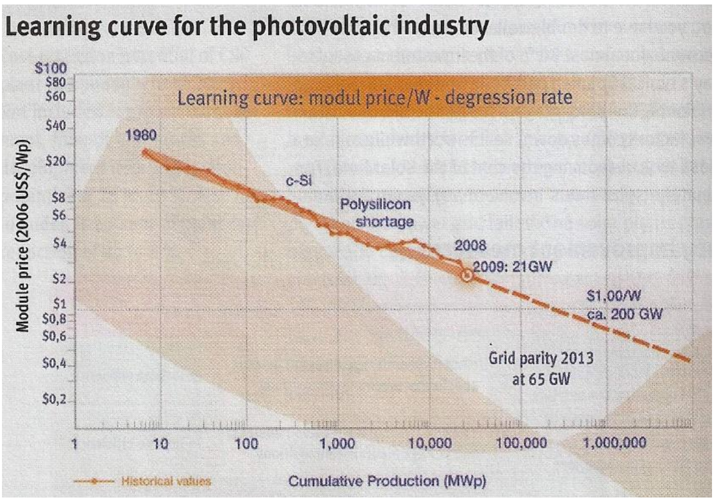


Figure 4: Learning curve for PV modules.

The trend in price for PV modules is illustrated in Fig. 4 [Photon Magazine] and exhibits a learning rate of in average 20 %. This means that for every doubling of accumulated production volume the price decreases 20 %. This trend has been pretty constant for the last 30 years or so with a few digressions e.g. the silicon feedstock shortage during 2007 and 2008. The expected market growth combined with the expected advancement in production technology and increase in performance indicates, that the PV technology will continue to follow the same learning curve at least until 2025.

Grid connected PV has in several regions reached a magnitude impacting both grid stability and quality and also with an impact on the electricity markets. With almost 2 % of the national electricity consumption being produced by PV, Germany has experienced summer days, where a significant share of the actual electricity consumption originates from the prioritized PV, forcing other more conventional producers out of the market. Also in Germany during peak load times the PV production influences the price level on the Leipzig electricity exchange, changing the possibilities for more conventional producers to obtain the very attractive peak load prices.

1.2. The Large Scale PV System Market

In the past global growth of PV installations was primarily in the form of small and medium sized installations with a capacity of less than 200 kW_p. PV installations with a capacity of 1 MW_p or even 10 MW_p were really the exception.

Since 2006-7 this has changed dramatically mainly due to decreasing prices for PV technology. In Figure 5 the LPV fraction of total installed PV capacity over the last 15 years are shown. The year 2008 illustrates the PV “bubble” in Spain, where more than 2.5 GW_p of PV power were installed - mostly as LPV installations. This resulted, according to the internet service pv-resources, in a situation where more than half of the 2008 global PV capacity expansion originated from LPV installations. In 2009 large scale PV plants with cumulative power more that 1.6 GW_p were connected to the grid out of an estimated global installed capacity of 7,8 GW corresponding to about 20 %.

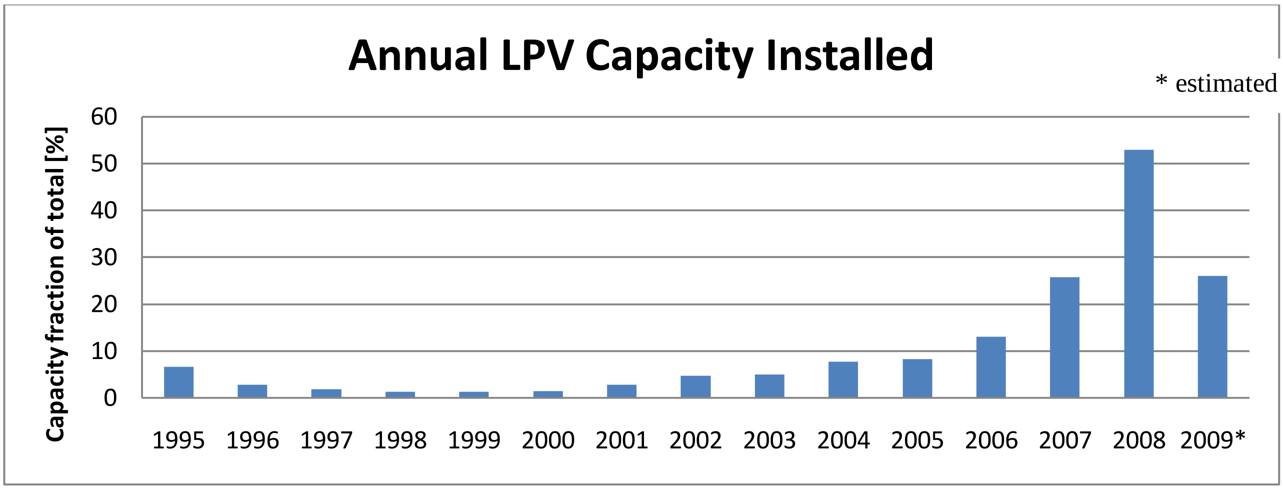


Figure 5: Annual LPV Capacity Installed in percentage of total installed PV capacity.

However, even disregarding the Spanish "bubble" there is a clear trend towards a higher percentage of LPV in the total installed PV capacity.

The corresponding development in cumulative installed capacity is shown in Figure 6.

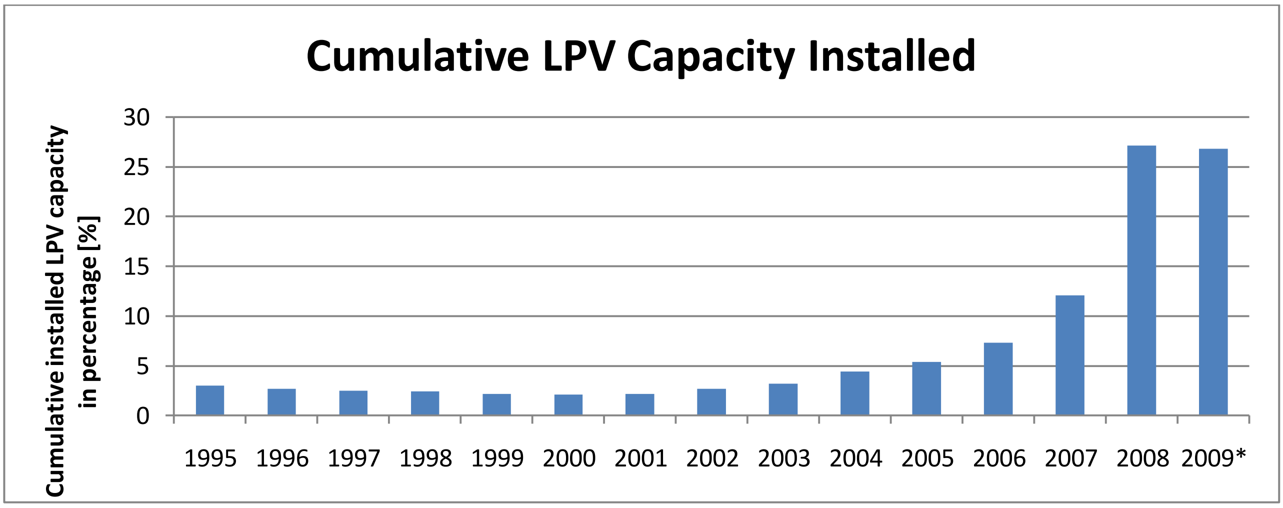


Figure 6: Cumulative installed capacity of LPV in percentage of total installed PV capacity.

The LPV capacity share of total installed PV is expected to decrease over the coming years, partly due to the one-year Spanish boost in 2008 and partly due to the recent political decisions in countries such as Germany, France, Belgium and the Czech Republic to reduce support for ground based LPV.

Most of the large scale PV plants are ground based, but an increasing number is located on large roofs of commercial buildings, this way benefitting from available space and infrastructure. A global overview of both the ground based and the roof mounted LPV systems up to 2010 is provided in Annex 1 and 2 respectively.

Market of the year in 2009 was Germany with about 600 MW_p of new large scale power capacity installed followed by Italy (about 200 MW_p), the USA and the Czech Republic. The USA is reported to have more than 2 GW_p of "utility scale" PV installations in the pipeline. Some other EU countries (Belgium, France, Greece and Bulgaria) also increased cumulative power capacity. However, EU countries such as Germany, The Czech Republic, France, Belgium and Spain have already or are discussing constraints on the deployment of in particular large scale PV plants.

Among Asian countries it is worth to mention China with several large scale PV power plants put into service and Thailand with a 72 MW_p plant under construction. The Indian solar energy plan up to 2023 targets a significant amount (>20 GW_p) of large scale PV installations. In Asia the recent Asia Solar Energy Initiative launched by the Asian Development Bank targeting 3 GW_p of PV inside three years is worth mentioning; many large scale PV installations are expected as a result of this initiative.

Also in Latin America large scale PV plants are emerging, e.g. a 30 MW_p plant in the Dominican Republic. On a global level more than 5 GW_p of large scale PV plants are estimated to be in the pipeline.

As mentioned previously the cost of PV technology decreases fast this way stimulating the deployment also of large scale installations, and this trend appears to continue fueled by large scale investment in production capacity and automation; PV technology production facilities are being expanded and streamlined using experiences from the automotive industry, and several companies have production capacities exceeding 1 GW_p/year. However, during 2010 a number of European countries, e.g. Germany, France, Spain, the Czech Republic and Belgium, all reduced incentives in particular for large scale PV plants. The political thinking behind these constraints for LPV deployment is a mix of:

- concerns about using public funds to support private investors; the political focus is on supporting small scale residential PV systems
- for countries/regions using feed-in-tariffs (FIT) concerns about rising cost of electricity or an increasing demand on government funds
- concerns about too little local content of the PV installations
- concerns about the environmental impact of LPV and the occupation of agricultural land.

Most LPV installations are connected to the grid at the medium voltage level. New grid codes on this level are under introduction and have been implemented in e.g. Germany. These codes demand that the LPV power plants can be disconnection upon request by the grid-operator can perform fault ride-through according to well-defined events and are able to deliver reactive power according to the needs of the local grid. It can be seen, that LPV plants are required actively to contribute to grid stability and power quality, which also are well within the technical capability of modern LPV technology. In case of forced short-down or reactive power supply request, the LPV power plant operators are entitled to some kind of compensation and this new risk factor with respect to future income assessments has to be take into consideration of the power plant owners/investors.

So far the largest PV installation in Denmark is the 300 kW_p system on the Skive Hus primary school in the city of Skive. However, more large scale PV installations can be expected in Denmark, and against this background the present investigation of large scale PV plants in Denmark shall be seen.

2. Status, trends and cost reduction potential in the value chain

2.1 Crystalline silicon modules

Crystalline silicon modules currently holds a marked share of more than 80 % and are expected to continue to be the product of choice for the majority of all large size PV projects to be established in Denmark (and other countries with similar meteorological conditions). The main reasons for the expected dominance of crystalline silicon modules over thin films also in Denmark are the expected restrictions in project area - which will favour installations with the highest area utilisation factor i.e. the highest module efficiency and maybe even tracker solutions. Also the fact that average ambient temperatures in Denmark are not very high will reduce the otherwise important competitive advantage of thin-films that usually have a lower power degradation temperature coefficient.

Due to the importance of crystalline silicon modules in the overall PV project value chain, the most important technical and marked related trends related to the manufacturing of this key component are discussed in detail.

2.2.1 Feedstock

Status

The base material for all crystalline silicon solar cells is silicon that is purified to either Solar-Grade (SoG) or Electronic Grade (EG) qualities. Whereas the input material for the purification process is abundant and cheap Metallurgical Grade (MG-) silicon, a limited amount of capacity for purification has given rise to severe bottleneck problems and marked instabilities. The main reason behind these capacity and capability limitations is related to the fact, that until recently the only know and implemented purification process routes were all based on CVD deposition of purified silicon compound gasses. These processes were developed and implemented with the purpose of producing feedstock material of the highest possible purity, a feedstock that's used in the manufacturing of integrated circuits, computer memory chips and power electronics. After several years with severe capacity limitations a number of new manufactures have finally succeed in establishing and operating new production capacity for silicon purification dedicated the PV market (OCI, LDK, GCL, M. Setek and PV Crystalox). Also alternative technologies with lower operational and capital expenditures (i.e. fluidized bed technologies from REC and Wacker Chemie and purified metallurgical silicon from Elkem Solar and 6N) have been developed and are now also in commercial operation.

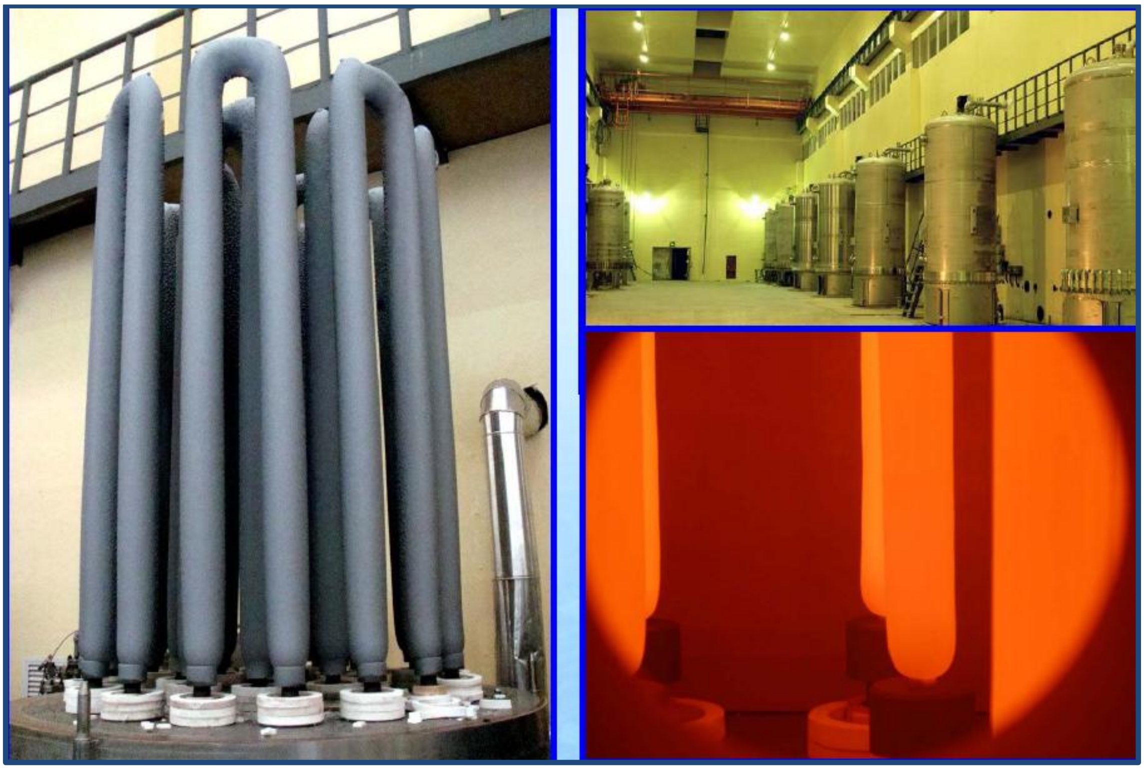


Figure 7: The first silicon rods manufactured by the LDK 1000 MT poly plant.

Marked trends

Due to the mentioned limited production capacity for silicon feedstock, the marked has been very much influenced by the unbalance in supply/demand which in 2008/9 resulted in extreme market conditions, where the price of silicon on the spot market was up to ten times higher than long term contract pricing. In order to secure market shares and growth opportunities it was necessary for the silicon customers to enter into long term contracts that requested both pre-payment of up to 25% of the contract value as well as take-or-pay conditions. Only companies with a strong financial background were able to fulfil such requirements and were able to gain market shares during the supply crises.

As much more production capacity has come online, the situation has changed, but still today the availability of silicon feedstock is limited with the result that spot market pricing of silicon (ca. 50-100 USD/kg) is still significant above the contract pricing (ca. 50 USD/kg). The general expectation is, that once the market has stabilised, the feedstock price could easily fall to a sustainable (profitable for most suppliers) level in the high 30'es (35-40 USD/kg) and eventually (2013) even down to the low 30'es. As many of the new entrants on the silicon manufacturing scene have high costs of operation due to less experience, start-up problems and de-bottlenecking challenges in the production flow, the current relatively high price level will support them in their effort to survive and grow in an otherwise quite challenging business environment. In practice this mean that the newcomers in this field can grow much faster than the old and experienced manufactures and as an illustration the Korean company OCI that has been delivering feedstock to the market for less than 2 years, are expected to become the world largest manufacturer of silicon feedstock for the PV industry already next year.

Cost reduction potential

As mentioned the gross margins in the silicon feedstock manufacturing step is currently high and for most companies the focus is on capacity expansion rather than cost reductions. It's quite clear however, that the cost structure is very different when comparing the traditional ("old") feedstock manufactures and the newcomers that have bought the technology, know-how and equipment during a period of "over-heated" market conditions, where all necessary resources and components (both access to experienced engineering and specialised components like high quality steel) was in short supply and overpriced. Based on these observations, a knowledge of historical silicon pricing (in the late 90'es virgin polysilicon was available at a price level down to 32 USD/kg), the fact that dedicated SoG feedstock manufactures with a targeted lower cost structure now are in operation all indicate, that there's room for significant cost and price reductions once the market conditions changes from demand driven into oversupply. A reduction of average silicon feedstock pricing up to 50% over the next few years could easily be the result.

2.2.2 Ingot

Status

The silicon feedstock needs to be converted into ingots with the appropriate electrical and physical properties by use of either monocrystalline or multicrystalline solidification processes. Whereas the monocrystalline solidification process has been studied and optimised for over 50 years the multicrystalline process has only been around for a little more than a decade. Both methods have similar conversion costs from feedstock to ingot and currently hold comparable marked shares. Whereas the multicrystalline ingots are easily cut into the preferred rectangular brick shape, the monocrystalline ingot in comparison are grown in a round shape and must be shaped into a pseudo-square geometry with some loss of crystal growth productivity (insignificant loss in terms of silicon as all the off-cuts can be reused) and resulting in a sub-optimised use of the module aperture area due to the slightly rounded corners of the solar cells. This geometrical disadvantage for the monocrystalline growth method is however offset by the higher conversion efficiency that can be obtained for such cells.

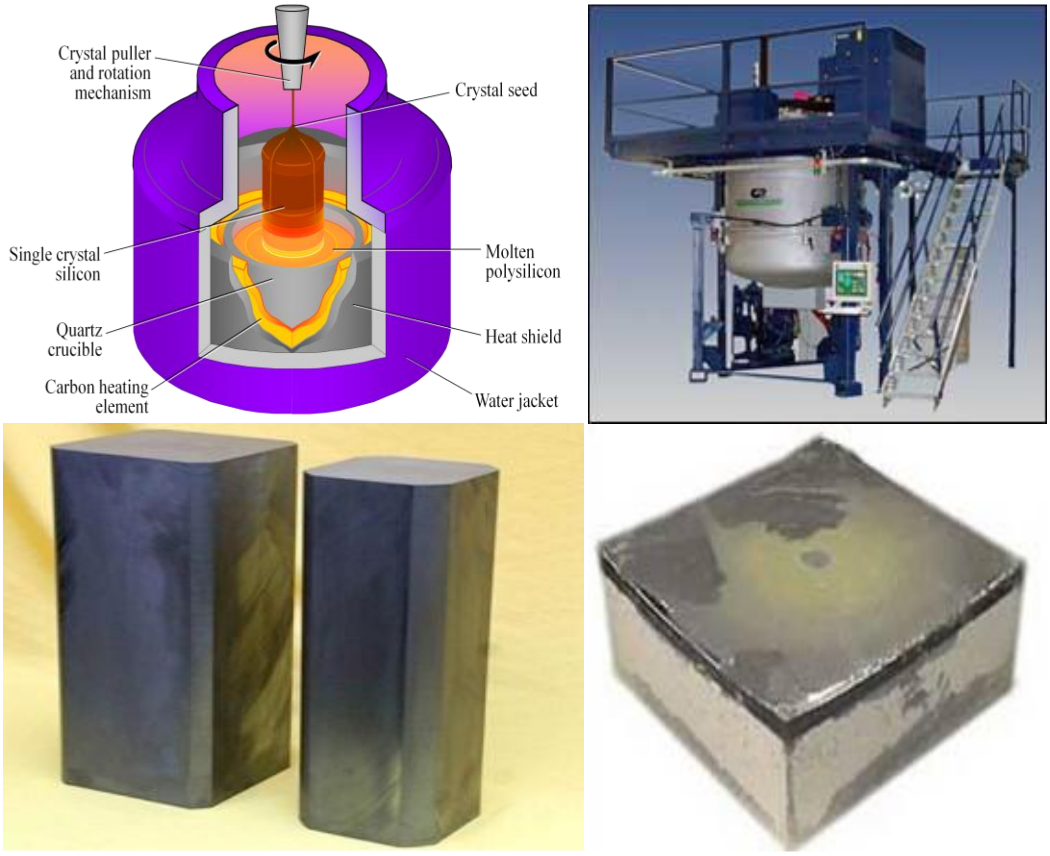


Figure 8: Crystallisation furnace for mono (left) and multi (right) and crystalline ingots of the corresponding ingot type underneath.

Marked trends

Also in the future, both mono- and multicrystalline ingot types are expected to be mainstream products. As the focus on quality and efficiency improvements for some time have had lower priority than growth in production capacity (that used to be faster and more flexible when based on multicrystalline processes), it is expected that this will change in the future, with more focus on high quality, high efficiency monocrystalline solutions.

Cost reduction potential

In general the crystallisation process represents a mature technology, and significant cost reductions in equipment and operations cannot be expected in the future. For multicrystalline casting however, it’s still possible to reach some additional economics of scale by introducing larger furnaces and crucibles and also recharging of monocrystalline furnaces will reduce the cost of operation. This however will be balanced by the increased risk exposure in case of power failure, crucible breakage or contamination that will affect a much larger and higher value production batch, so it’s not absolutely clear if this development trend really will materialize. Beside the issues related to technology development, all other traditional advantages related to mass production will contribute to further cost reductions, i.e. increased productivity due to more focus on quality and maintenance, larger batch sizes, improved purchase power for consumables and services, automation, lean production flow etc.

2.2.3 Wafer

Status

Today all solar wafers are cut from the ingots by use of multi-wire saws that can cut four ingots of up to 60 cm in length into ca. 6000 wafers in one operation. The saw, auxiliary equipment, wire and slurry can all be purchased commercially from a couple of equipment vendors, that all have many years of experience in this field. Due to the standardised type of service and operation, it's quite difficult to differentiate between wafer suppliers – the main difference being in the yield (breakage rate) and otherwise running cost of operation. For some years the main focus has been on improved feedstock utilisation that can be achieved through a reduction of the wafer thickness. Today the standard thickness of a PV wafer is around 160-180 µm and is still expected to decrease over the coming years, although not as fast as previously and not below 100 µm. About 6-8 grams of silicon ingot material in form of wafer (50%) and kerf-loss (50%) are currently used per unit power (W) of the solar cell.

Technology development is underway by changing the traditional slurry (glycol with SiC particles) based sawing method to the use of diamond-covered wires cooled with plain water. The advantage should be less sub-surface damage, higher yield, less kerf loss and fewer issues with upgrading of the used slurry. Another focus area is automatic de-gluing, cleaning, inspection and packaging of the wafers. As these auxiliary operations today still are done with a high content of manual labour and high breakage rates, a more automated and optimised production layout would represent a significant cost reduction potential.

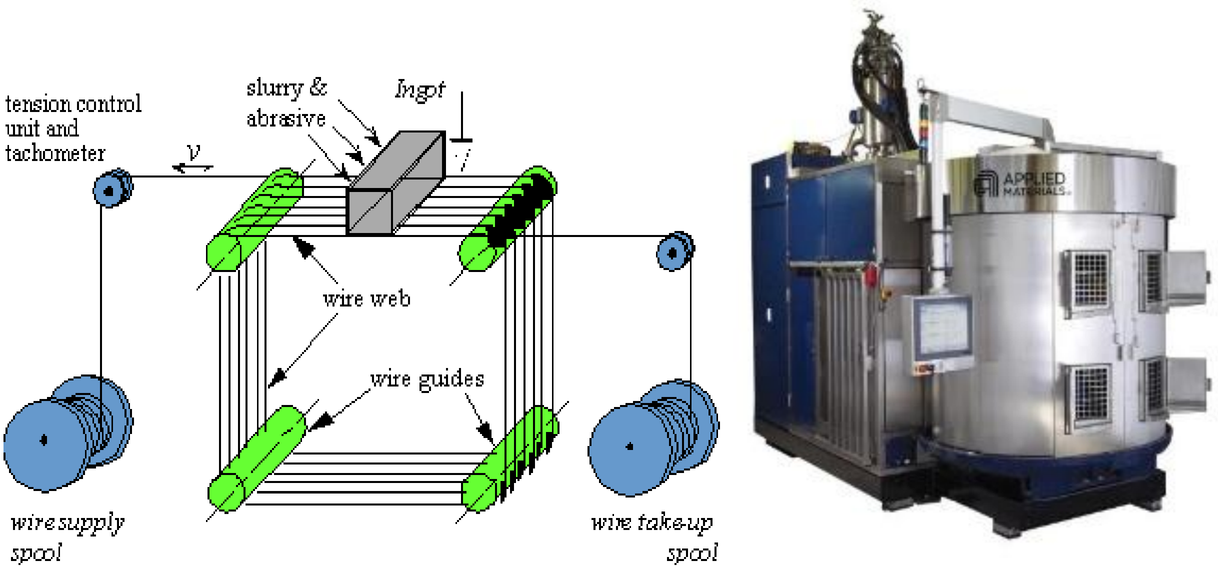


Figure 9: Principle of wiresaw operation (left) and wiresaw equipment (right).

Marked trends

Over the last years the wafering operation has traditionally been an area with little technological differentiation among the professional wafering companies and therefore a decision to enter into this business segment has primarily been related to the ambition of the supplier to become fully (or partly) integrated within the value chain. As we in the future probably will observe that the access to finance will be more constraint, it might be more common to outsource this operation to specialised companies where a focussed operation can ensure higher yields and overall lower processing costs than with an in-house operation with less direct management focus.

Cost reduction potential

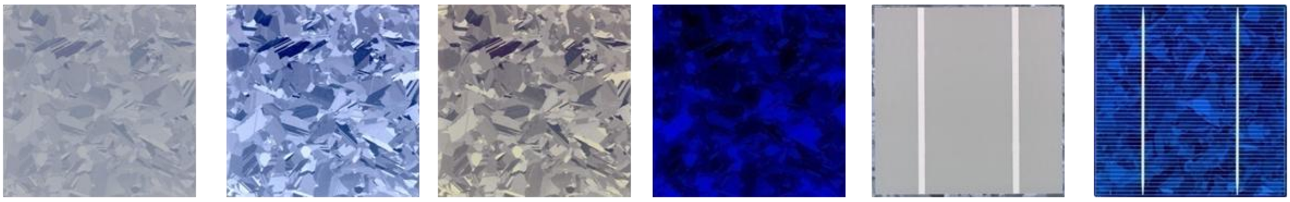
Although the basic wafering operation can be considered quite mature, there're still significant cost reductions potential related to change of cutting agent (from silicon carbide to diamond), and optimisation of the auxiliary operation like slurry upgrading, de-gluing, cleaning, automated inspection and packing. Beside these technical developments also general cost reduction due to increased scale of operation can be expected.

2.2.4 Cell

Status

Most solar cells are today manufactured with one and the same screen-printing technology. This standard process is implemented with only small variations (like in-line vs. horizontal diffusion furnaces) world-wide for both mono- and multicrystalline cells and generates very similar output all over the world. Equipment is supplied by experienced turn-key equipment and process suppliers that offers yield and output guarantees for their (standard process) lines.

As focus for most manufactures over the last years have been on volume growth - on behalf of product development – there're many fully developed technology improvements that have not yet been implemented in the production lines. This goes for innovative emitter structures (i.e. locally diffused, emitter wrap through), metallisation (metallisation wrap through, metallisation paste type), contact layout (back-side contacting) etc. Several of these innovative designs and ideas have been presented at conferences over the last years but still few of them have been introduced into mass-production. As production capacity now seem to be close to outgrow marked demand we'll probably see the innovative ideas implemented in mass-production in the coming years, as some cell manufactures probably will focus on differentiation as one way to stay in business – beside the unavoidable constant focus on cost reduction and quality/efficiency improvements.



Bare multi-crystalline wafer

Saw damage removal & Texturisation

Junction forming by P-diffusion

Anti-reflective coating

Back contact

Front contact

Figure 10: Standard Screen Printing Solar Cell Manufacturing Process.

Marked trends

As for all other steps in the value chain, the focus on cost in cell manufacturing will be intense over the coming years as also the competition between major Chinese, Taiwanese and European manufacture brands will increase. Higher efficiency cells have been in demand for years and various process upgrades have been suggested and developed to support this trend but not until recently have these alternative cell structures reached the market as we now see with the Pluto cell introduced by Suntech, Maple cell from JA Solar, the cell with selective emitter from China Sunergy or backside contacted concepts from Photovoltech and Solland solar.

Cost reduction potential

For the cell production it's expected that there will still be significant room for cost reduction related to both the new materials (i.e. new metallisation pastes), improved purchase power, introduction of professional manufacturing systems with more focus on process stability, preventive maintenance, statistical process control etc. On the other hand, the improvement of processes needed for increasing the cell efficiency will not be cost neutral, and therefore the manufacturing cost pr. cell-watt might not show as significant reductions.

2.2.5 Module

Status

The standard method to manufacture PV modules is more or less the same among all manufacture. Solar cells are equipped with tabs, connected into strings by automatic soldering robots and are laminated to a 3.2 mm thick tempered glass pane by used of an encapsulant material like EVA or PVB and are protected on the backside with a water tight foil like Tedlar. The strings are collected in a junction box with 1-3 by-pass diodes in a box that are glued to the back of the module and finally the module edges are protected with an aluminium frame to ensure the necessary stiffness and protection of the module.

The area of module assembly has not seen much innovation during the last years. This is not only due to same focus on volume growth that we have mentioned for all other steps of the value chain, but also due to a wish to introduce as few product changes at the module level as possible. This conservative approach is due to the fact the module need an expensive and time consuming (re-) certification every time there's a change in the materials used or in the manufacturing method. In addition it's on the module product level that the most important production guarantees are issued, and these include a 25 year performances warranty that is a an important market standard. When dealing with quite expensive products that are sold in large quantities to end-users that really do care about these guarantees and are able to exercise their claims also in 10-20 years, it's quite risky for the module manufacture to introduce new materials, cost reduction initiatives or changed production methods, unless they have carefully analysed the long term module performance following this change (and this is both difficult and expensive).

The point is, that many innovative ideas are still pending to be introduced in mass production and a significant potential for improvements and cost reductions are therefore possible. Among the possibilities for cost reduction could be mentioned, manufacturing of front glass with a dedicated focus for PV, introduction of thinner front glass or glass-glass modules, improvement in anti-reflective and self-cleaning properties for the front glass, use of cheaper back-sheet and encapsulant materials and encapsulant material like silicon with less optical absorption, use of stack laminators etc.

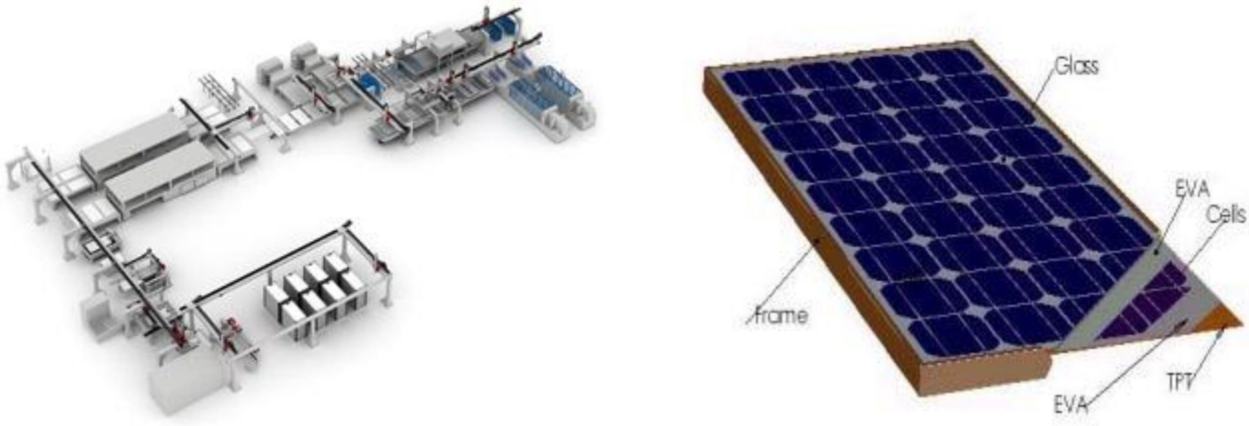


Figure 11: Integrated module manufacturing line (left) and typical construction of a PV module (right).

Marked trends

Today most PV modules are manufactured in China and transported to Europe by ship. As the module prices are expected to fall over time, the relative importance of transportation cost will increase, and module manufacturing close to the end customers will be more important. Beside product improvements by the above mentioned means, also focus on bankability will continue to be of importance, i.e. the request from the end-user (investor) that the modules installed in large solar power plants are manufactured by financial solid and well-reputed companies, that are in a position to stand behind their product guarantees, in case problems with the products should emerge.

Cost reduction potential

As mentioned many innovative technology solutions and manufacturing improvements has been developed and will probably be implemented over the next years. It’s therefore foreseen, that significant cost reduction can be realised over the next years. The module manufacturing is still considered in the early phase of its product lifecycle.

2.2 Thin-film modules

Status

Currently there are three different versions (material) of thin film solar cells that can be considered commercially mature. The most important player is First Solar that has been very successful in establishing a very large and low cost production capacity for CdTe based PV modules. These modules have a very decent efficiency of 11 % and also very attractive low manufacturing cost – now around 0.77 USD pr W_p.

Modules made of amorphous silicon (a-Si) with either a single, two (Tandem Junction) or even three different junctions (triple junction) on top of each other, are also manufactured at low cost and high volumes. The efficiency of such modules can reach up to 10 %.

Finally modules manufactures that are working with CIGS material are able to make modules with almost same efficiency (13.5%) as crystalline modules with a cost structure that also are almost as low as the average crystalline silicon module manufacture.

Thin film modules of CdTe

The materials Cadmium and Tellurium mixed in a stoichiometric ratio exhibits very good characteristics as a thin film photovoltaic material. It is a direct band gap material with a bandgap of 1.45 eV which is quite perfect for solar cell applications. It also has a high absorption coefficient that ensures that most of the light will be absorbed with a layer thickness of only few micro meter of material.

CdTe solar cells as manufactured by First Solar are made by vacuum deposition sublimation/condensation where a thin film of CdTe is deposited at high temperatures (~500 °C) where it grows a naturally p-type layer. A transparent layer of CdS (n-type) is then added to achieve a p-n heterojunction.

CdTe solar cells can reach efficiencies in the order 9-11 % and in the laboratory up to 16.5%. In order reach the high efficiency level it's necessary to "activated" the material in an atmosphere containing Cl, typically $CdCl_2$.

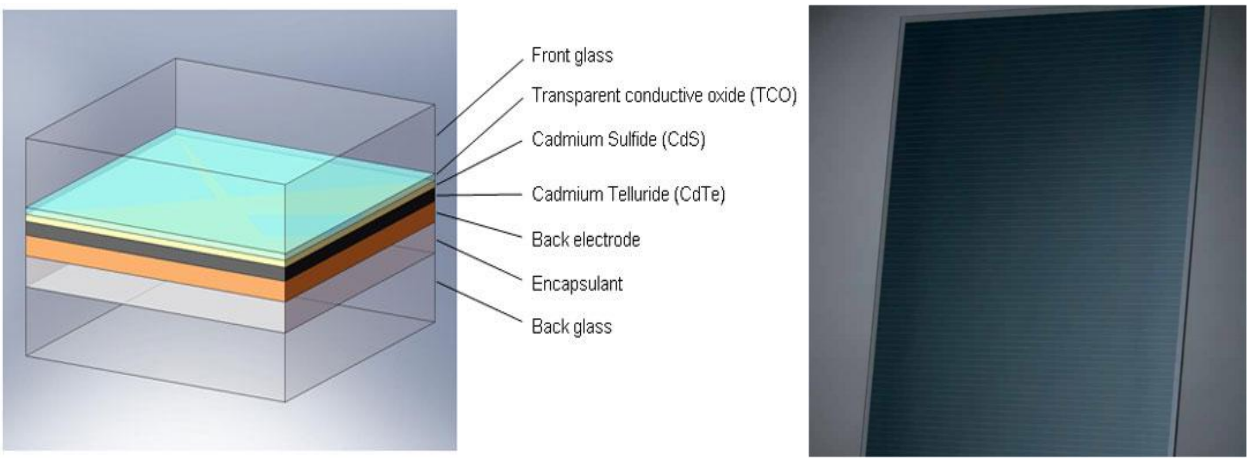


Figure 12: CdTe module structure (left) and finished module from Calyxo (right).

Silicon thin film modules

The basic amorphous silicon (a-Si) thin film solar cell is made with a p-i-n structure, where a thin (~80 nm) intrinsic separator layer is sandwiched between a 0.3 µm thick p-layer absorber layer and an n-type junction layer. This structure is capable of converting only around 6 - 8 % of the energy content in the solar spectrum into electrical power, and the shortcomings relate to both the unstable performance (LID) and also the ability to utilise the energy in the long wavelength part of the solar spectrum.

To overcome these shortcomings a double structure consisting of both an a-Si (top) and a microcrystalline (µc-Si) (bottom) solar cell has been developed. In this Tandem Junction (TJ) device the bottom cell is designed to utilise that fraction of the solar energy that has passed through the top cell as illustrated in **Error! Reference source not found.**. The thickness of the a-Si layer will typically be around 0.3 µm whereas the bottom µc-Si layer in a tandem junction will be around 1.8 µm. All layers are deposition by Plasma Enhanced Chemical Vapour Deposition (PECVD) on a glass superstrate.

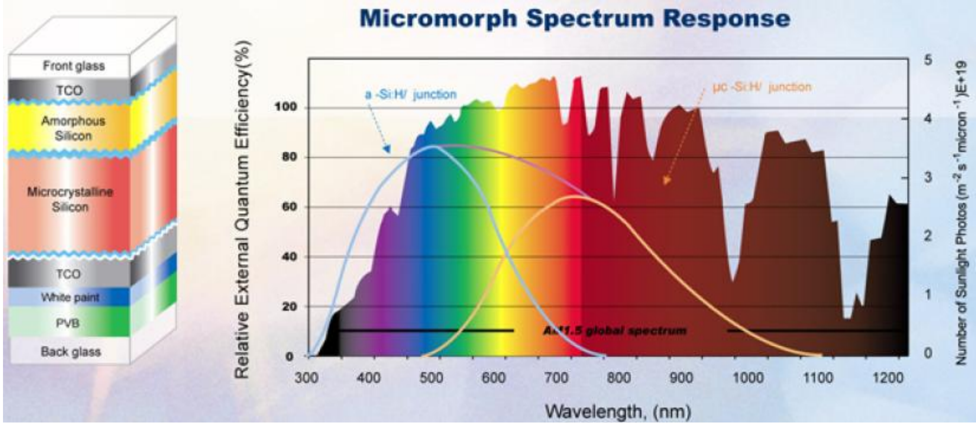


Figure 13: Cell structure and corresponding spectrum response of a tandem junction silicon thin film solar cell (Auria Solar).

The cost structure of these modules are not as low as for CdTe and for several manufactures the equipment investment have also proven much too high to ensure satisfactory operational conditions. The otherwise very professional equipment manufacture Applied Materials have sold several turn-key factories at high prices in year 2008, and several of these customers are now in financial trouble (or even bankrupt) due to too high operating and depreciation costs. It seems like manufactures that are using production equipment from Oerlikon – that basically will be doing the same type of PV modules just smaller – are in a better shape, although their cost structure still is much higher than their thin film competitor First Solar.

CIGS solar cells

Another class of thin film solar cells are made of elements from group I, III and VI in the table of elements, most often Cobber, Indium, Gallium and Selenium like in the compound $CuInSe_2$. These solar cells have a high optical absorption and good optical and electrical characteristics. As this type of solar cells are not often used in large solar installations, and also currently does not show promises to become market leader in cost-efficiency, we do not consider this type of modules further.

Marked trends

First Solar are doing well as a clear cost leader. Direct manufacturing cost is now below 0.77 USD/W_p which is quite low. The main market for First Solar is for utility scale installations, a market that is expected to continue to grow. First Solar is expected to continue to dominate the lowest cost and lowest efficiency utility scale market with a very cost competitive product.

For the other thin film products is might take further development with necessary step changes in either efficiency or cost reduction before they become competitive for use in large scale installations. Such a development is absolutely possible, as there are still a lot of R&D activities assigned to this area. As an example Oerlikon has recently claimed to be able deliver manufacturing equipment that can produce silicon thin film solar cells at a cost close to 0.5 USD pr W_p.

Cost reduction potential

As for the crystalline counterpart, it's absolutely reasonable to expect continued development and improvements in this area which will result in improved performance pr. cost ratios. Such improvements can relate to the transparent conduction oxide layer, which sometimes are deposited by used of relatively expensive sputtering methods. Also the requirements for vacuum deposition increases cost and manufacturing complexity and could potentially be changed to more cost efficient methods. In general increased volume will drive down cost for consumables like sputtering target, junction boxes, encapsulant and even the front and back glass.

None of these technologies have reached maturity in their product lifecycle and the future cost reduction path will most likely continue to follow the standard experience curve for PV modules also many years ahead.

2.3 Mounting structures

Status

The mounting structures for solar panels are typically made of galvanised steel or aluminium. The requirements are low material consumption, sufficient strength and fast/easy installation and module mounting. Most of the current suppliers of structures are companies already in the steel/construction business that have just included an extra business division for this market segment (i.e. Sadef and Alcoa). So far the level of innovation and differentiation has been low which also leave room for further improvements.

Tracker systems have been developed in many versions by a lot of different companies with varying success. Since the Spanish market almost came to a hold in 2009, the market growth has been slow with few possibilities for the suppliers to expand and develop their products further. Trackers are not inherently complicated to design and construct, but it actually takes a quite some engineering and experience to make a product that fulfil the requirements for many years stable operation with a minimum of maintenance and at the same time consume a minimum of materials and manufacturing effort.

Figure 14: Ground mounting system ready for module installation.

Marked trends

Standard mounting structures come in various versions optimised for different fixation methods (foundation as dependent on soil class) and module types (i.e. framed and unframed modules). Low cost structures also require reduced transportation which does favour manufacturing shops close to the installation site.

As more high efficiency modules become available, the relative advantage of using tracker solutions will increase again. Also the fact that large solar power plants often are restricted in area and require the maximum possible leverage of the fixed cost expenditures (everything from project development, grid connection, to on-site guard, maintenance and legalisation and financing costs), it's still expected that tracker solutions will be of importance for utility scale solar power plants in the future.

Also the possibility to pre-mount and pre-connect (even frameless) modules on the tracker pane in an indoor manufacturing environment will improve quality and reliability and will reduce construction challenges related to on-site labour experience/professionalism and non-predictable weather conditions during construction (modules cannot be connected when there's heavy rain). Several companies like SunPower and Exosun have developed lean manufacturing models for a fast and efficient solar park construction for their tracker solutions. Other companies might develop and focus on similar excellence in construction, once the market and the companies become more mature.

Cost reduction potential

Although the cost of mounting structures and trackers show a relatively high dependence on the actual market price for construction materials like steel, aluminium and concrete – material prices that are dominated by the overall business cycles in the construction business – there's still room for cost reduction as the market players recognise the PV market as a dedicated high growth market that can accommodate specially designed products, manufacturing methods and tools.

2.4 Inverters

Status

The inverter converts the electrical energy produced by the PV modules from dc- to ac-current that further can be feed into the grid. Except for minor variation in local requirements for current quality (i.e. power loss factor) and grid code regulation conformance, the most important parameter when rating inverters are the efficiency by which is can perform this conversion. Additional features will be the input voltage range and the power range at which the high conversion efficiency can be achieved. The inverter also run a constant optimisation routine, a so-called maximum power point tracking (MPPT), in order to ensure that the inverter are always operating at the point on the power curve where the maximum amount of power can be extracted.

For large power plants one can use either a few large central inverters (up to 1 MW per unit) or many smaller string inverters (typical 5-20 kW in size). Whereas the larger inverters might perform slightly better with respect to conversion efficiency and price, one also have to consider potential shadowing from these units, and the risk of downtime production loss as the larger units seldom can be as fast repaired in case of problems as the small units, which easily can be exchanged on-site in case malfunction.

As indicated also parameters that describes the availability and reliability of the inverter becomes important when used in power plants. These properties can be described by the Mean Time Between Failures (MTBF) as well as the operational lifetime of the inverter and also the product warranty period and the financial strength of the inverter manufacture will be issues of importance when qualified for power plant use.

Figure 15: String inverter from Danfoss Solar Inverters.

Marked trends

Like all other PV related business areas, the PV inverter business is very dynamic. For some year the marked has been dominated by small but dedicated companies that have focussed on developing exactly this type of electric products (i.e. SMA). This background was probably important to ensure that dedicated PV inverters with all necessary features like multiple MPPT, current quality optimisation, external communication and performance data storage were developed and brought to the marked. As the focus so far has been mostly on product development and innovation, less focus has been on design for low cost manufacturing. During the last years also the very large manufactures of electronic components like Siemens, ABB, Delta – and Danfoss, have started to focus on this market.

Cost reduction potential

As mentioned the focus in the early phase of the product lifecycle have been mostly on product development and less on cost optimisation. A recent survey in Photon International found, that the mere cost of components in a German manufactured inverter was significantly higher than one made by a Chinese competitor – with very little performance related justification. This is a clear signal that indicates a significant cost reduction potential that are expected to follow similar steep learning curves as for other types of electronic components.

2.5 BOS components

Status

Connector boxes, switches, surge/lightning protectors and cables

The electrical design of a large PV installation has to conform to local grid regulations with respect to protection gear i.e. type and location of switches, lightning protection, transformer construction etc. The wiring layout with combiner boxes and cables has to be designed specifically for each power plant, although also standard solutions now can be found. The level of innovation in this area is low and most components are general purpose items.

Security surveillance system

As a PV installation consist of high value PV modules that can be sold as a commodity on the open market, one has to consider the need and appropriate means to protect the installation against theft. At exposed sites in Italy it's necessary to install both high fences, penetration/movement sensors and day/night cameras for surveillance of the park - in addition to an on-site guard. In addition to such security hardware a high speed communication connection is required in case a remotely located security company shall have access to such camera information.

In a Danish context it might be sufficient to secure the modules on the installation by use of special mounting screws, security wires that activate an alarm when disconnected, RFID tags and other traditional protection systems.

Marked trends

For some of the items, dedicated PV products start to emerge. This is the case for dc solar cables and connectors that basically represent a minor variation of standard components.

Cost reduction potential

As most of the BOS materials used are general purpose components, it can be difficult to reduce the manufacturing cost with specific reference to the PV application. This is the case for electrical hardware like cables and combiners. Some cost reduction due to mass production and larger purchase power however can be expected as the size of the PV power plants increase and the EPC contractors becomes larger and more professional.

2.6 Construction/EPC

Status

The construction of PV power plants is in many ways a simple and straightforward operation in line with other building and infrastructure construction tasks. Access roads to the construction site must be ensured, obstacles must be removed and the earth has to be levelled according to the landscape curvatures. A fence is raised to protect the high valued components. The exact positions of the structures are located, foundations or pole-holes are made (if required) and the mounting structures are raised. Underground ducts that shall carry the cables from the distributed combiner boxes till the inverter and transformer centre(s) are prepared. Modules are mounted on the structures and all electrical connections including security and surveillance systems are finalised.

As in all construction projects several different kind of skills are required and a professional organisation of the work to ensure a fast and efficient project execution is very important.

Several companies like Phoenix Solar, Conergy, SunPower, Iberdrola and Colexon have specialised business divisions to perform this kind of operations. Again such an operation will have to conform to local rules and regulations in all and every aspect, which include as different issues as establishing a security organisation, waste handling, getting permits to work and operate, specific security measures for handling of high voltage, security distances from high voltage pylons to other installations etc.

Marked trends

As the market gets more mature, the interest among larger and more experienced and solid epc companies to enter this business segment is expected to increase. As an illustration the US engineering company Flour have entered this scene.

Another trend is the development of standard solutions that can more or less be used as copy-paste solutions. SunPower has developed a concept they call Oasis for exactly this purpose, and also the tracker and epc company Exosun are focusing on the excellence in execution.

Cost reduction potential

As described, most projects are still designed and engineered with a limited number of “engineering building blocks” due to specific variations with respect to i.e. soil condition, choice of components and local legal requirements. For this reason the EPC contractors mostly have to do case-by-case engineering which is more expensive and makes it harder to optimise for standard solutions based on low cost components. For this reason, a significant cost reduction potential can be identified also in this part of the value chain.

2.7 Project Development

Status

Project development is the activity related to establishment of the legal and economic framework behind the construction of the solar park. This activity is typically organised by private investors or utilities on behalf of private (institutional) investors or by utilities with public service obligations. Technology-wise this process is supported by various simulation tools for solar resource prediction and preliminary production estimates. The legal framework for the project in terms of land-lease agreements, PV project building permit, grid connection agreement and power sales contract must be prepared and a detailed engineering of the optimum selection, connection and installation of key components must be prepared.

Market trends

PV projects that are fully developed and ready to build, is regarded an asset that can be traded on an open market – typically through certain brokers. The price for a fully developed project depends on the expected income as given by the irradiation and power price and on the expected cost to construct and connect the PV power plant. As the development costs are the same independent of the size of the project, and as the sales price for a developed project is given pr. installed power

(€/W_p), all parties often see an advantage in maximising the installed power pr. project, as this will increase the profit relative to the invested development cost.

It's quite simple to determine the market value of a PV project. The cash flow of the project that covers both the price of the finished, connected and legalised project, the net income over the remaining project lifetime and the scrap value (expense) of the installation at the end of the project lifetime. Then the market price can be found as the price that satisfies the investor expectations for economical return (IRR) of their investment. Except for small variations in IRR expectations for different countries that reflect the overall trust and confidence in the overall business conditions, exchange rate, alternative investments etc, the investor equity IRR requirements typically lies in the 10-15% range of which the country specific market premiums in 2009 lay around 4% for Germany, 4½% for Spain and 5½% for Italy reflecting both the expected uncertainty of the long term survival of the FIT law as well as the difference between support systems based on consumer paid surcharge (FIT) and green certificates (Italy).

Cost reduction potential

As an illustration price levels for projects in Italy lay around 0.2 – 0.5 €/W_p for a fully licensed and ready-to-build project ult. 2010. The exact price will depend on the expected net income and expected turn-key construction price. Prices for projects in Germany are significantly lower than this level, which is indicative for a much more tough market with a smaller profit pool to divide among project developers, component manufactures, installers and final investors.

3. Institutional aspects of LPV in a Danish context

3.1 LPV application for construction and grid connection

The legal framework of relevance when constructing PV power plants in Denmark is related to the application procedure, the ownership structure, grid connection opportunities and power sales options:

- The application procedure covers all issues related to the use of land (spatial planning) and is handled by the local municipality. The main topic will be conformance of the proposed land-use with the intentions stated in the municipality plan which as a general rule never anticipated nor even mentioned such a use.
- The ownership of the PV power plant has to conform to the purpose of the PV power plant. Ownership could be organised as a personal ownership, within a private company or in the form of an A/S or KS. The choice of company structure will depend on the intentions of the investor and the opportunity of the investor to achieve the best possible return on investment.
- Access to the public electricity grid is often essential, as the power production from a PV power plant normally will exceed the self-consumption of most owners. Except for projects that are deliberately projected for 100% self-consumption, the electricity produced has to be sold at the open market. The grid-access is handled by the local utility as well as the TSO EnergiNet.dk who must provide transport capacity until delivery at the end-user.
- Finally the power sales conditions are of importance, as the PV electricity sales need economical subsidy in order to attract professional investors. According to the current

Danish VE law, the PV generated power can achieve a guaranteed price of DKK 0.6/kWh for 10 years of operation, but as this price cannot even cover the direct production costs at present, this level of subsidy will not be sufficient to encourage IPPs to invest in Danish PV installations.

An application for at PV installation on open land shall be sent to the local municipality, where the Technical and Environmental department will handle the case. The application shall describe the intended use off the particular area but otherwise no special application forms are required. The overall application process is illustrated in **Error! Reference source not found.**.

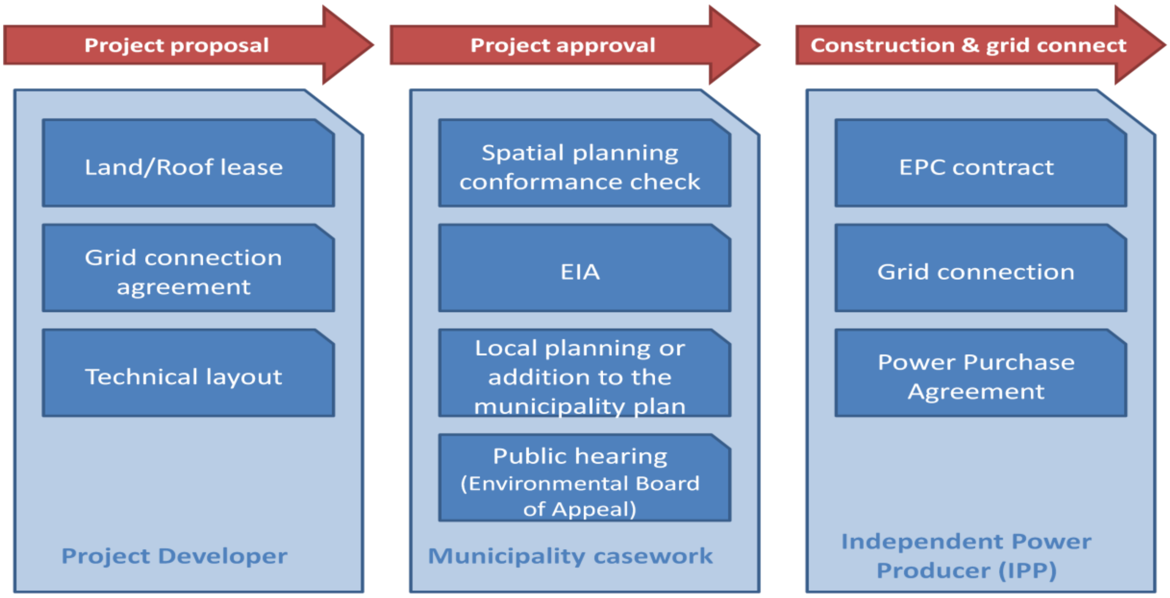


Figure 16: Administrative flowchart for the realization of a PV power plant in Denmark.

3.1.1 Municipality plan

The first action by the municipality official will be to check with the municipality plan what the planned intended use of the particular area in question is. Based on guidelines from the Nature Agency (Naturstyrelsen), all municipalities have prepared plans that describe how the various parts of the municipality shall be utilised – presently and in the future. These guidelines define a number of specified "themes" that must be included in the planning and cover issues like areas assigned for industry, residential, landfill, windmills etc. The current guidelines does not mention a potential application for PV power plans, so no areas have so far been selected and reserved for this purpose.

Applications to establish PV power plants in areas assigned for industrial use or on industrial roofs does not require any permits from the municipality (unless other specific issues and requests has been mentioned in the municipality plan).

Applications to establish PV power plants in rural areas will require a permit from both the municipality and the Regional Board of Agriculture (Jordbrugskommissionen). For minor projects (size up to ca. ½ ha) and for projects that already conforms to the scope of existing plans, the municipality can issue a direct approval in form of a local planning (landzone tilladelse) following a fast casework. For larger projects (area larger than ca. ½ ha) and for projects that are clearly outside the scope of use in the current municipality plan, the case must be handled according to standard procedures in the commune dealing with an addition to the municipality plan and local planning.

3.1.2 Addition to the municipality plan & local planning

An application for construction of a large PV power plant in the countryside, i.e. on property that's not already assigned for industrial purposes, will be assessed with respect to the following aspects in the municipality:

- EIA reporting; it has to be considered if a full EIA (Environmental Impact Assessment) (VVM, Vurdering af Virkninger på Miljøet) report is required. So far it's not considered necessary to prepare a full EIA if the PV power plant otherwise does not seem to imply significant environmental impact. PV power plants are currently not on the list of installations that by default requires an EIA.
- As alternative to the full EIA, the municipality can perform an internal "screening EIA", to cover the following issues:
    - Assurance that the installation will be constructed and grid-connected according to all relevant legal requirements, i.e. according to current laws of electricity, safety, power plant operation, grid-connection etc.
    - Specific requirements to environmental conditions (visual impact/aesthetics, allowed noise levels, access of small animals to the site etc.)
    - Assurance that the project is not in conflict with specific local nature-protection issues
- Grid connection – access route to connection point assigned by the local utility.
- Specific requirements to the restructuring of the land after decommissioning of the plant.

Following the case handling by the municipality, an approval can be issued in form of an addendum to the municipality plan and local plan. The addendum to the municipality plan describes the updated conditions for planning in the specific area. The local plan is more specific and detailed, and covers the exact plans for the PV power plant in question, with clarification of specific conditions that apply to the project (i.e. a request to stay below a certain max. height, a certain max. noise level, a certain level of transport to/from the site, visual cover in form of an array of trees to be planted etc.). Proposals for the addendum to the municipality plan and the local plan will be presented in a public hearing for at least 8 weeks where anyone with an interest in the plan can comment on and propose changes to the plan. After the final approval has been granted by the municipal council, the public have the possibility to claim the approval to be invalid in a claim towards the Environmental Board of Appeal (Natur og Miljøklagenævnet).

For LPV projects that shall be established on areas with agricultural obligations, a dispensation has to be obtained from the Regional Board of Agriculture. There are two ways to obtain this dispensation. Either the PV project owner can purchase the land and obtain a permanent dispensation from the agricultural obligations. Alternatively the land can be leased and a temporary permit can be obtained. This approach can be used for lease duration up to 25 years as this is considered non-permanent. In both cases the Regional Board of Agriculture will grant permission for this non-agricultural use in accordance with the recommendations from the municipality. For lease periods longer than 25 years, it has to be considered if this project might obtain unlimited right of use (hævd), which will not be accepted. It's not considered possible, that an otherwise approved project could be halted or rejected by this authority.

3.1.3 Other issues

The Nature Agency together with the Local Government Denmark (LGDK or Kommunernes Landsforening, KL) jointly develops a set of guidelines for the preparation of Municipality plans. As construction of LPV power plants so far never has been considered relevant, these guidelines do not mention this possibility. This implies that whenever the municipality has to consider a specific application, no references to these guidelines or any other official planning related policy can be made. In case these official bodies would start to include PV power plants as a theme in the planning process, it would be very supportive for the future case handling in the municipalities.

Although no ground-mounted LPV power plants have been erected in Denmark so far, there are several examples of large solar heating installations that have been build in connection with district heating plants. As the basic appearance in the landscape of both power plant types are quite similar, one should expect that the case handling of the PV power plants can be handled quite smoothly, with reference to these similar cases.

As an example of the area potentially available for the construction of ground-mounted LPV power plants, the "rural-like" municipality Næstved has assessed that almost 50 % of the area of the municipality are potentially accessible for PV power plants as illustrated in Figure 17.

Figure 17: Area allocation map of Næstved municipality. All olive-green coloured areas are in principle useable for LPV project development.

3.2 Grid connection issues

The rules for connecting electricity producers to the Danish grid are regulated by:

- The Danish Safety Technology Authority (Sikkerhedstyrelsen)

- Energinet.dk (the Transmission System Operator (TSO))
- Local grid system operators (netselskaber)

The Danish Safety Technology Authority sets the standards in safety technology in Denmark including those of electricity. Based on the "Law on Electricity Power" (Stærkstrømsloven) the Danish Safety Technology Authority will publish (inter alia) two relevant guidelines:

- Stærkstrømsbekendtgørelsen
- Lavspændingsdirektivet

Both publications (in Danish) describe and detail safety issues related to electricity and to connection to the grid, and all installations in Denmark including LPV plants shall follow these instructions. For further details please consult the publications downloadable at www.sik.dk.

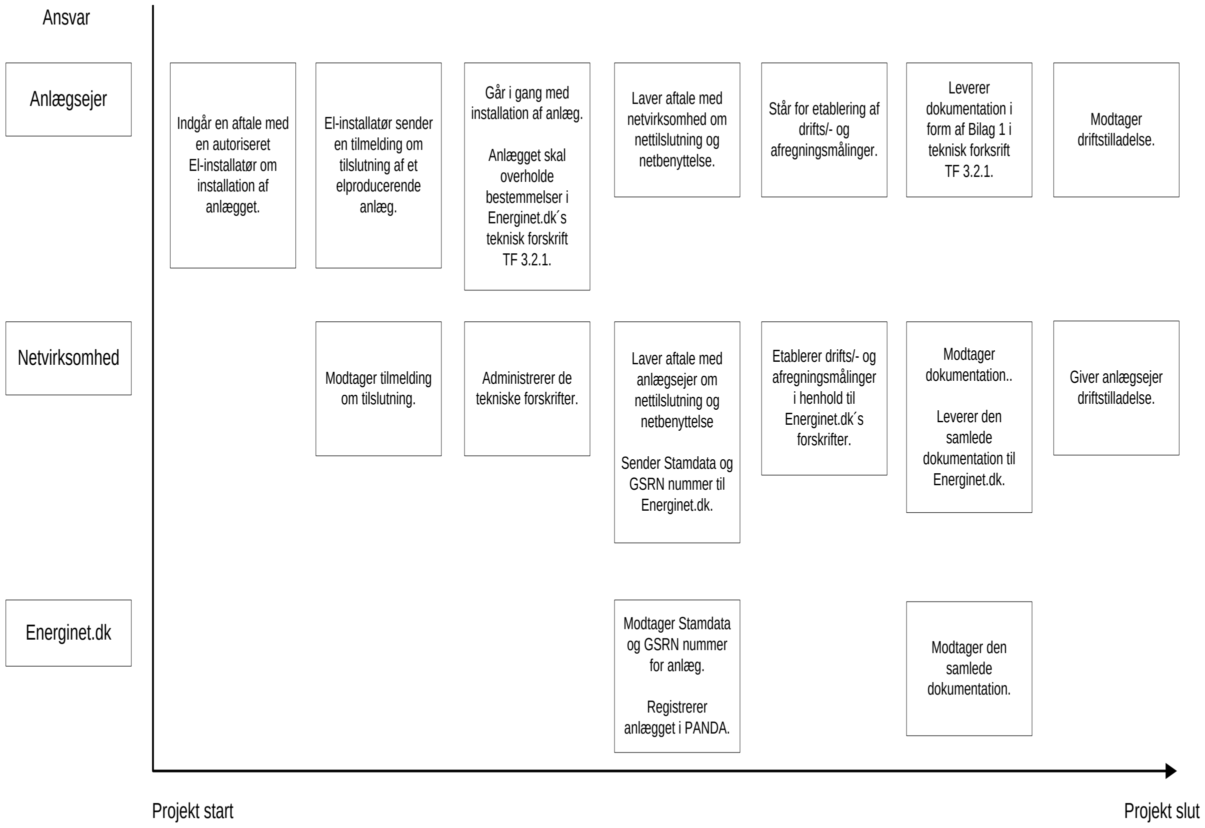
The Danish transmission system operator (TSO) Energinet.dk has the overall responsibility for the Danish electric transmission system and publish on its homepage (www.energinet.dk) numerous regulations and guidelines for the connection of "own generators" (egen producenter) to the grid. Except for the so called "net metering scheme" covering "own generators" including PV plants up to 6 kW, there is not yet any specific regulations for PV or LPV plants. However, the regulation regarding wind energy installations can to a large extent be expected as covering also LPV plants. It is recommended to consult the various regulations on the website of Energinet.dk. Here only three process diagrams will be included (all in Danish) that covers:

- Own generators up to 11 kW
- Wind turbines connected to the grid at below 100 kV level
- Wind turbines connected to the grid at above 100 kV level

As so far no LPV plants have been realised in Denmark it is recommended well in advance to contact both the local grid operator and the TSO for guidance and advice.

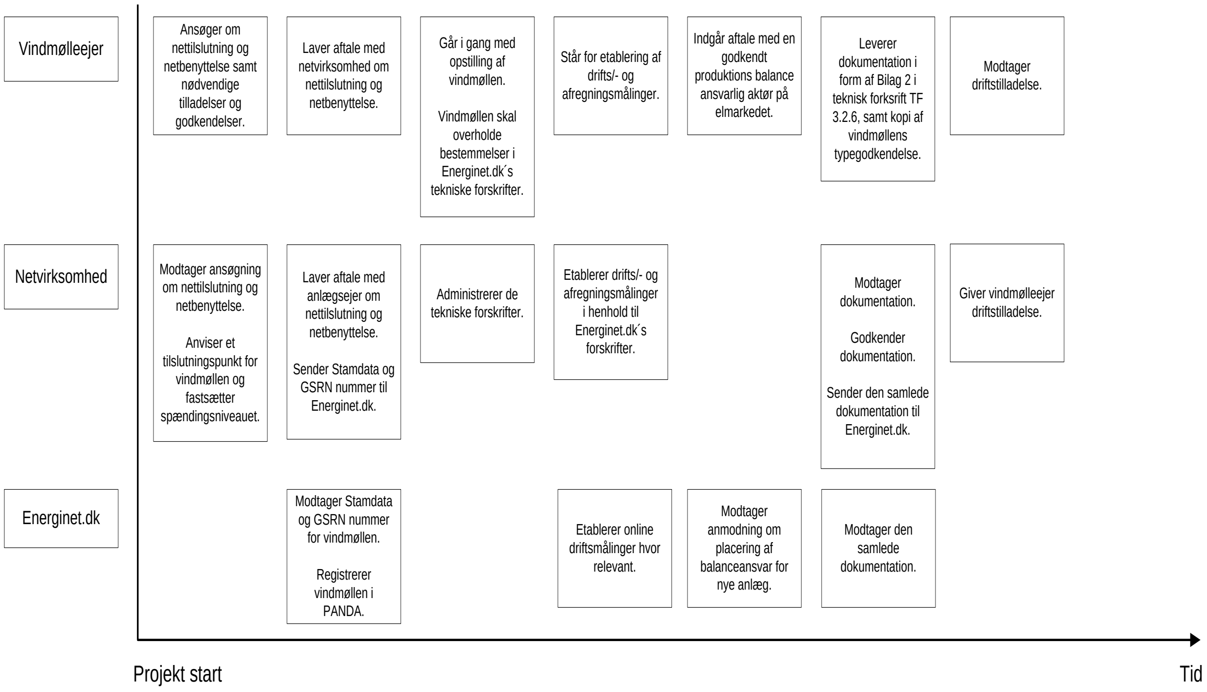
Grid codes in Europe are undergoing change in order to accommodate a higher penetration of inverter-dominated de-central generators, e.g. wind turbines and PV plants. Instead of just regarding the grid system as an infinite power sink, the de-central generators will be required actively to contribute to the balance and stability of the grid system. This entails dispatchable control - by remote control or local set points - of both active power and reactive power. Furthermore the grid tied inverters are required to briefly assist the grid in fault situations – fault ride through capability.

Although not a requirement yet in Denmark, the same grid codes are expected to be valid for Denmark as well in the near future. Future LPV plants will thus have to comply with these new grid codes, outlined in more technical detail in Annex 3.



Ansvar							
Anlægsejer	Indgår en aftale med en autoriseret El-installatør om installation af anlægget.	El-installatør sender en tilmelding om tilslutning af et elproducerende anlæg.	Går i gang med installation af anlæg. Anlægget skal overholde bestemmelser i Energinet.dk´s teknisk forskrift TF 3.2.1.	Laver aftale med netvirksomhed om nettilslutning og netbenyttelse.	Står for etablering af drifts/- og afregningsmålinger.	Leverer dokumentation i form af Bilag 1 i teknisk forksrift TF 3.2.1.	Modtager driftstilladelse.
Netvirksomhed		Modtager tilmelding om tilslutning.	Administrerer de tekniske forskrifter.	Laver aftale med anlægsejer om nettilslutning og netbenyttelse Sender Stamdata og GSRN nummer til Energinet.dk.	Etablerer drifts/- og afregningsmålinger i henhold til Energinet.dk´s forskrifter.	Modtager dokumentation.. Leverer den samlede dokumentation til Energinet.dk.	Giver anlægsejer driftstilladelse.
Energinet.dk				Modtager Stamdata og GSRN nummer for anlæg. Registrerer anlægget i PANDA.		Modtager den samlede dokumentation.	

Figure 18: Administrative process diagram for stand-alone power production installations at 11 kW and smaller.



Vindmølleejer	Ansøger om nettilslutning og netbenyttelse samt nødvendige tilladelser og godkendelser.	Laver aftale med netvirksomhed om nettilslutning og netbenyttelse.	Går i gang med opstilling af vindmøllen. Vindmøllen skal overholde bestemmelser i Energinet.dk´s tekniske forskrifter.	Står for etablering af drifts/- og afregningsmålinger.	Indgår aftale med en godkendt produktions balance ansvarlig aktør på elmarkedet.	Leverer dokumentation i form af Bilag 2 i teknisk forskrift TF 3.2.6, samt kopi af vindmøllens typegodkendelse.	Modtager driftstilladelse.
Netvirksomhed	Modtager ansøgning om nettilslutning og netbenyttelse. Anviser et tilslutningspunkt for vindmøllen og fastsætter spændingsniveauet.	Laver aftale med anlægsejer om nettilslutning og netbenyttelse. Sender Stamdata og GSRN nummer til Energinet.dk.	Administrerer de tekniske forskrifter.	Etablerer drifts/- og afregningsmålinger i henhold til Energinet.dk´s forskrifter.		Modtager dokumentation. Godkender dokumentation. Sender den samlede dokumentation til Energinet.dk.	Giver vindmølleejer driftstilladelse.
Energinet.dk		Modtager Stamdata og GSRN nummer for vindmøllen. Registrerer vindmøllen i PANDA.		Etablerer online driftsmålinger hvor relevant.	Modtager anmodning om placering af balanceansvar for nye anlæg.	Modtager den samlede dokumentation.	

Figure 19: Administrative process diagram for windmills connected to the grid at voltages below 100 kV.

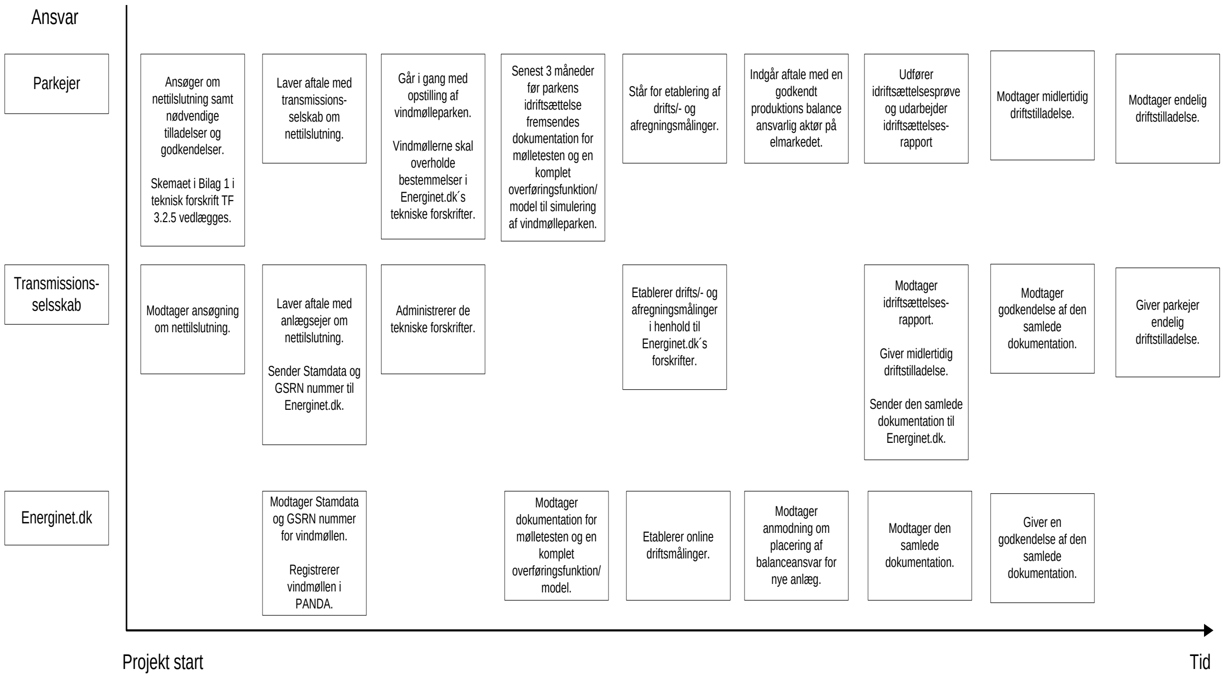


Figure 20: Administrative process diagram for wind parks connected to the grid at voltages above 100 kV.

3.3 Legal and financial issues

A LPV power plant can basically be build and owned by individuals, cooperatives and companies. In a Danish context the company structures of relevance would be of the type A/S, Aps and KS. Whereas the A/S and Aps are intended for professional long term investors the KS is mostly used for private tax focused investors.

By organising the PV project ownership in a KS (Kommanditselskab), it's possible for smaller private investors to participate in larger business activities (up to 10 times their own engagement) with a limited liability. The only requirement is, that at least one of the partners (among a total of up to ten) will be liable for the entity as a whole. The main advantage of organising the PV project as a KS is the tax transparency between the investor and the company. This implies that depreciations and deficit in the company can be deducted in the personal income, and as most such IPPs will have quite high depreciations during the first years, it can be quite attractive for private high-taxed investors. The current Danish tax law allows for a yearly depreciation of 25% of the book value for PV installation (operating asset).

3.4 Project financing

In general a LPV project could be financed with a depth structure of 80-90 %. For wind and PV projects abroad it's quite common to establish project financing, where the security is fully covered within the project itself with no additional guarantees needed from the equity providers.

Whereas the interest rate currently is quite low even in Denmark, it's also possible to obtain even lower interest through German banks using the special KfW loans. This however requires, that the German banks are involved already from the point when the project is constructed, as it's not possible to convert bridge financing to KfW loans after the project has been finished.

4. LPV energy production (incl. case studies)

4.1 Physical space and insolation conditions

4.1.1 Physical space

Use of land in Denmark has changed significantly over the last 100 years[2], e.g. the built-up area has increased from 3 % in the late 1800's to almost 10 % in 2000. The use of land in 2000 is outlined in Figure 21.

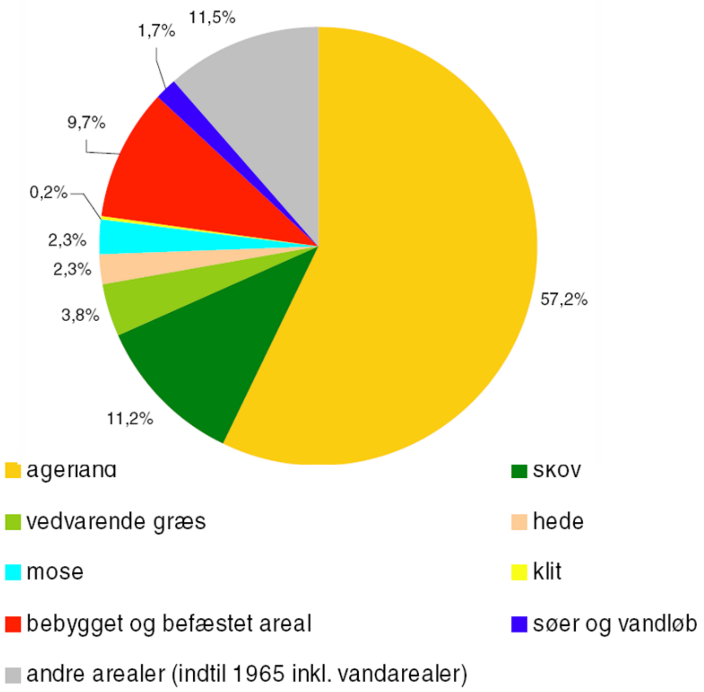


Figure 21: Relative use of the Danish area in year 2000. In order of colour: agricultural (orange), forrest (dark green), permanent grass (light green), heather, marsh, dunes, build-land (red), lakes and streams (blue), other.

Today about 4.500 km^2 are so called built-up area inclusive roads, railroads and other solid infrastructure. It is estimated that buildings alone has a footprint corresponding to 15 % of this or about 600 km^2. To produce the current yearly electricity consumption of Denmark of about 34 TWh with PV one would need about half of this area or ca. 300 km^2. Due to constraints as to orientation, shadowing, etc. the theoretical, technical potential for building applied and building integrated PV plants is estimated to a quarter of the area of the buildings; about half of the current electricity consumption can thus in theory be provided by PV plants on buildings[3].

If ground mounted PV plants are included in the future deployment of PV technology in Denmark there is no doubt, that the necessary about 300 km^2 for PV to - in theory – produce the total electricity demand of the country easily can be found.

As an illustrative benchmark for accessible area, one can consider that the area assigned for growth of raps for energy purposes, is presently estimated to be 650 – 800 km^2.

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[2] DMU, Faglig Rapport nr. 682, 2008 (Source. www.dmu.dk/Udgivelser/DMUNyt/2008/16/**areal**anvendelse.htm)

[3] 600 km^2 x ¼ = 150 km^2; 1 kW solceller fylder 7,5 m^2 og yder p.t. ca. 850 kWh/år svarende til i alt ca. 17 TWh.

4.1.2 Space requirement of LPV on flat roofs or ground

Flat industrial roofs and flat ground constitute an important potential for easy deployment of LPV also in Denmark, and a typical mounting approach for flat areas is illustrated below.

Figure 22: Ground mounted (left) and roof mounted (right) LPV installations.

This mounting method for PV modules is dictated by the wish to optimize annual electricity production and the tilt reflect the latitude, where the PV plant is erected; in Denmark the optimal tilt is around 40-45°.

The overall layout including the distance between the rows is a compromise between land requirement (and cost of land) and generation losses due to shadowing. Under Danish conditions with a low solar height during the winter months this compromise can be quite difficult to find as will be illustrated in Figure 23.

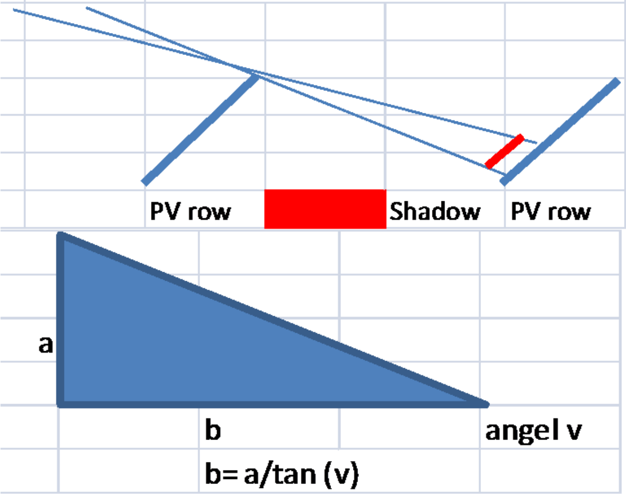


Figure 23: Calculation of the minimum spacing between rows to avoid shading at a given solar height.

At a given solar height (low during winter), one can calculate the minimum distance between rows that's necessary in order to avoid shadowing (direct beam shadowing of all rows except the first). The actual energy loss depends on this amount of shadowing as well as the electrical lay-out of the row, the number of modules pr. string, the number of by-pass diodes in the modules etc.

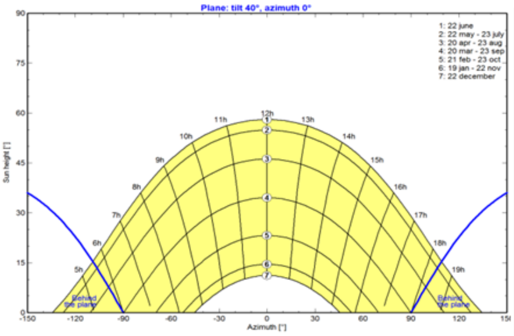
In Table 1 the calculated amount of shading as function of solar height (angle "v") is given.

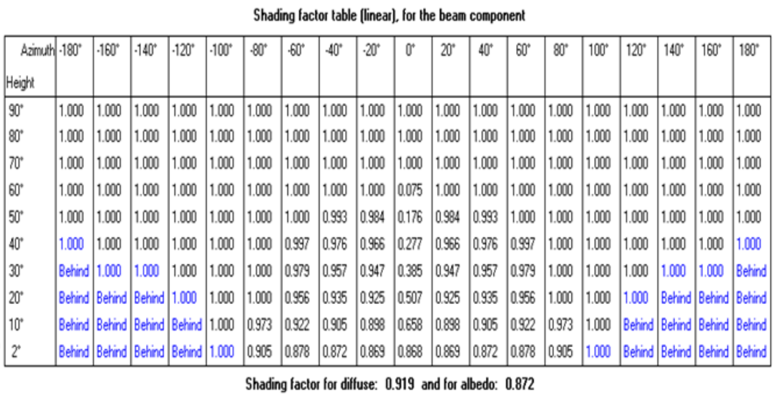
	Angel v	tan (v)	b	Area	Production
	[grader]	-	-	-	[%]
Ekstreme	0	∞	∞	∞	100
Ekstreme	90	0	0	0	0
	1	0,017455	57,28996		
	1,5	0,026186	38,18846		97,3
	2	0,034921	28,63625		97,5
	2,5	0,043661	22,90376		97,0
	3	0,052408	19,08113		95,2
	3,5	0,061163	16,34985		92,7
	4	0,069927	14,30066		92,2
	4,5	0,078702	12,7062		91,7
	5	0,087489	11,43005		89,6
	6	0,105104	9,514363		88,4
	7	0,122785	8,144346		87,8
	8	0,140541	7,115369		86,3
	9	0,158384	6,313751		85,4
	10	0,176327	5,671281		84,1
	12	0,212557	4,70463		82,2
	15	0,267949	3,73205		78,8
	20	0,36397	2,747477		73,2

Table 1: calculated row distance (b) as function of solar height ("v") and corresponding production loss.

As an example consider that with a maximum solar height of 3º and a height of the first PV row of 1 m (unit), the required distance between rows to avoid direct beam shadowing will be 19.1m; at a solar height of 10º the corresponding distance will be 5.7 m. The last column in the table describes the associated production loss of the second row of a generic PV system located at Copenhagen.

For the position of Copenhagen the solar height over the year is illustrated in Figure 24. During the winter months the solar height is quite low reaching a maximum of about 12º at noon; close to sunrise and sunset the solar height will be 1º. The direct beam shadowing effect for a "typical" PV array configuration is shown in the above table.




Shading factor table (linear), for the beam component

Azimuth Height	-180°	-160°	-140°	-120°	-100°	-80°	-60°	-40°	-20°	0°	20°	40°	60°	80°	100°	120°	140°	160°	180°
90°	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
80°	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
70°	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
60°	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.075	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
50°	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.993	0.984	0.176	0.984	0.993	1.000	1.000	1.000	1.000	1.000	1.000	1.000
40°	1.000	1.000	1.000	1.000	1.000	1.000	0.997	0.976	0.966	0.277	0.966	0.976	0.997	1.000	1.000	1.000	1.000	1.000	1.000
30°	Behind	1.000	1.000	1.000	1.000	1.000	0.979	0.957	0.947	0.385	0.947	0.957	0.979	1.000	1.000	1.000	1.000	1.000	Behind
20°	Behind	Behind	Behind	1.000	1.000	1.000	0.956	0.935	0.925	0.507	0.925	0.935	0.956	1.000	1.000	1.000	Behind	Behind	Behind
10°	Behind	Behind	Behind	Behind	1.000	0.973	0.922	0.905	0.898	0.658	0.898	0.905	0.922	0.973	1.000	Behind	Behind	Behind	Behind
2°	Behind	Behind	Behind	Behind	1.000	0.905	0.878	0.872	0.869	0.868	0.869	0.872	0.878	0.905	1.000	Behind	Behind	Behind	Behind

Shading factor for diffuse: 0.919 and for albedo: 0.872

Figure 24: Solar height and shading loss over the year for a LPV installed in Copenhagen.

Besides the direct beam shadow effect, there will also be a shadow effect for the diffuse light and for the albedo - the reflected light – the last two shadowing effects being quite difficult and complex to assess. As almost half of the power generated by a PV module in Denmark originates from diffuse light, these effects can be quite important to evaluate.

In Figure 24 the relationship between row distance in a PV system of two rows and the associated production loss is shown with the blue columns indicating the distance in meters between the two rows and the red columns indicating the associated reduced production in percentage of a no shadow situation[4]. It is clear, that under Danish conditions one will normally have to live with a not inconsiderable loss factor due to shadowing. An economic optimization process will have to be carried out to determine the optimal balance between land use (cost of land) and loss of electricity production. Again, under Danish conditions, a surface with even a slight tilt to the South will dramatically improve the situation for a given LPV plant configured in rows of tilted modules.

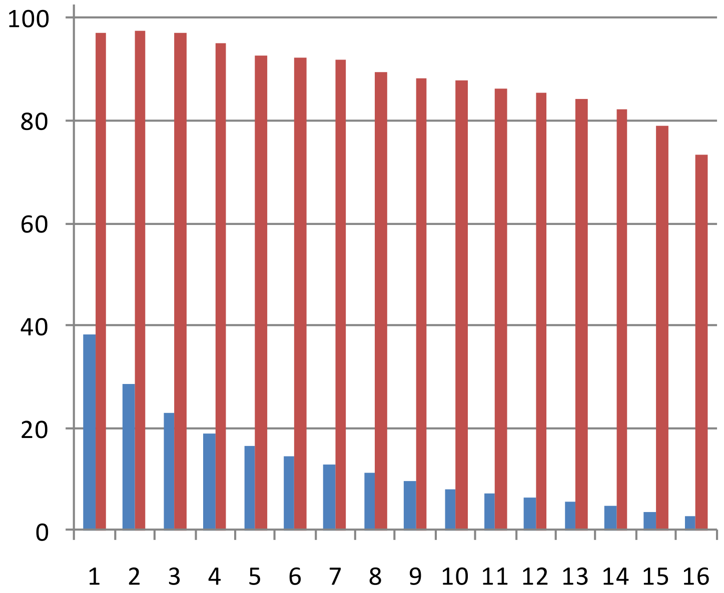


Figure 25: Area requirement in terms of row distance (blue) and relative shading loss (red).

4.2 Irradiance conditions

As an average, a south facing surface with 30-50 degrees tilt receives an energy amount of almost 1150 kWh/m^2 annually in Denmark. For optimum design of a PV plant, it is important to know the distribution on intensity and wavelength. A calculated distribution of annual available solar energy in solar irradiance bins for an optimum oriented surface in Denmark (Meteonorm) is presented here.

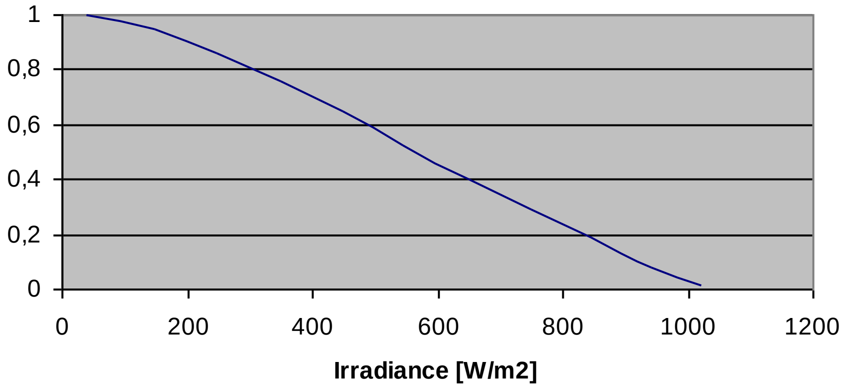


Figure 26: Accumulated energy distribution as function of irradiance.

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[4] The shadow effect includes both direct beam, diffuse and albedo effects as simulated in PV-SYST 5.4

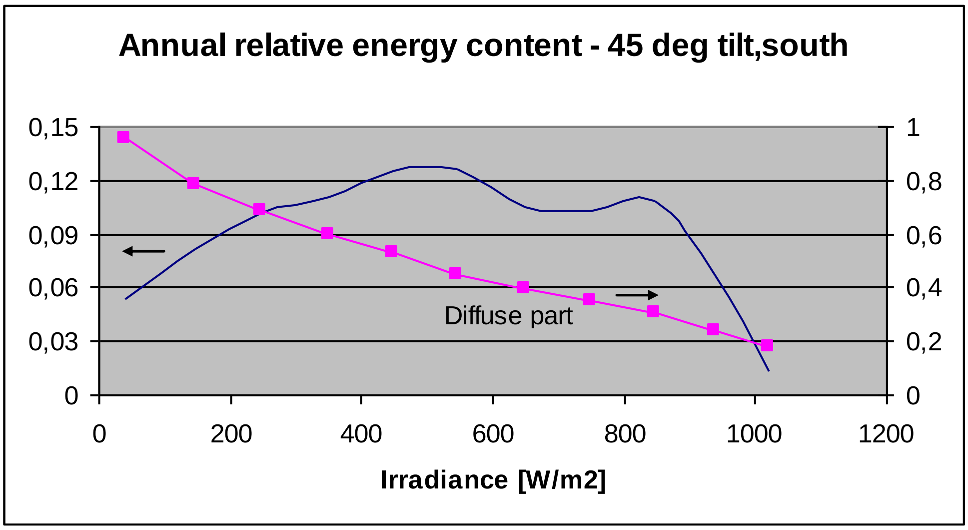

Figure 27: Annual relative energy content for a 45 degree tilted south facing plane.

From these graphs it is clear, that the PV plant should respond to a wide range of irradiances, only the very high and very low values do not contribute to the annual yield.

As expected, most of the energy in low light situations arises from diffuse radiation. Over the whole year, almost half of the energy on the surface comes from diffuse light. There are very few measurements of the solar spectrum, but Bason[5] reports some Danish measurements.

Solar maps or irradiation tables are essential tools in planning and dimensioning of solar energy installations. In this study we have tried to collect most of the available data sources for the solar climate of Denmark and analysed the differences. It is important to distinguish between statistical data and time specific data series; the latter may differ substantially from year to year, but a systematic analysis of these variations is outside scope of this project. The statistical data sources identified in this context are:

- Danish design reference year (DRY) based on long term data from Danish Meteorological Institute
- Meteonorm database found in the Swiss Meteonorm software package
- PVsyst database in PV simulation software PVsyst
- RetScreen database from the Canadian web tool of same name
- ARCO solar data base from a former major PV module manufacturer
- PVGIS solar data from the website www.pvgis.org

Some of the data above represent average values for all of Denmark, while other contain data from specific stations (It is not always clear how the detailed data are obtained, for example RetScreen uses a large number of stations, but it looks like they are using data from only a limited number of measured stations).

Apart from statistical data, monthly measurements have been compared from a number of DMI stations and 16 stations connected to geographically distributed PV systems in Denmark. This should provide a certain overview of the regional variation of solar irradiance.

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[5] Danish Energy Agency project 51181/99-0003; Frank Bason.

DRY data.

The Danish Design Reference Year DRY is an artificially created data set, based on long term (1960-1991) measurements from Danish Meteorological Institute, DMI. It is one of the most widely used data sets for solar energy calculations, and has therefore been selected as a reference in this report. The monthly irradiance on a horizontal surface, compared to other sources, is presented in Table 2.

	DRY	**ARCO**	**Meteonorm**	**PV GIS**	**RetScreen**
Jan	16	12	16	14	19
Feb	32	30	32	31	36
Mar	65	72	63	63	78
Apr	114	117	115	112	119
May	163	156	156	159	165
Jun	165	182	154	154	165
Jul	160	164	165	162	164
Aug	134	138	132	129	138
Sep	82	85	80	80	89
Oct	43	45	45	44	50
Nov	19	19	19	19	23
Dec	10	11	11	10	16
Year	***1002***	**1031**	**988**	**976**	**1062**

Table 2: Monthly irradiance on a horizontal surface in Denmark in units of kWh/m^2.

The above DRY data are as indicated somewhat old, and a process to create a more update version of the DRY has been initiated. It is important to mention that the data from PVGIS, RetScreen and Meteonorm are selected for a representative site that is Taastrup in the Copenhagen area.

The annual sum of DRY values is seen to be significantly lower than the RetScreen data set and the old ARCO data, but higher than the PVGIS map indicates. Not surprisingly, the DRY value corresponds very well with the map from DMI since the raw data are similar. The question is why, and one explanation could be that some of the data sets use average values, and other are geographically specific. It is therefore important to have a look on a solar map for Denmark. On the map in Figure 28 it is clear that one finds a geographical variance in the irradiation of about 15 % across the country.

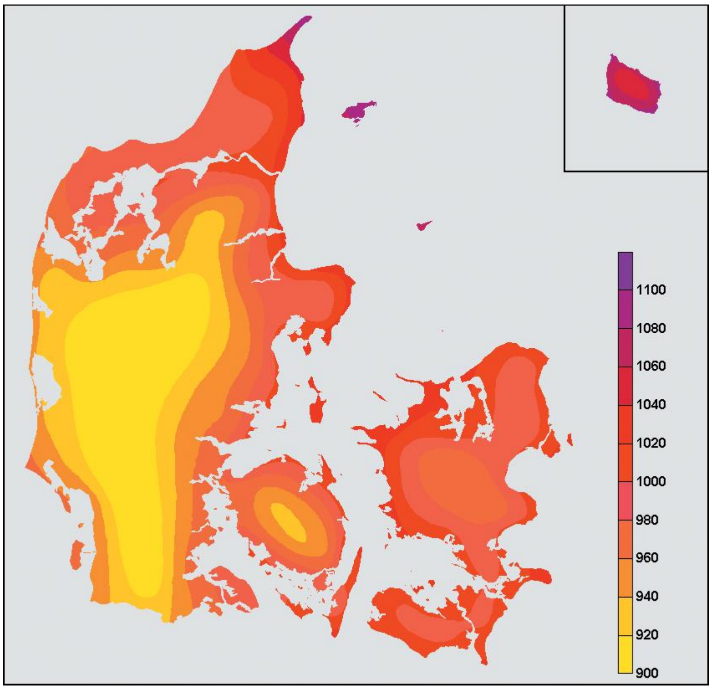

Figure 28: Global irradiance for Denmark (kWh/m^2) based on DMI measurements

Historical data of solar irradiance can only be found as sunshine hours, originally being recorded with a solar autograph, which burns a trace in a strip of paper. Sunshine hours are defined by the World Meteorological Organization (WMO) as the number of hours where the direct irradiance level exceeds 120 W/m^2. Sunshine hours are still used for weather reports but nowadays electronic sensors are used.

Owners of PV systems or simulation software cannot use this unit directly to estimate the output of a PV system, therefore a simple correlation is proposed in the graph below for the solar irradiance as a function of the monthly sunshine hours. The graph is based on empirical values. It is obviously not showing a perfect fit to the measurements, therefore actual irradiance measurements should always be preferred if they are available for a specific site.

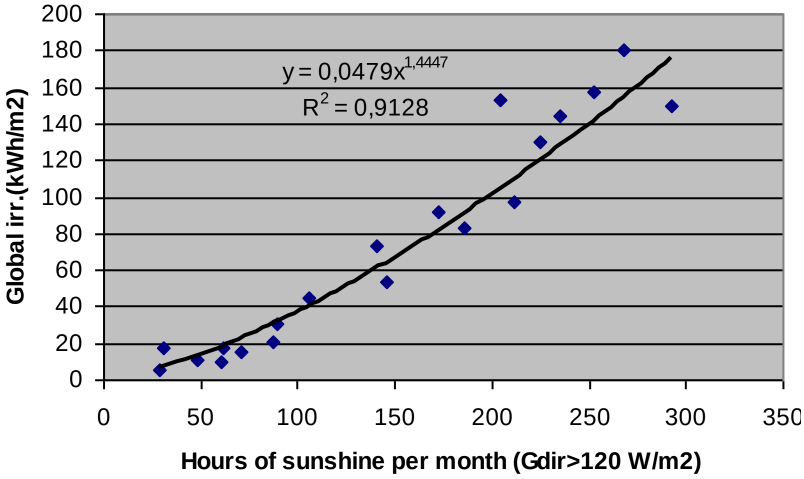

Figure 29: Global irradiance vs. monthly hours of sunshine.

Summary

Solar irradiance[6] is the single most important parameter for evaluation of PV system performance, so for simulation and evaluation purposes it is important to select the best possible data series. The study has shown that the different data sets are not very consistent when it comes to site-specific irradiance.

Though Denmark is a small country, there can be significant geographical variation in irradiance data, in particular between inland and coastal regions. The cloud cover can also cause significant variations of 10-15% from year to year. For simulation of average performance on a specific location, it is therefore suggested to use the DRY data series and subsequently correct the annual values according to the solar map produced by DMI. Other data series can also be used, as long as the annual global irradiance is close to the value on the DMI map. For evaluation of the performance in a specific year, collection of own irradiance data should be preferred, second option would be to download monthly data from the nearest DMI station(s) from www.dmi.dk; if data from three or more nearby DMI stations are available an interpolation (weighted mean value) to the actual site can be carried out using this formula (example with three nearby stations):

Ix = (Ia/a^2 + Ib/b^2 + Ic/c^2)/(1/a^2 + 1/b^2 + 1/c^2)

where:Ix = irradiation at actual site of PV plant

Ia, Ib and Ic = known irradiation at three nearby DMI stations

a, b and c = distance from each station to site x

4.3 Energy production from LPV power plants

The useful amount of energy that can be delivered to the grid from a PV power plant depends not only on the amount of irradiation received at the location but also on the technical realisation of the project. Avoiding all the technical details, the most commonly used parameter to describe the overall technical performance of the power plant is the Performance Ratio (PR), that is a measure of the realised production (ac) normalised by the size of the installation and the irradiation received, where the irradiation shall be referred to the plane-of-array (POA), i.e. a irradiation sensor need to be installed at the same angle as the modules. The calculation formula is:

$$PR = \frac{\dfrac{\text{Production [kWh]}}{\text{Installation size [kW}_\text{p}\text{]}}}{\text{Irradiation }[\frac{\text{kWh}}{\text{m}^2}]}$$

where the period of reference for both the production and the irradiation can be specified between minutes and year. When using the units as indicated above, the PR will be provided in units of [%]. This unit is not obvious from the formula above, where some constants and corresponding units related to the definition of the module peak power have been omitted.

When entering into an Engineering-Procurement-Construction (epc) contract with a turn-key installer, the performance guarantee for the LPV project will be tied to the PR. Beside the PR

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[6] For a more thorough analysis of irradiation in Denmark, please refer to the report: Optimization of Design of Grid-Connected PV Systems under Danish Conditions; www.solenergi.dk

guarantee the contractor also need to warrant the availability of the power plant and the Operation & Maintenance contract should clarify the responsibility of the epc contractor to guarantee both the full year PR and the availability – at least during the initial warranty period which is typical 2-5 years.

The PV module manufactures provide product warranties that typical guarantee 90 % of the minimum specified nominal peak power value of the module after 10 year. In the remaining guaranteed lifetime of the module (year 11 to 25), the performance guarantee is typically 80% of this value. This step change in performance guarantee for the modules are typically transferred to the epc contract guarantee, and often implemented as a percentage wise yearly reduction of the guaranteed performance. The yearly degradation in performance contracts typically lie between 0.3 and 0.5 % p.a. which mean that the PR stated in the epc contract also each year decrease with this amount.

4.3.1 Ground and roof mounted LPV case

The Performance Ratio for a typical ground mounted LPV in Denmark is expected to lie in the interval 78–85 %. The lower value could be reasonable if the power plant is installed at a location where some shadowing are unavoidable or when the installation is done with modules installed at a sub-optimal tilt angle. The higher level of PR represent a well designed project with a good selection of matching components (i.e. high performance modules), cables with sufficient cross-section and an optimal layout (optimised dc and ac Ohmic loss).

As a reference for further comparison of production numbers, the following rule of thumb can be used. A typical (=reference in this report) LPV project installed in Denmark can be expected to deliver 920 kWh to the grid each year pr. kW_p of installed capacity (nominal module power) based on the following assumptions:

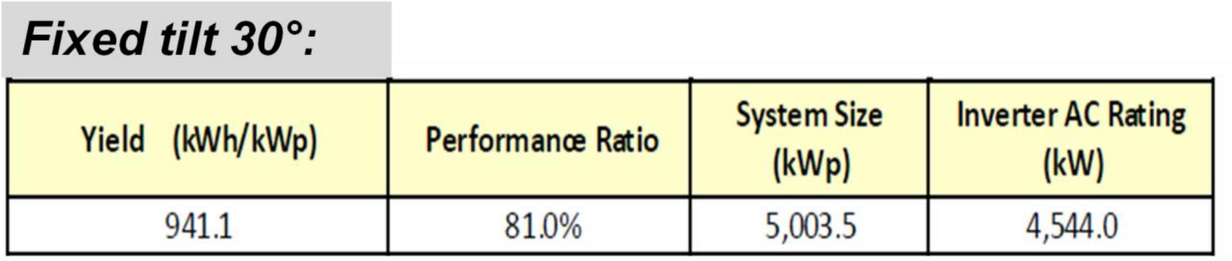
- the irradiation received on a horizontal surface is 1000 kWh/m^2,
- the irradiation received at the POA is 15% higher than this horizontal value and
- a Performance Ratio of 80% can be achieved.

The specific performance of 920 kWh/kW_p can also be referred to as the energy yield or as the number of full-load hours, i.e. number of hours [h] during a year, that the project will produce energy according to the full nominal power of the modules.

For the purpose of obtaining updated and realistic data for LPV production and economics, we have asked three experienced and internationally respected companies to provide epc offers for a turn-key LPV project to be installed in Denmark this year.

The German company Phoenix Solar that is listed on the Prime Standard segment of the Frankfurt Stock Exchange, has provide a very detailed (69 pages) quotation for a 5.3 MW_p ground mounted project to be build and commissioned in Denmark dated January 28th 2011. This proposal is very detailed with respect to physical and electrical layout of the LPV and also with respect to the components to be used. However so far there's no production estimates provided, and therefore the above mentioned rule-of-thumb production figure of 920 kWh/kW_p will be used when analysing this offer.

In order to complement this indicative experience number with a reference to another serious installer of LPV systems, the American company SunPower has been asked to provide an offer to install a 5 MW project in Toftlund, Denmark. Based on their extensive experience (more than 600 MW of LPV already installed) in construction and supervision of PV power plants, they have developed and verified a modelling tool, that enables very accurate performance predictions, and based on this model they are able to offer to install a fixed mounted system with a guaranteed performance as follows:



Fixed tilt 30°:

Yield (kWh/kWp)	Performance Ratio	System Size (kWp)	Inverter AC Rating (kW)
941.1	81.0%	5,003.5	4,544.0

Please notice, that the indicated energy yield of 941.1 kWh/kW$_p$ is 2 % higher than the previosuly introduced reference yield of 920 kWh/kW$_p$. This difference is related to both a difference in real performance (energy yield) of the modules used and a higher expectation for the yearly global irradiation to be received (1015 kWh/m^2 as compared to reference case of 1000 kWh/m^2). Although all modules are power rated according to the same standard procedure (IEC 61215, where the standard test conditions are defined as 1000 W/m^2 of AM1.5 irradiation and 25 °C module temperature) they do not all generate eaxctly the same energy under true field conditions and in this case the SunPower modules are expected to generate ½ % more energy over the year compared to standard modules.

A summaray of the main characteristics of the fixed mounted LPV project offers to be analysed is presented in Table 3.

1. Project	**SunPower F30°**	**Phoenix Solar**	**German Installer**
Project description	Fix 30° tilt project with very high efficiency modules	Fix 30° tilt project with std. modules	Fix 30° tilt project with std. modules
Module Power [W$_p$]	320	230	230
Module Area [m^2]	1.63	1.64	1.64
Number of modules [pcs]	15 636	23 328	23 328
Total park power (at STC) [W$_p$]	5 003 520	5 365 440	5 365 440
2. Site selection			
Horizontal global irradiation [kWh/m^2/yr]	1 015	1 000	1 000
Irradiation increase due to tilt angle [%]	14.5%	15.0%	15.0%
Ground Coverage Ratio [%]	50%	55%	55%
Area required for power plant [ha]	5.1	6.9	6.9
3. System design			
Performance Ratio [%]	81.0%	80.0%	80.0%
Energy yield [kWh/kW$_p$]	941	920	920
Energy gain (rel. to 920 kWh/kWp) [%]	2%	0%	0%

Table 3: Main characteristics of fixed mounted LPV project offers.

4.3.2 Tracking LPV case

When it comes to the power production potential of tracker solutions, it's necessary to differentiate between:

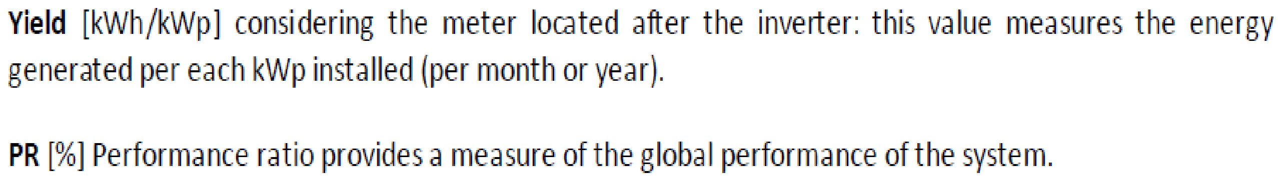
1. Trackers with a single horizontal axis where the panels follow the sun from east-to-west or
2. Trackers with a single tilted axis (raised 15 - 25° relative to horizontal) where the panels follow the sun from east-to-west or
3. Two-axis trackers where the panels are always oriented towards the sun.

In order to present both realistic and updated performance and economical numbers, a set of commercial offers have been collected from a pair of experienced tracker installers, SunPower and ExoSun.

The SunPower solution is illustrated in Figure 30.

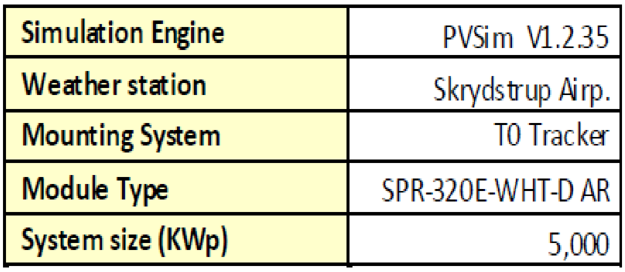
Figure 30: The SunPower T0 horizontal tracker.

SunPower has provided an offer dated January 28th 2011 that's based on the T0 tracker. According to this offer the horizontal tracker can deliver:

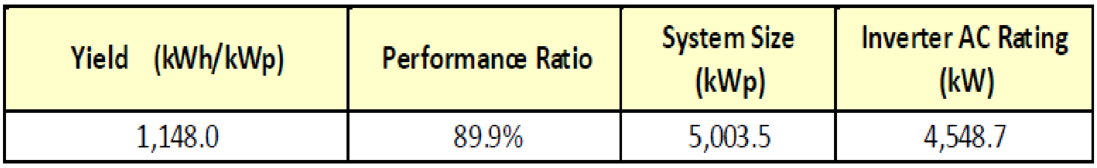


Yield [kWh/kWp] considering the meter located after the inverter: this value measures the energy generated per each kWp installed (per month or year).

PR [%] Performance ratio provides a measure of the global performance of the system.



Simulation Engine	PVSim V1.2.35
Weather station	Skrydstrup Airp.
Mounting System	T0 Tracker
Module Type	SPR-320E-WHT-D AR
System size (KWp)	5,000



Yield (kWh/kWp)	Performance Ratio	System Size (kWp)	Inverter AC Rating (kW)
1,148.0	89.9%	5,003.5	4,548.7

Note that this production of 1148 kWh/kW$_p$ is 25 % higher than the previously mentioned reference yield of 920 kWh/kW$_p$ for a fixed system.

Also the french tracker specialist company ExoSun has been asked to provide offers for installations in Denmark. Exosun can supply both single axis and two-axis trackers as is illustrated in Figure 31.

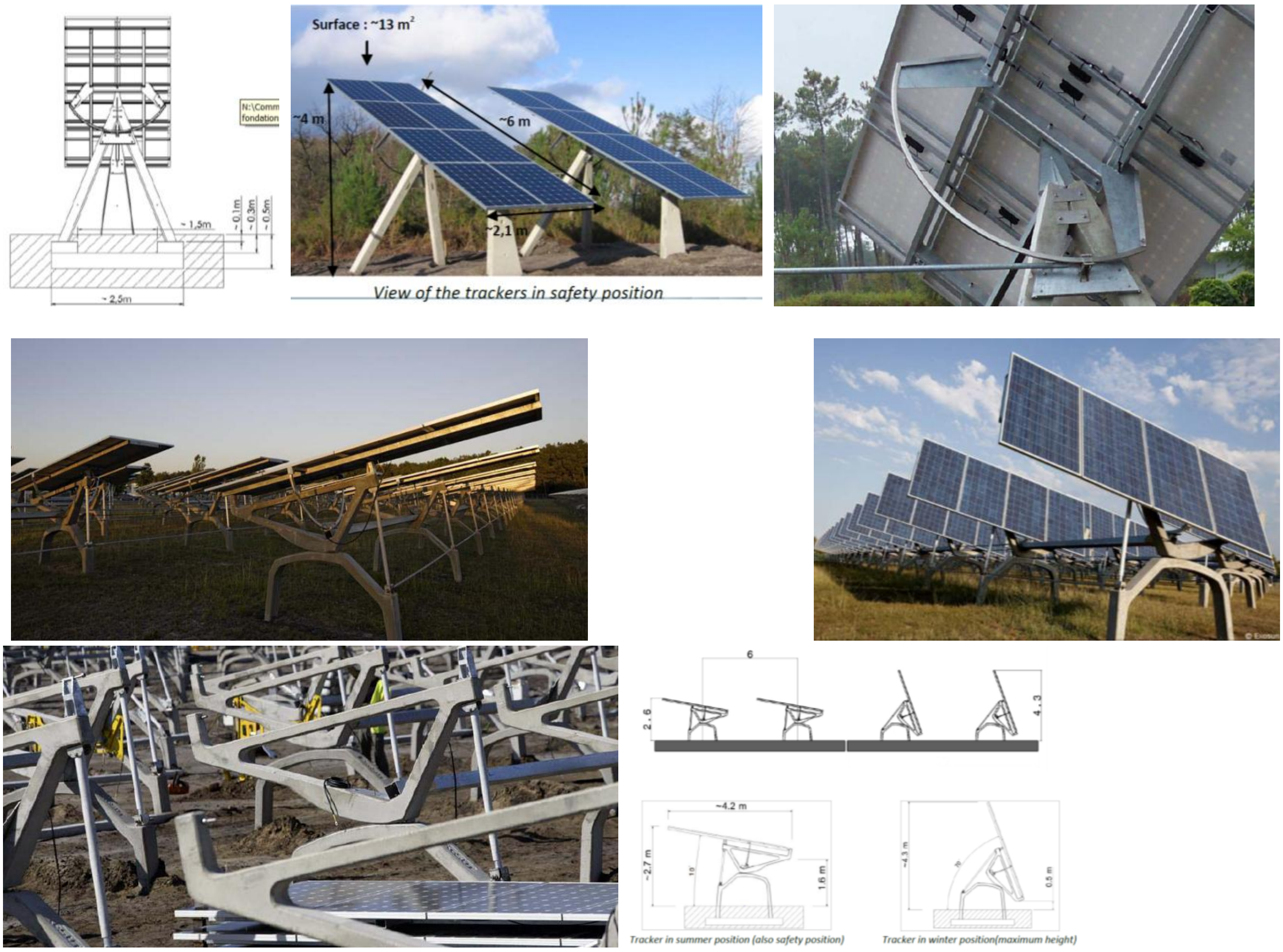


Figure 31: The ExoSun trackers with 1 and 2 axis.

As for SunPower, ExoSun, has developed their own modeling tool capable of predicting the energy production of their tracker solutions. The following Table 4 summarises the performance that can be expected when installed in Denmark.

1. Project	**SunPower T0**	**ExoSun#1**	**ExoSun#2**	**ExoSun#3**	**ExoSun#4**
Project description	Horizontal tracker with very high efficiency modules	1 axis tilted tracker with low concentration modules	1 axis horizontal tracker with std. modules	1 axis tilted tracker with std. Modules	2 axis tracker with high efficiency modules
Module Power [W$_p$]	320	150	230	230	290
Module Area [m^2]	1.63	1.37	1.64	1.64	1.94
Number of modules [pcs]	15 636	33 334	21 740	21 740	17 242
Total park power (at STC) [W$_p$]	5 003 520	5 000 100	5 000 200	5 000 200	5 000 180
2. Site selection					
Horizontal global irradiation [kWh/m^2/yr]	1 015	1 000	1 000	1 000	1 000

Irradiation increase due to tilt angle [%]	25.8%	24.3%	25.1%	37.0%	50.4%
Ground Coverage Ratio [%]	35%	33%	33%	33%	27%
Area required for a 5 MW power plant [ha]	7.3	13.8	10.8	10.8	12.4
3. System design					
Performance Ratio [%]	89.9%	80.0%	80.0%	80.0%	80.0%
Energy yield [kWh/kW$_p$]	1 148	994	1 001	1 096	1 203
Energy gain (rel. To 920 kWh/kWp) [%]	25%	8%	9%	19%	31%

Table 4: Main characteristics of tracker based LPV project offers.

Again it must be noted, that it’s actually possible to obtain significantly higher production output from a given installation size (measured in kW$_p$) than the rule-of-thumb number of 920 kWh/kW$_p$, if the modules are allowed to track the sun. Whether the tracking also represents cost efficient solutions will be discussed in the next chapter.

5. LPV economics

Four different aspects of LPV economics will be covered in this chapter. First the investment cost is discussed. Both the total turn-key price but also the breakdown of this price into cost components is of relevance, as we also want to discuss the target installation price some years ahead based on the reporting on the technical and economic marked trends that were presented in chapter 2. Secondly we consider the cost of electricity manufactured from these proposed LPV installations using the commonly accepted Levelized Cost of Electricity (LCOE) concept. The third issue that is addressed will be the sales price that can be obtained, when this renewable power is sold in Denmark. Lastly we consider the overall project economy as assessed by a professional investor/IPP.

5.1 LPV prices – turnkey installation

The LPV turn-key prices and cost breakdown for the various examples considered are shown in Table 5. In all cases the epc company has provided an offer for turn-key installation in Denmark. It’s assumed that the site is ready for construction and do not impose any special challenges like “soft” soil or difficult access conditions. The price stated is without VAT.

1. Project	**SunPower T0**	**SunPower F30°**	**Phoenix Solar**	**German Installer**	**ExoSun #1**	**ExoSun #2**	**ExoSun #3**	**ExoSun #4**
Project description	Horizontal tracker with very high efficiency modules	Fix 30° tilt project with very high efficiency modules	Fix 30° tilt project with std. modules	Fix 30° tilt project with std. modules	1 axis tilted tracker with low concentration modules	1 axis horizontal tracker with std. modules	1 axis tilted tracker with std. modules	2 axis tracker with high efficiency modules
4. Project and system components cost								
Development and other fixed costs [€]	Not considered							
Construction (civil and manual work) [€/W$_p$]	0.00	0.00	0.15	0.00	0.55	0.45	0.65	0.60
Mounting structures [€/W$_p$]	0.00	0.00	0.23	0.00	0.75	0.50	0.75	1.10
BOS components [€/W$_p$]	0.00	0.00	0.19	0.00				
Inverter [€/W$_p$]	0.00	0.00	0.14	0.00				
Transformer & grid connection [€/W$_p$]	0.00	0.00	0.02	0.00				
Modules [€/W$_p$]	0.00	0.00	1.31	0.00	1.20	1.30	1.30	1.30

Turn key unit price [€/W$_p$]	3.00	2.60	2.04	1.95	2.50	2.25	2.70	3.00

Table 5: Turn-key prices and price breakdown of all LPV project offers.

Whereas SunPower did not provide a breakdown of their turn-key installation price, Phoenix Solar has provided a very detailed breakdown. ExoSun has divided their offer into construction, the dc-part (tracker incl. dc-cables, connection boxes) and modules. Both Phoenix Solar and Exosun use the market price for crystalline silicon modules (1.3 €/W$_p$) that obvious contribute to the overall systems cost with a weight between 43 % (2-axis solution from ExoSun) to 64 % (fixed tilt solution from Phoenix Solar).

Already around 2½ month later the market price for crystalline silicon modules has fallen, and based on actual offers from reliable Taiwanese suppliers, a module price of 1.16 €/W$_p$ can be considered reasonable by ultimo march 2011. In addition another German installer with installation experience for more than 100 MW of projects was visited on March 7th 2011, and when asked about prices for turn-key projects installed in Denmark this year, an oral non-negotiated offer of 1.95 €/W$_p$ was given.

5.2 Levelized Cost of Electricity (LCOE)

In order to be able to compare the cost of electricity generated by different technologies and under different operational and financial conditions, the concept of Levelized Cost of Electricity has been introduced and has now become a widely accepted standard. The LCOE is defined as the net present value (NPV) of all lifecycle costs during the lifetime of the PV power plant divided by the accumulated discounted electricity production and can be calculated by use of the following formula[7]:

$$\frac{\text{Initial Investment} - \sum_{n=1}^{N} \frac{\text{Depreciation}^n}{(1+\text{Discount Rate})^n} \times (\text{Tax Rate}) + \sum_{n=1}^{N} \frac{\text{Annual Costs}^n}{(1+\text{Discount Rate})^n} \times (1-\text{Tax Rate}) - \frac{\text{Residual Value}}{(1+\text{Discount Rate})^n}}{\sum_{n=1}^{N} \frac{\text{Initial kWh/kWp} \times (1-\text{System Degradation Rate})^n}{(1+\text{Discount Rate})^n}}$$

The exact meaning of the various components in this formula as well as the assumptions and values used when applying the formula to the specific cases analysed in this project, are:

- The initial investment is given by the sum of the epc contract price and all cost related to project development and project financing. Whereas the project development cost has been neglected in this context, the financial cost has been set to 1 % of the overall investment and is included in the equity part of the financing according to the formula: Equity fraction = 100 % - Depth fraction + 1 %.
- According to current tax law, a Danish company can depreciate 25 % of the book-value of the PV project (operating assets) each year.
- A company tax rate of 25 % has been used to calculate the depreciation tax benefit.

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[7] SunPower white paper (August 14th 2008): *"The Drivers of The Levelized Cost of electricity for Utility-Scale Photovoltaics"*

- The annual costs consist of land lease, operation & maintenance cost, insurance, bookkeeping and interest on the project loan. For the calculations in this report we use an estimated yearly land lease of DKK 10.000 pr. ha[8], a yearly O&M cost corresponding to 1.5 % of the investment (all inclusive)[9]. All annual costs are adjusted by a constant 2 % p.a. inflation rate. For project financing we consider an equity fraction of 16% and a depth fraction of 85 % covered by a 20 year KfW type of project loan with an interest of 3.6 % p.a[10]
- For the purpose of LCOE calculation we'll consider the full technical operating lifetime of the PV power plant, which - when a replacement of the inverters are taken into account - are currently expected to be 35 years for a LPV project installed after 2008[11]. When the technical lifetime of the installation is used in the calculation, we'll not consider any residual value. It's assumes that this value will be close to zero or at least compatible with the expenses needed to clean and restore the land after the lease period has expired
- As for the system degradation rate it's estimated to be as low as 0.25 % p.a. for all newer installations[12]
- As for the discounting rate, we've chosen to use the discounting rate that's recommended by The Economic Council (Det økonomiske råd) for large energy and infrastructure projects which currently is 3.0 %[13]. This is significantly lower than the current official Danish discounting rate as stated by the Ministry of Finance, but as it's known that this discounting rate is up for revision[14], and as the overall idea in this project is to analyse the potential of deploying LPV power plants in Denmark in light of the growth, experience and progress realised in Germany during the last years, it's assumed appropriate to use this lower discounting rate that's even above the discounting rate of 2.2 % that used in Germany for this type of projects.

By use of all above assumptions the LCOE can be calculated for the various Danish generic PV project proposals and the results are summarised in Table 6 below.

1. Project	**SunPower T0**	**SunPower F30°**	**Phoenix Solar**	**German Installer**	**ExoSun# 1**	**ExoSun# 2**	**ExoSun# 3**	**ExoSun# 4**
Project description	Horizontal tracker with very high efficiency modules	Fix 30° tilt project with very high efficiency modules	Fix 30° tilt project with std. modules	Fix 30° tilt project with std. modules	1 axis tilted tracker with low concentration modules	1 axis horizontal tracker with std. Modules	1 axis tilted tracker with std. modules	2 axis tracker with high efficiency modules
5. Power production & sale								

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[8] Andreas von Rosen, European Green Field A/S (2011). Personal communication.

[9] Ch. Breyer and A. Gerlach (2010): *"GLOBAL OVERVIEW ON GRID-PARITY EVENT DYNAMICS".* 25th PVSEC.

[10] IEA webpage (http://www.iea.org/textbase/pm/?mode=re&action=detail&id=3596): KFW-PROGRAMME PRODUCING SOLAR POWER

[11] A.T. Kearney GmbH & Phoenix Solar AG (November 21st 2010): *"The True Value of Photovoltaics for Germany".*

[12] A.T. Kearney GmbH & Phoenix Solar AG (November 21st 2010): *"The True Value of Photovoltaics for Germany".*

[13] Børsen (February 10th 2011): *"Finansministeriet bremser grøn energi".*

[14] Børsen (February 10th 2011): *"Finansministeriet bremser grøn energi".*

Technical lifetime of installation [year]	35	35	35	35	35	35	35	35
PV system (module) degradation (%/yr)	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%
6. Land lease, O&M and guarantees								
Land lease [€/ha/yr]	1 342	1 342	1 342	1 342	1 342	1 342	1 342	1 342
O&M [€/kW$_p$/yr]	44.97	38.97	30.63	29.25	37.50	33.75	40.50	45.00
land Lease and O&M inflation rate [%]	2%	2%	2%	2%	2%	2%	2%	2%
7. Financing								
Dept ratio (%)	85.0%	85.0%	85.0%	85.0%	85.0%	85.0%	85.0%	85.0%
Equity (%)	16.0%	16.0%	16.0%	16.0%	16.0%	16.0%	16.0%	16.0%
Amortisation [year]	20	20	20	20	20	20	20	20
Bank Interest - loan [%]	3.6%	3.6%	3.6%	3.6%	3.6%	3.6%	3.6%	3.6%
Discount rate (%)	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%
Depreciation [% pr. year]	25%	25%	25%	25%	25%	25%	25%	25%
Tax rate (%)	25%	25%	25%	25%	25%	25%	25%	25%
8. Results								
Accumulated 35 year production [MWh]	192 721	157 993	165 625	165 623	166 760	167 937	183 876	201 826
LCOE [DKK/kWh]	1.24	1.31	1.06	1.01	1.21	1.08	1.18	1.19

Table 6: Economical key figures for all LPV projects analysed in this chapter.

The lowest cost of electricity is obtained with the new German offer for a fixed installation, which gives rise to a LCOE of 1.0 DKK/kWh. This new offer is the only one that have taken the last month price reduction of PV modules into account, as it was given based on a assumption of a PV module price of 1.16 €/W$_p$ can be obtained. As we already have evidence that this price really is obtainable, we’ve recalculated the above offers based on this “version 1.16” and the LCOE obtained are shown in Table 7.

1. Project	**Phoenix Solar**	**ExoSun#2**	**ExoSun#3**	**ExoSun#4**
Project description	Fix 30° tilt project with std. modules	1 axis horizontal tracker with std. Modules	1 axis tilted tracker with std. modules	2 axis tracker with high efficiency modules
4. Project and system components cost				
Development and other fixed costs (€)	Not considered			
Construction (civil and manual work) (€/W$_p$)	0.15	0.45	0.65	0.60
Mounting structures (€/W$_p$)	0.23	0.50	0.75	1.10
BOS components (€/W$_p$)	0.19			
Inverter (€/W$_p$)	0.14			
Transformer & grid connection (€/W$_p$)	0.02			
Modules (€/W$_p$)	1.16	1.16	1.16	1.16
Turn key unit price (€/W$_p$)	1.89	2.11	2.56	2.86
8. Results				
LCOE [DKK/kWh]	0.98	1.01	1.12	1.14

Table 7: Economical results version 1.16: LCOE calculations for those LPV projects that utilise a standard c-Si modules updated by use of a module price of 1.16 €/W$_p$.

With the updated PV module price most LPV projects that are using standard crystalline silicon modules will demonstrate LCOE over the technical lifetime of the power plant just below DKK 1.0/kWh (DKK 0.98 /kWh = 13 €c/kWh).

5.3 Conditions for LPV power sale

The electricity produced from a grid connected PV installation can be sold at a guaranteed price of DKK 0.60/kWh for the 10 years of production. The following year a minimum price of DKK 0.40/kWh are guaranteed.

Power produced by PV does not have to pay electricity tax, that otherwise apply for all power produced no matter if it's self-consumed or sold. However the IPP still will have to pay a PSO (Public Service Obligation) surcharge approx. DKK 0.07/kWh for all power produced.

5.4 LPV project calculation

When a professional investor or Independent Power Producer (IPP) shall assess an investment opportunity, the important factor to consider is the return on investment (ROI). This parameter is often referenced by use of the Internal Rate of Return (IRR) of the annual cash flows over the economical lifetime of the project, where the cash flow is given by the net earnings after interest and amortization (=EBDT).

The economic lifetime is much shorter than the technical lifetime and typical corresponds to the loan period which again also will reflect the number of years where the sales price for the electricity is know/guaranteed and backed by a long term power purchase agreements (PPA). Without a guaranteed off-take contract for the electricity produced, the basis for long term project financing is questionable, and the IRR project model as described above will probably not apply.

As we currently do not have a suitable long term off-take mechanism in place for grid delivered PV electricity in Denmark, the basis for LPV projects in Denmark with project finance are currently not in place. If we anyhow for the purpose of illustration consider the hypothetical case that the power sales was guaranteed for 20 year with a flat rate sales price at the same level as can currently be obtained for ground mounted systems in Germany (24.26 €ct/kWh or 1.81 DKK/kWh), our Danish IPP investors would obtain the pre-tax IRR as given in Table 8.

1. Project	**SunPower T0**	**SunPower F30°**	**Phoenix Solar**	**German Installer**	**ExoSun #1**	**ExoSun #2**	**ExoSun #3**	**ExoSun #4**
Project description	Horizontal tracker with very high efficiency modules	Fix 30° tilt project with very high efficiency modules	Fix 30° tilt project with std. modules	Fix 30° tilt project with std. modules	1 axis tilted tracker with low concentration modules	1 axis horizontal tracker with std. modules	1 axis tilted tracker with std. modules	2 axis tracker with high efficiency modules
8. Results								
Investment IRR (21 year EBDT cash flow by equity) [%]	5.3%	2.2%	15.0%	18.0%	6.9%	13.9%	8.5%	7.7%

Table 8: IRR calculated for all LPV projects when assuming an electricity sales price corresponding to the current German FIT and offers received in February 2011.

6. Summary of the Danish situation in 2010

The situation for LPV in Denmark by end of 2010 will be summarized in this section and scenarios and recommendations related to the future of LPV in Denmark will be briefly described.

6.1 Opportunities

There are three major options for LPV in Denmark:

1. Roof mounted PV plants on large commercial buildings
2. PV plants as noise barriers along roads and railroads or in connection with other physical infrastructures
3. Ground mounted PV plants

6.1.1 Roof mounted PV plants

Although the actual potential in terms of km^2 of suitable large scale flat roofs in Denmark is not known, it is estimated to be significant for the deployment of LPV. Of the overall building located PV potential of about 150 km^2 estimated in section 4.1.1 about one third or 50 km^2 is projected to be large scale flat roofs on commercial buildings constituting a technical potential for PV generation of 5-6 TWh/year.

PV plants on the roof of commercial buildings will normally not qualify for the current Danish net-metering scheme, but will receive a Renewable Energy guaranteed tariff of DKK 0.60/kWh for the first 10 years and less the following years. As described in chapter 5 this subsidy level is not sufficient to support a LPV market growth. However, if most or all of the PV production can be used on the premises and replace more costly electricity and if the company in question will/can use the green image usually associated with PV to brand the company as green and to strengthen its CSR profile, the investment in a PV system on the flat roof of a commercial building may turn out being quite viable.

6.1.2 PV plants on other infrastructures

The potential for multifunctional PV applications on other infrastructures than buildings has so far not been assessed in a Danish context. However, the physical area potential as outlined in section 4.1.1 must be quite considerable constituting many km^2.

Besides a few very modest demonstration systems PV as a multifunctional element in large-scale constructions such as noise barriers, wind barriers or visual barriers have so far found little use in Denmark in contrast to other EU countries such as Germany, the Netherlands and Switzerland. If you face the need of a large scale surface and the orientation and shadowing effects are acceptable, PV modules can constitute the required surface area and at the same time produce electricity. PV plants also acting as noise barriers, wind barriers of visual barriers will hardly be able to qualify under the current net-metering scheme, unless located on or very close to a building housing an institution with adequate floor area and adequate consumption of electricity. However, the PV modules will replace other cladding materials this way saving cost and may present a more attractive aesthetical solution.

6.1.3 Ground mounted PV plants

Ground mounted PV plants are in a Danish context a new application. As far as is known only one medium scale (about 70 kW_p) ground mounted PV plant is under construction in Denmark beginning of 2011 at the company Linak on Als.

In terms of energy harvest PV plants will under Danish conditions exhibit an overall efficiency of about 10 % in conversion of the energy content of the light compared to about 0.3 % for biomass. The theoretical ground area needed to produce the present total annual electricity consumption of Denmark (33-35 TWh) is about 300 km^2 or an area equivalent to that of the island of Langeland. The potential area for ground mounted LPV plants in Denmark is estimated at much more than 250 km^2 using only “marginal land”.

The lead time to establish a ground mounted LPV plant is very short. Experiences from Germany shows, that given all permits and administrative issues are in place, the average construction time is less than 1 month per MW_p capacity for plants in the range of 3 - 10 MW_p.

Compared to other RE electricity generating alternatives LPV plants can easily be integrated into the surrounding landscape by putting a “shield” of bushes or threes, and the operation of the LPV plant is completely silent in contrast to wind turbines.

The Danish power grid system covers the country in a fine mesh allowing for relative cheap grid connection, and PV generated electricity fits well with the daily demand curve and complements the wind generation of electricity.

6.2 Barriers

As already outlined above the main barrier for LPV plants in Denmark is the tariff system. The net-metering scheme excludes most LPV applications, except for PV plants on very large institutions such as hospitals.

The economic analysis in section 5 exhibits LCOE figures for LPV plants in the range of DKK 0.98 – 1.24/kWh, and with the present feed in tariff for wind turbines - which is expected to cover also LPV plants – at around DKK 0.60/kWh, the fundamental economics are against LPV plants at present.

Other main barriers against LPV deployment in Denmark are lack of information and lack of know-how on how to quantify the various added values of PV as described previously.

As outlined in section 4 and in comparison with the fast increasing number of large scale solar thermal parks (for district heating applications), there appears to be few if any institutional and permitting barriers for LPV plants.

6.3 Scenarios and recommendations

Over the last four decades the learning curve of the PV technology exhibits a cost reduction of about 20 % for every doubling of the accumulated installed volume, and there is nothing to indicate that this learning curve trend will not continue in the coming two decades. The global production volume of PV cells increased from about 13 GW in 2009 to about 27 GW in 2010 – an annual increase of more than 100 %. In 2011 the production volume is estimated to increase by 80-90 % compared to 2010.

This will lead to fast decreasing prices. The German solar industry association (BSW) has indicated, that they expect the cost of PV technology to be at least halved by 2020 compared to 2010, and the European PV industry association (EPIA) has publicized similar forecasts. If these price reductions materialize the LCOE of LPV plants in Denmark will be reduced from presently DKK ~1.0/kWh to less than DKK 0.50/kWh.

The scenario for Denmark is consequently, that with an unchanged RE-tariff of DKK 0.60/kWh LPV plants will become an attractive investment up towards 2020.

It is therefore recommended as soon as possible to create framework conditions that will allow a sufficient number and size of LPV plants to be implemented in Denmark in order to give the key market actors the necessary data and experience to face the time, when LPV plants may take off.

The key market actors in this context are seen as the developers, the municipalities and regional authorities, the transmission and distribution system operators, the financial & insurance sectors and the general public.

The necessary framework conditions can be either a temporary PV dedicated feed-in tariff or a quota system. Each approach will have its own advantages and disadvantages as discussed in detail at the recent conference on Copenhagen “Support to Renewable Energy – how?”[15]

It shall also be mentioned in conclusion, that the project “Large Scale PV – also in Denmark” has been presented at various stages of development at a number of meetings and seminars including those of the Danish Solar Cell Association (DSF) and the VE-NET PV Group, and the project approach and findings have been discussed. This has provided very valuable input and inspiration to the project.

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[15] Støtten til vedvarende energi – hvordan? Radisson Blu Royal Hotel, 31 marts 2011.

Annex 1. 50 Largest Ground Based PV Power Plants

Power	Location	Description	Constructed	MWh/GHG	Picture
97 MW	Canada, **Sarnia** (Ontario) Picture courtesy: First Solar	Sarnia PV power plant GM	2009-2010		
84.2 MW	Italy, **Montalto di Castro** (Lazio) Picture courtesy: SunRay Renewable	Montalto di Castro PV power plant GM	SunPower Corp. SunRay Renewable 2009-2010		
80.7 MW	Germany, **Finsterwalde** Picture courtesy: Q-Cells International	Solarpark Finsterwalde I,II,III GM	Q-Cells International 2009-2010		
70 MW	Italy, **Rovigo** Picture courtesy: SunEdison	Rovigo PV power plant GM	2010		
60 MW	Spain, **Olmedilla** (Castilla-La Mancha) Picture courtesy: Suravia S.A., fotografia aerea	Parque Fotovoltaico Olmedilla de Alarcón GM	2008	85 GWh	
54 MW	Germany, **Straßkirchen** Picture courtesy: Q-Cells International	Solarpark Straßkirchen GM	Q-Cells International 2009	57 GWh	
53 MW	Germany, **Turnow-Preilack** Picture courtesy: juwi	Solarpark Lieberose GM	juwi 2009		

50 MW	Spain, **Puertollano** (Castila-La Mancha) Picture courtesy: SkyFotoFactory fotografia aerea	Parque Fotovoltaico Puertollano GM	2008	
48 MW	USA, **Boulder City**, NV	Copper Mountain Solar Facility GM	2010	
46 MW	Portugal, **Moura** (Alentejo) Picture courtesy: ACCIONA Energia	Moura photovoltaic power plant GM, TRAC	ACCIONA Energia 2008	
40 MW	Germany, **Brandis** Picture courtesy: juwi	Solarpark Waldpolenz GM	juwi 2007 2008	
36 MW	Germany, **Reckahn**	Solarpark Reckahn I,II GM	2010 Reckahn II under construction	
35 MW	Czech Republic, **Veprek**	FVE Veprek GM	2010	
34.5 MW	Spain, **Trujillo** (Cáceres) Picture courtesy: Suravia S.A., fotografia aerea	Planta Solar La Magascona & La Magasquila GM, TRAC	2008	
34.4 MW	Germany, **Dörlesberg**	Solarpark Ernsthof Ost, Ernsthof West I-IV GM	2010	
34 MW	Spain, **Arnedo** (La Rioja) Picture courtesy: SkyFotoFactory fotografia aerea	Planta Solar Arnedo GM	T-Solar 2008	

31.8 MW	Spain, **Dulcinea** (Cuenca)	Planta Solar Dulcinea GM	2009		
31 MW	Germany, **Tutow** (Mecklenburg-Vorpommern) Picture courtesy: juwi	Solarpark Tutow I,II GM	juwi 2009-2010		
30 MW	Spain, **Merida** (Extremadura) Picture courtesy: Suravia S.A., fotografia aerea	Parque Solar "SPEX" Merida/Don Alvaro GM, TRAC	Deutsche Bank AG ecoEnergías del Guadiana Solarparc AG SolarWorld AG September 2008		
26 MW	France, **Gabardan**	Gabardan PV power plant GM	2010		
26 MW	Spain, **Fuente Álamo** (Murcia) Picture courtesy: Suravia S.A., fotografia aerea	Planta solar Fuente Álamo GM	2008	44 GWh	
25.7 MW	Germany, **Helmeringen** Picture courtesy: Gehrlicher Solar	Solarpark Helmeringen GM	Gehrlicher Solar 2008-2010		
25 MW	Germany, **Eiche**	Solarpark Eiche GM	to be completed soon		
25 MW	USA, **Arcadia**, FL	DeSoto Next Generation Solar Energy Center GM, TRAC	2009		
24.5 MW	Germany, **Finow**	Solarpark Finow GM	2010		
24 MW	France, **Les Mees**	Parc Solaire Les Mees GM	Solairedirect 2010		

24 MW	Korea, **Sinan** Picture courtesy: Conergy	Sinan power plant GM, TRAC	Conergy 2008	33 GWh 24,000 t CO_2	
23.4 MW	Canada, **Arnprior** (Ontario)	Arnprior PV power plant GM	2009		
23.2 MW	Spain, **Lucainena de las Torres** (Almeria) Picture courtesy: MEPGroup	Planta fotovoltaica de Lucainena de las Torres GM	MEPGroup 2008		
23.1 MW	Spain, **Abertura** (Caceres) Picture courtesy: Suravia S.A., fotografia aerea	Parque Fotovoltaico Abertura Solar GM, TRAC	2008	47.4 GWh 49,800 t CO_2	
23 MW	Spain, **Hoya de Los Vincentes**, Jumilla (Murcia)	Parque Solar Hoya de Los Vincentes, Jumilla GM, TRAC	2008	41.6 GWh 42,000 t CO_2	
22.068 MW	Spain, **Almaraz** (Caceres) Picture courtesy: Suravia S.A., fotografia aerea	Huerta Solar Almaraz GM, TRAC	2008		
22 MW	Germany, **Pocking** Picture courtesy: Martin Bucher Projekt-entwicklungen	Solarpark Pocking I,II GM	Martin Bucher Projektentwicklungen Pocking I 2006 Pocking II 2009		
21.78 MW	Germany, **Mengkofen**	Solarpark Mengkofen GM SolarWorld modules	Solarparc AG 2009		

21.47 MW	Spain, **El Coronil** (Andalucia) Picture courtesy: Suravia S.A., fotografia aerea	Parque Solar Parque solar El Coronil I + II GM, TRAC	2008	40 GWh	
21.2 MW	Spain, **Calavéron** Picture courtesy: Suravia S.A., fotografia aerea	Solarpark Calavéron GM, TRAC	EPURON 2008	40 GWh	
21 MW	USA, **Blythe**, CA	Solar electric power plant, Blythe GM	2009		
20 MW	China, **Sheyang** (Jiangsu)	Sheyang PV power plant GM	2010		
20 MW	China, **Xuzhou City** (Jiangsu) Picture courtesy: GPL-Poly Energy Holdings	Jiming Hill, Xuzhou City PV power plant GM	2010		
20 MW	Germany, **Rothenburg** (Sachsen) Picture courtesy: Gehrlicher Solar	Solarpark Rothenburg GM	Gehrlicher Solar 2009		
20 MW	Korea, **Seoul** Picture courtesy: Siemens	Seoul power plant GM	2009		
20 MW	Spain, **Granadilla de Abona** (Canary Islands)	Parque Fotovoltaico SOLTEN I+II, Granadillas Industrial Estate GM	2008		

20 MW	Spain, **Calasparra** (Murcia) Picture courtesy: Suravia S.A., fotografia aerea	Planta solar fotovoltaico Calasparra GM	2008		
20 MW	Spain, **Beneixama** (Alicante) Picture courtesy/photo: City Solar Accener S.L.	Solarpark Beneixama GM 200 x 100 kW Sinvert Master inverters	City Solar AG Accener S.L. 2007	30 GWh 30,000 t CO_2	
20 MW	Spain, **El Bonillo** (Albacete)	Parque Solar El Bonillo GM	2008		
18 MW	Germany, **Senftenberg** (Brandenburg) Picture courtesy: Phoenix Solar AEE AG	Solarpark Senftenberg GM	Phoenix Solar AEE AG 2010		
18 MW	Germany, **Thüngen**	Solarpark Thüngen GM	2010		
18 MW	Spain, **Olivenza** (Badajoz) Picture courtesy: Suravia S.A.	Parque Solar Olivenza GM, TRAC	2008		
18 MW	Spain, **Las Gabias** (Granada)	Huerta Solar Las Gabias GM, TRAC	2008		
16 MW	USA, **San Antonio**, TX Picture courtesy: juwi	Blue Wing solar electric power plant GM	juwi 2009		

Annex 2. 50 Largest PV Power Plants Roof Mounted

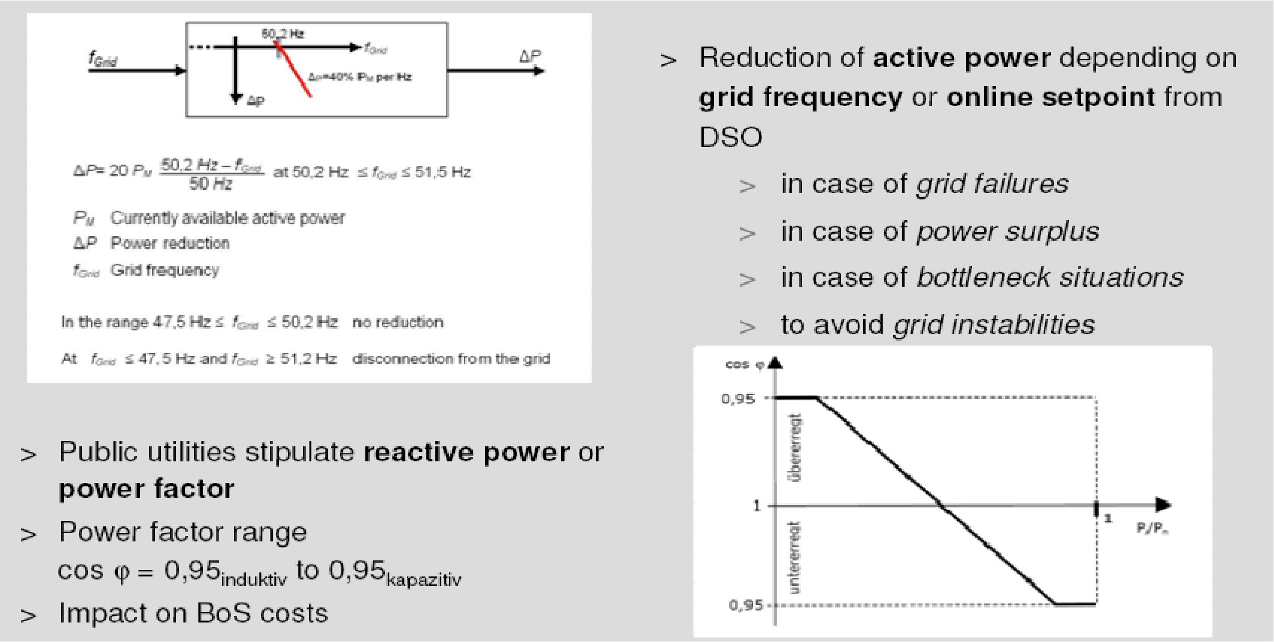
Power	Location	Description	Constructed	MWh/GHG	Picture
11.8 MW	Spain, **Zaragoza** Picture courtesy: United Solar Ovonic LLC	GM facility RM	Veolia Environnement Clearvoyant Energy September 2008	15.1 GWh	
9.1 MW	France, **Perpignan**	St.Charles International RM	2010		
5.21 MW	Japan, **Kameyama**	Sharp plant, Kameyama BIPV, DIST, TRANS	2006	3,400 t CO_2	
5.2 MW	Spain, **Castala** (Valencia)	Actiu Technological Park RM	2008		
5 MW	Germany, **Bürstadt** Picture courtesy: TAUBER-SOLAR	Bürstadt PV power plant RM	TAUBER-SOLAR activ solar Ralos May 2005	4.5 GWh 3,200 t CO_2	
4.7 MW	Italy, **Serravale Scrivia** (Piemont)	KME Group RM	ErgyCapital 2009		
4.64 MW	Germany, **Hassleben** (Brandenburg) Picture courtesy: Colexon	Hassleben feedstock farm, roof mounted system RM	Colexon December 2008		
4.64 MW	Germany, **Rain am Lech** (Bayern) Picture courtesy: S.A.G. Solarstrom	Dehner Gartencenter RM	2009		
4.2 MW	Belgium, **Sint-Baafs- Vijve**	Balta facility RM	2010		

3.839 MW	Germany, **Muggensturm**, Rastatt Picture courtesy: TAUBER-SOLAR	Co. Hartmann Logistik in Muggensturm along A5 motorway Exit "Rastatt" RM	TAUBER-SOLAR December 2006	3,700 MWh 2,600 t CO_2	
3.8 MW	Germany, **Stuttgart**	Fair Stuttgart RM	Greenpeace Energy IBC SOLAR 2009		
3.7 MW	Germany, **Kronwieden**, Dingolfing Picture courtesy: Deutsche BP	Fischer's family warehouse RM .	BP Solar October 2005	3,600 MWh 2,500 t CO_2	
3.5 MW	Germany, **Homburg**(Saarland) Picture copyright: Michelin	Michelin Reifenwerke KGaA RM, BIPV, part of 9 MW Michelin Solarpark Part of Solar Return Fund I and II	EPURON SunTechnics Michelin Reifenwerke KGaA 2,6 MWp December 2004 expanded to 3,5 MWp in June 2005	5,000 t GHG	
3.36 MW	Spain, **Barcelona**	Barcelona Fair, roof mounted system pavilions 1,2,3,4,6,8 RM	Fira 2000 2008		
3.3 MW	Germany, **Wolfsburg** Picture courtesy: S.A.G. Solarstrom	VW facility PV plant RM 6228 modules	S.A.G. Solarstrom 2008		
3.26 MW	Germany, **Dingolfing** Picture courtesy: Goldbeck Solar GmbH	Co.Mückenhausen RM, BIPV, some FM and CONC modules used roof mounted plant 18736 Solara, Sharp and Kyocera (facade) modules used 11 SMA inverters.	Goldbeck Solar October 2004	3,050 MWh	
3.12 MW	China,	Shanghai World Expo 2010	2010		

	Shanghai	RM			
3.04 MW	Germany, **Waldeck** Picture courtesy: Colexon	Geflügelhof Waldeck RM	Colexon 2008	2,800 MWh 2,650 t CO_2	
3 MW	China, **Yangcheng**	Roof mounted PV power plant Yangcheng City RM	2010		
3 MW	Spain, **Madrid** Picture courtesy: Suravia S.A.	Telefónica Madrid RM	2006	3,600 MWh 1,600 tons CO_2	
3 MW	Germany, **Biberach/Riß**	Liebherr corp. RM Part 1: Constructed by City Solar AG 6690 modules Part 2: Würth-Solar	City Solar Würth-Solar September 2005	2,838 MWh 2,200 t CO_2	
2.975 MW	Belgium, **Waregem**	Roof mounted PV power plant RM	2009		
2.906 MW	Italy, **Prato**, PR	Coop Prato RM	2009		
2.8 MW	Italy, **Pontenure**, PI	Upim, roof mounted PV power plant RM	Ecostream 2009		
2.786 MW	Spain, **Abrera** (Catalonia)	Planta Solar Planta Solar Aigües Ter Llobregat RM	2009		

Annex 3. New grid codes – new requirements for LPV inverters.

Static requirements:



$$\Delta P = 20\, P_M \frac{50{,}2\ Hz - f_{Grid}}{50\ Hz} \quad \text{at } 50{,}2\ \text{Hz} \le f_{Grid} \le 51{,}5\ \text{Hz}$$

P_M Currently available active power
ΔP Power reduction
f_{Grid} Grid frequency

In the range 47,5 Hz ≤ f_{Grid} ≤ 50,2 Hz no reduction

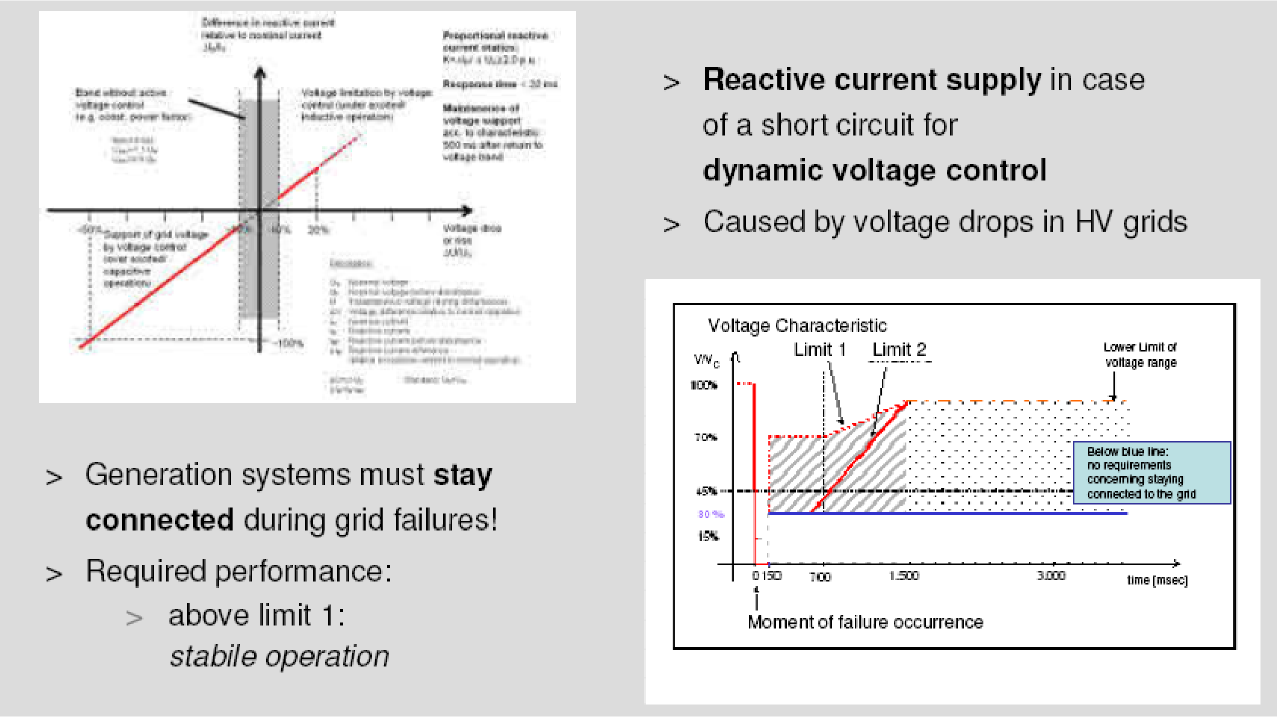
At f_{Grid} ≤ 47,5 Hz and f_{Grid} ≥ 51,2 Hz disconnection from the grid

> Reduction of **active power** depending on **grid frequency** or **online setpoint** from DSO
  > in case of *grid failures*
  > in case of *power surplus*
  > in case of *bottleneck situations*
  > to avoid *grid instabilities*

> Public utilities stipulate **reactive power** or **power factor**
> Power factor range
cos φ = $0{,}95_{\text{induktiv}}$ to $0{,}95_{\text{kapazitiv}}$
> Impact on BoS costs

Origin: Erzeugungsanlagen am Mittelspannungsnetz. BDEW, Release June 2008

Dynamic requirements:



> **Reactive current supply** in case of a short circuit for **dynamic voltage control**
> Caused by voltage drops in HV grids

> Generation systems must **stay connected** during grid failures!
> Required performance:
  > above limit 1:
  stabile operation

Origin: Erzeugungsanlagen am Mittelspannungsnetz. BDEW, Release June 2008