

SOLAR ENERGY TECHNOLOGY PRIMER: A SUMMARY

BACKGROUND

Solar energy is an important energy source for Singapore, but its potential is limited since Singapore is a highly urbanized, densely populated island state. Solar photovoltaic (PV) panels harness the sun's energy, turning it into electricity, while emitting no greenhouse gases such as carbon dioxide during operation.

Photovoltaics ("PV") is the direct conversion of solar energy into electrical energy using devices called a solar cells. Most modern solar cells use semiconductor materials, whereby silicon wafer based technologies dominate today's market. Sunlight can be considered as a flux of particles called photons, whereas an electric current is a flux of electrons. In essence, solar cells convert the energy of a photon flux into electric energy, whereby each incoming photon with sufficient energy leads to an energetically excited electron that can deliver energy to an external load. To have a high PV efficiency, a solar cell must: (i) absorb the incoming solar photons in an optimal way; and (ii) efficiently separate the light-generated electrical charge carriers, so that negative charge builds up at one surface of the cell and positive charge at the opposite surface. Charge carrier separation is usually realised using a so-called p-n junction. *Figure 1* shows a schematic representation of a solar cell.

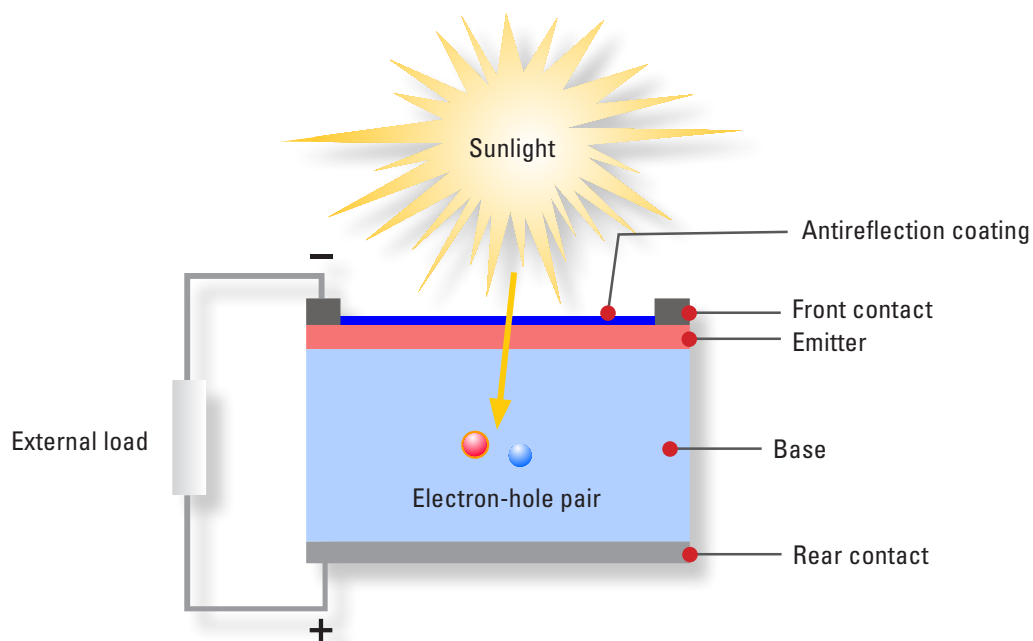


Figure 1: Schematic representation of a solar cell. Today's standard solar cells have a thickness of less than 0.2 mm and an area of 15 x 15 cm².

POTENTIAL OF PV ELECTRICITY GENERATION IN SINGAPORE

The potential of PV electricity generation in Singapore depends primarily on the availability of space and on the energy yield of the PV systems. The capability of the grid to integrate fluctuating solar electricity is critical if large amounts of solar electricity are to be delivered into the electricity supply system.

The current annual electricity demand in Singapore is 42 TWh¹ (see *Figure 2*). The scale of the total installed solar PV capacity in Singapore is currently about 4 MWp² for both residential and non-residential installations. 4 MWp generate approximately 4.8 GWh electric energy per annum or a little more than 1/10,000 of today's electricity demand.

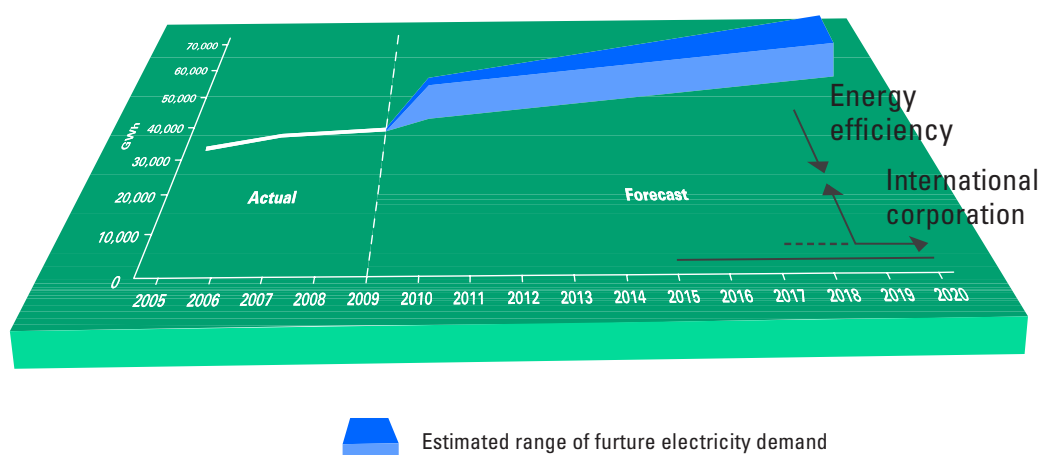


Figure 2: Total electricity demand trends and solar electricity generation potential for Singapore. Upper curves: forecast based on GDP and population projections.¹ This projection does not take into account possible changes in Singapore's economic structure and due to energy efficiency measures. Solid black horizontal line: mid-term potential of solar electricity generation in Singapore and (dashed black horizontal line) long term-potential. Energy efficiency measures can reduce the energy demand of Singapore significantly. International cooperation on solar energy harvesting in neighbouring countries can increase the amount of solar-derived energy to be used in countries such as Singapore and the region by a considerable extent.

Not taking into account the restrictions of today's grid,³ the potential of PV electricity generation in Singapore is assessed to be approximately 14 TWh per year (long-term potential). This amount of solar electricity can of course only be harvested after a sufficient transition period. The mid-term potential of solar electricity generation in Singapore is assessed to be about 7 TWh/year. (See *Figure 2*)

¹ Statement of Opportunities, EMA (2010).

² MWp or Megawatts-peak is a measure of power output, used in relation to solar PV panels. A 1 MWp solar PV system will produce 1 MW electricity under ideal conditions.

³ Opening remarks by CE/EMA at the Solar Awards Ceremony on 30 Nov 2010. "350 MWp is the estimated limit that our current grid can integrate while maintaining power quality and reliability, without an upgrade of the existing infrastructure."

The integration of such a large amount of fluctuating electric energy into Singapore's electricity grid constitutes a significant technological challenge as well as considerable investments. Essential characteristics for an appropriate grid structure include: (i) control of peak generation of PV installations ("peak shaving"), (ii) leveling out of very fast fluctuations in solar electricity through efficient electricity transport within Singapore, (iii) fast control of complementary fossil fuel power plants, (iv) extensive load management (including strategic extension of switchable loads), (v) installation and activation of storage systems (e.g. e-mobility), and (vi) forecast of solar energy generation. It is noted that gas turbines as used in Singapore have low thermal inertia and are highly responsive. They can thus follow the time pattern of the lumped solar electricity generation in a complementary way.

Figure 3 compares the load pattern of a typical week-day in January 2011, the daily PV electricity production for a capacity of 350 MWp and the production of a PV installation of 5.6 GWp.⁴ The theoretical estimate of 5.6 GWp of solar capacity is based on utilisable PV deployment area of 40 square kilometres,⁵ an area factor of 0.14 kWp per square metre, and a yield factor of 1300 kWh per kWp by the authors. The PV potentials given are based on an assessment and not on a careful scientific analysis. In reality the potentials may turn out to be lower or higher.

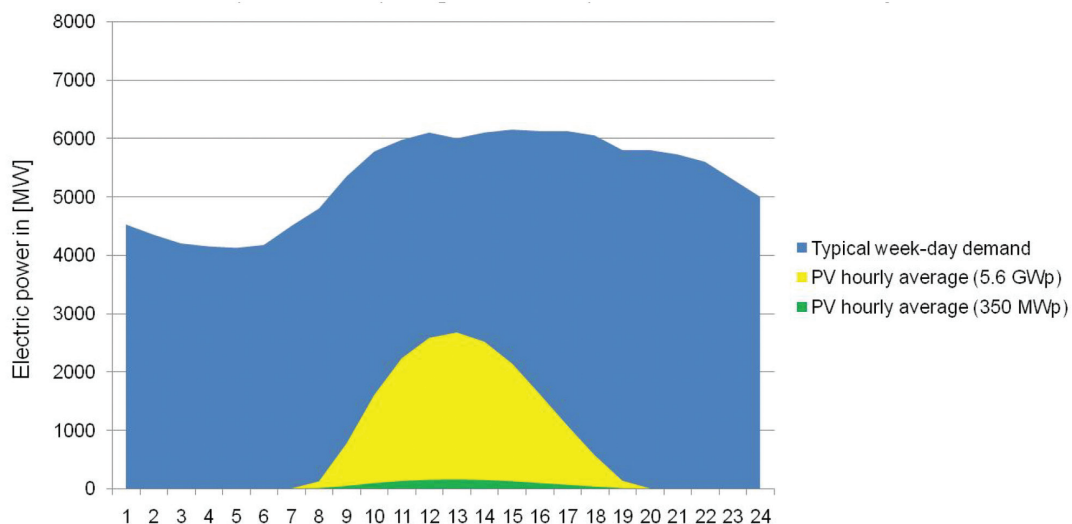


Figure 3: Electricity load profile (demand) of Singapore on a typical week-day in January 2011 (in blue)⁶ and solar PV generation on the same typical day (see Figure A1 and A2 in Appendix A) as hourly averages for 2 installed capacities: 5,600 MWp (yellow area) and 350 MWp (green area)

⁴ No detailed official study on the PV potential of Singapore was available to the authors of this solar technology primer. However, the authors estimate the potential to be higher than the projected grid limit of 350 MWp. 5.6 GWp will generate approximately 7 TWh per year as mentioned above.

⁵ This includes PV on: 48% of the HDB rooftop space, 65% of other commercial building rooftop space, and also 20% of ground-mounted PV around the islets, and 25% of inland waters to be covered with floating PV.

⁶ Adapted from information in the Energy for Growth: National Energy Policy Report, MTI (November 2007). <http://app.mti.gov.sg/data/pages/2546/doc/NEPR.pdf>

OUTPUT FROM PV SYSTEMS IN SINGAPORE

Output from PV systems will be greatest during periods of highest demand (see *Figure 3*).

Sharp peaks in solar electricity generation in Singapore usually occur only for very short periods of time. Although they can go up to 120% of the rated PV capacity due to irradiances higher than the value of 1,000 W/m² that is commonly used for standardization, the actual energy generated during those times is relatively small. Thus solar electricity generation is suitable for “peak shaving”⁷ (see *Figure A1 in Appendix A*). This helps to avoid critical situations in the power grid.

Short term fluctuations in solar electricity supply level out if a high number of spatially dispersed solar electricity generators are interconnected (see *Figure A2 in Appendix A*). This helps to reduce the need of fast complementary operation of peaking power plants⁸ and lowers the overall emission of power generation.

POTENTIAL STORAGE POSSIBILITIES

As an alternative to the peak shaving, any energy generated by PV – be it excess or temporarily unused – can also be stored to avoid local over-voltages or grid instabilities. Electricity storage at the MWh level offers numerous advantages. Such storage is not generally viable at present, but the development of such a technology would result in a significant commercial opportunity. Among the advantages that storage would offer are:

- **Load smoothing.** PV electricity will fluctuate with varying insolation⁹ – clouds and particulates in the atmosphere will affect generation in a stochastic manner. These fluctuations will create problems for grid management unless addressed in a fundamental way.
- **Electricity arbitrage.** In cases where electricity is subject to short term price variations, storage offers the prospect of moderating price excursions, and indeed of profiting from them.
- **Integration into “smart grids”.** Through the merging of IT technologies and power systems, intelligent load management will be possible, both on individual building level, as well as on local grid level.

REGIONAL ELECTRICITY GENERATION

The contribution of PV electricity to Singapore’s electricity supply could be much larger if non-island solutions are considered such as regional electricity generation and distribution. Such schemes would also facilitate grid integration of fluctuating renewables generation. If Singapore can successfully implement a trans-national grid connection with ASEAN, this would also ease the intermittency and raise the threshold of PV electricity which can be incorporated.

⁷ Peak shaving of PV electricity can be applied via smart controls which cut off the production at the intended threshold even though the total installed PV base is higher than the threshold.

⁸ Peaking power plants are plants fired up during periods of peak demand, and may use more expensive (and less clean) electricity sources. The cost of fossil fuel generation is the highest in the day, and coincides with peak PV power generation.

⁹ Insolation is a measure of solar radiation energy received on a given surface area in a given time.

GRID PARITY AND COST PARITY OF SOLAR PV IN SINGAPORE

Over the past decade, the capital cost of PV in Singapore and other countries have fallen dramatically (see *Figure 4*), while fossil fuel energy costs continue to rise. Grid parity has already occurred in some international markets, and can be expected in Singapore. *It is very likely that grid parity¹⁰ in Singapore is expected to be achieved between 2014 and 2016, and cost parity¹¹ to be achieved by 2020. The assumptions are: (i) the existence of turn-key system prices of mass markets outside Singapore; (ii) the cost of turnkey PV installations will be reduced by 7% to 13% per year; (iii) electricity prices will increase by 0% to 5% per year; and (iv) capital costs are 5% per year.*

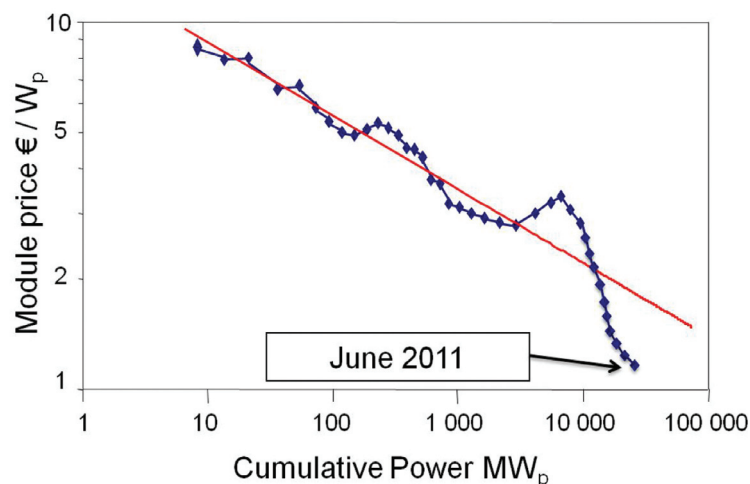


Figure 4: Price experience curve (learning curve) for silicon wafer based photovoltaic modules. World market prices are shown as a function of the global cumulative shipment (logarithmic scales). The red line represents price reductions according to a learning factor of 0.8, i.e. a price reduction by 20% for each doubling of the shipment. The strong reduction of prices is due to: (i) economy of scale; (ii) optimisation of production in industry; (iii) reduced company margins in the course of the economic crises and (iv) a multitude of highly essential innovations from R&D.

BALANCE-OF-SYSTEM (BOS) COMPONENTS AND PV SYSTEMS

A photovoltaic (PV) system consists of multiple components, including array of PV modules, mechanical and electrical connections and mountings, and means of regulating and/or modifying the electrical output. The electricity generated can be either stored, used directly (island/standalone plant) or fed into a large electricity grid (grid-connected/grid-tied plant) or combined with one or many domestic electricity generators to feed into a small grid (hybrid systems).¹²

¹⁰ Grid parity: Grid parity is the point where the cost of renewable electricity generation is equal to or cheaper than retail electricity prices.

¹¹ Cost parity: Parity with the cost of traditional electricity generation (e.g. from fossil fuels). The cost of grid operation is included.

¹² Website of Florida Solar Energy Centre: (accessed 26 February 2011) http://www.fsec.ucf.edu/en/consumer/solar_electricity/basics/types_of_pv.htm

GRID CONNECTED SYSTEMS

Grid-connected or utility-interactive PV systems are designed to operate in parallel with and interconnected with the electric utility grid (see *Figure 5*). The primary component in grid-connected PV systems is the inverter, or power conditioning unit (PCU). The PCU converts the DC power produced by the PV array into AC power consistent with the voltage and power quality requirements of the utility grid, and automatically stops supplying power to the grid when the utility grid is not energised. A bi-directional interface is made between the PV system AC output circuits and the electric utility network, typically at an on-site distribution panel or service entrance. This allows the AC power produced by the PV system to either supply on-site electrical loads or to back-feed the grid when the PV system output is greater than the on-site load demand. Frequently feed-in tariff schemes or net metering¹³ are applied for interfacing the PV system with the utility. These schemes are introduced in order to support the deployment of PV electricity generation during a ramp-up phase.

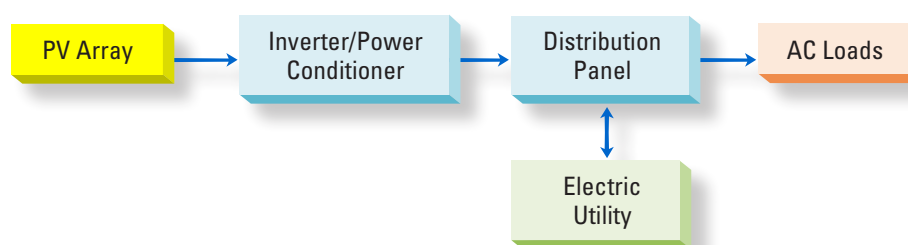


Figure 5: Diagram of a typical grid-connected photovoltaic system

STAND ALONE PV SYSTEMS (OFF-GRID APPLICATIONS)

Stand-alone PV systems are designed to operate independent of the electric utility grid, and are generally designed and sized to supply certain DC (direct current) and/or AC (alternating current) electrical loads. In many stand-alone PV systems (see *Figure 6*), batteries are used for energy storage as the power requirement can then be met at times when sunlight is not available. As most appliances run on AC, an inverter is often used in the system to convert the DC power output generated from the PV modules array to AC. A charge controller may be incorporated in the system in order to avoid battery damage by excessive charging or discharging and for optimizing the production of the cells or modules.

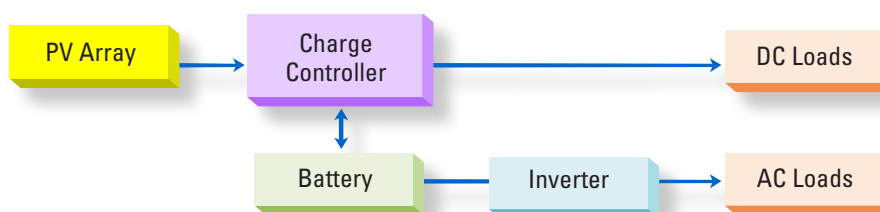


Figure 6: Diagram of a typical stand-alone photovoltaic system

¹³ Under the net metering scheme generally most of the solar electricity is consumed in the building where the PV system is installed (e.g. high rise buildings). The electricity meter runs in both directions counting supplied and feed-in electricity at the same price. This scheme supports PV electricity since the cost for providing the grid and its service is not taken into account. A net metering scheme in this sense is not in place in Singapore.

In some applications, a hybrid system combines PV with other forms of generation, usually a diesel generator or possibly other renewable energy generator such as wind turbines. Hybrid systems have the inherent advantage of redundancy and complementarity in energy generation. Thus higher supply security can be achieved at lower battery capacities

Apart from the basic components of the PV systems as described above there are also other important components in the system that makes it robust and reliable. PV modules are assembled into arrays on some kind of a mounting system, which could be racks, bins or some other building integrated solutions. A solar tracker can substantially improve the amount of power produced by a system by enhancing morning and afternoon performance. It is in particular employed for concentrated PV systems. It is also important to incorporate a performance monitoring system in order to track the health of the system components and take necessary control and maintenance actions, as and when required.

STANDARDS, QUALITY ASSURANCE, SAFETY

Given the rapidly growing number of suppliers for both solar modules and system components, it is absolutely crucial to ensure quality and reliability of products and systems. Since solar PV installations are expected to last for 25-30 years almost without degradation, and often get financed with tenures of up to 20 years, these standards of quality assurance and safety are ever increasingly important. While there are established certifying bodies in the USA (by UL, Underwriters Laboratory) and Japan (by JET, Japan Electrical Testing Laboratories) on a worldwide level, the most recognized standards are those defined by International Electrotechnical Commission (IEC) based in Switzerland.

Historically, all standards (IEC, UL, JET) have been developed in moderate climate zones where – still today – the majority of the installations are located. In harsher climate zones such as the tropics with constant high temperatures and high humidity, the existing standard tests may prove not to be sufficient – especially when taking into account that modern inverters operate with voltages of up to 1,000VDC. *Therefore additional, tightened component testing for tropical climates would be required benefitting both, the end-user (to have peace-of-mind) and the manufacturers (to substantiate the 25-year warranty for the tropics).*

AREAS OF R&D FOR SINGAPORE

Apart from PV, a variety of commercial solar technologies exist, some of which are suited for Singapore's climatic conditions. These are given in the *Appendix B*.

Within solar PV technologies, there are differentiations based on the materials used for energy harvesting. Today's market leading PV technologies on land are based on silicon wafers ("crystalline Si PV", market share > 80%) and on thin-film cells made from the semiconductor materials amorphous silicon (a-Si) and cadmium telluride (CdTe). Other upcoming thin film technologies are micromorph silicon (m-Si) and copper indium gallium selenide

(CIGS) films. Singapore has built-up capabilities with research ongoing in the investigation of energy harvesting performance of various materials used in solar panels.

However, to realise the full potential of solar PV, application-oriented R&D should be focused on further cost reduction in PV electricity generations, and the analysis and design of an appropriate grid structures (smart grids). Optical concentrating technologies such as Concentrating Solar Photovoltaics (CSP) are not suitable for application in Singapore¹⁴ but may be considered for manufacture.

Low cost PV module technologies have lower energy conversion efficiency values due to higher area-related costs arising from the need for larger space, extended support structures and cabling. For city states such as Singapore whereby land is a constraint, PV module technologies with low energy conversion efficiency are not therefore suitable. The authors recommend that Singapore's R&D efforts targeted at PV applications in Singapore could focus on high efficiency low cost PV cells and modules.

In understanding Singapore's PV needs, detailed mapping of the solar potential in Singapore, in terms of assessment of rooftop space and better data collection of PV site real-time monitoring data is necessary for accurate modeling to be done. The instantaneous AC active power in kW (measured at PV's inverter output), with solar irradiance and ambient temperature at the PV site, at a sampling rate of at least 1 minute has to be collected. This data would help advance our knowledge of the conditions faced in Singapore, which our PV have to operate under.

There are also environmental concerns when manufacturing and implementing this technology. *Looking through solar module life-cycle – (i) fabrication, (ii) installation, (iii) recycling, and (iv) materials; conscious choices needed to be made at each phase of solar module development.* Singapore should remain aware of these needs as it seeks to develop capabilities in solar panels.

Apart from PV, the solar irradiance in Singapore is sufficient for solar water heaters to be efficiently deployed. *However, due to the large number of high-rise buildings, rooftop installations cannot provide sufficient water for all domestic dwellers. Installations in commercial settings such as food-courts and other industrial areas where hot water is required, on the other hand, would be good opportunities for solar water heaters.* Solar assisted air-conditioning systems would also potentially be beneficial applications for Singapore.

¹⁴ In the Singapore context, diffused irradiation due to mostly cloudy conditions and non-availability of large open land limit the potential of any sizeable CSP plant implementation.

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ELECTRICITY LOAD PROFILES SHOWING INTERMITTENCY OF
INDIVIDUAL AND AGGREGATED PV MODULES

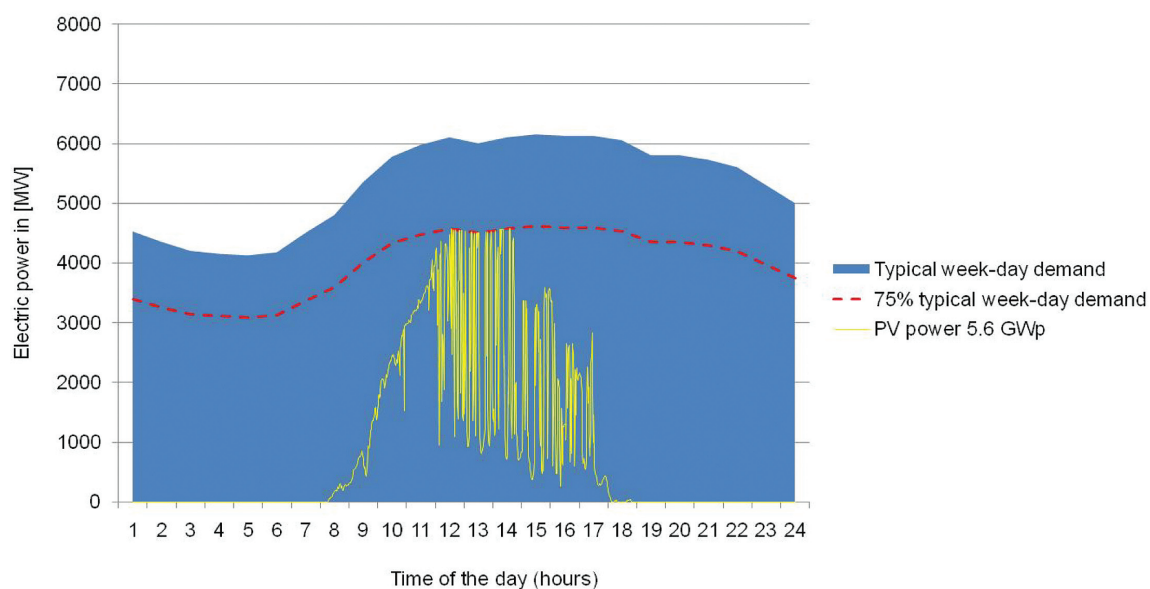


Figure A1: Electricity load profile (demand) of Singapore on a typical week-day in January 2011 (in blue) and solar PV generation as 1-min values for an installed capacity of 5,600 MWp (yellow line), capped at 75% of total demand, effectively foregoing the energy generated during the peaks above 75%. The integral over time of the area above 75 % is less than 2% of the total annual energy generated. This is referred to as “peak shaving”.

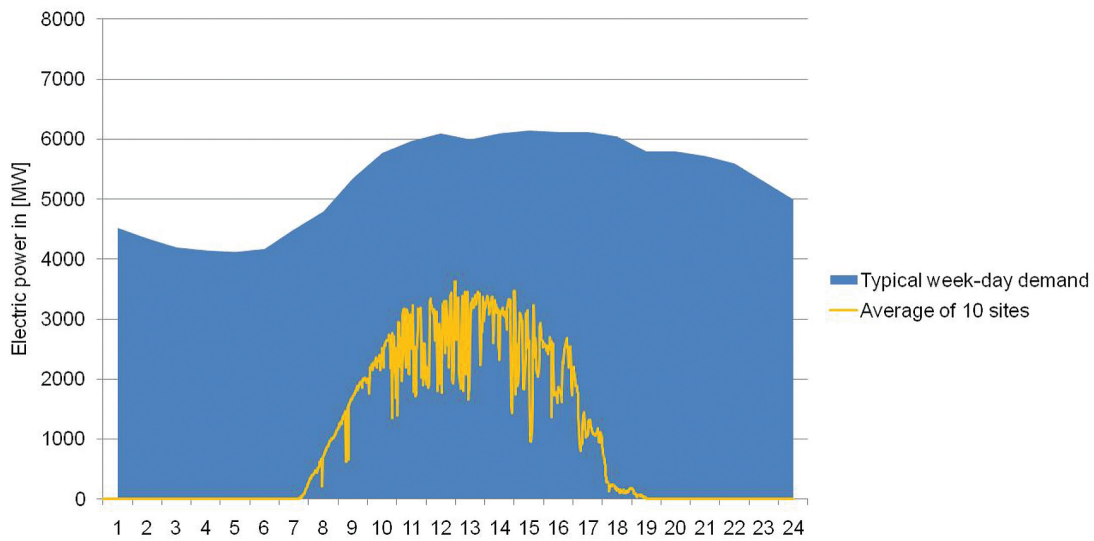


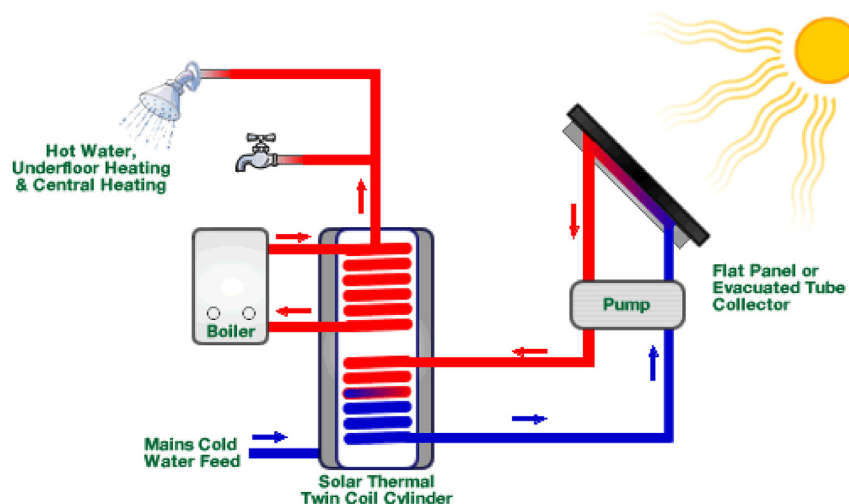
Figure A2: Lumped electricity output of 10 hypothetical photovoltaic power plants installed across Singapore. The lumped installed photovoltaic capacity is 5,600 MWp as in Figure A1. One minute synchronised values of measured meteorological data (same date as in Figure A1) were used to simulate the lumped power output.¹⁵ It may be seen that the fluctuations are levelled out considerably and that (following the assumption in the legend of Figure A1), no peak shaving is necessary. The effect of levelling out of fluctuations will increase considerably if more than 10 PV installations are considered.

¹⁵ Meteorological data measured by SERIS. Data with time resolution better than 10 seconds will be available at SERIS by the end of 2011.

SOLAR HEATING TECHNOLOGIES SUITED TO SINGAPORE'S CLIMATE

Solar water heaters

Typically, a solar water heater consists of the solar collector(s), a tank to store hot water and insulated piping. (See *Figure B1*) For larger systems, an electric pump along with electronic controls is also required. Flat-plate solar collectors have an absorber plate that are made of copper, steel or plastic and coated with spectrally selective high high-absorbance coatings. Other collectors such as evacuated-tube collectors are also used for water heaters depending on their applications. Solar water heating systems represent one of the most popular applications of solar thermal energy due to their simple design and low costs.



*Figure B1: Schematic of a Solar Thermal domestic hot water system.*¹⁶

Combined PV-Thermal (PVT) collectors

A PVT system is by definition a 'combination' system which produces both electricity and heat from one integrated system using the same surface area. The main benefit of such a system is that it can significantly increase the energy production of a traditional PV system by augmenting it with thermal collectors. It also allows the PV component to operate at its peak electrical output and mitigates the degradation of PV cells due to overheating. And because the two types of energy are produced from one surface area, it also solves the growing problem of competing roof space. One such system was installed at the 2009 Beijing Olympic Village and this concept is recently gaining popularity. The inherent constraints of the system are integration of mechanical heating/cooling system and optimal heat transfer between PV and the collector liquid without compromising electrical insulation. They also tend to be bulky and costlier compared to PV modules.

¹⁶ Save Energy UK Limited website available at: (Accessed 1st March 2011.)
http://www.saveenergyuk.com/solar_thermal_water_heating.htm