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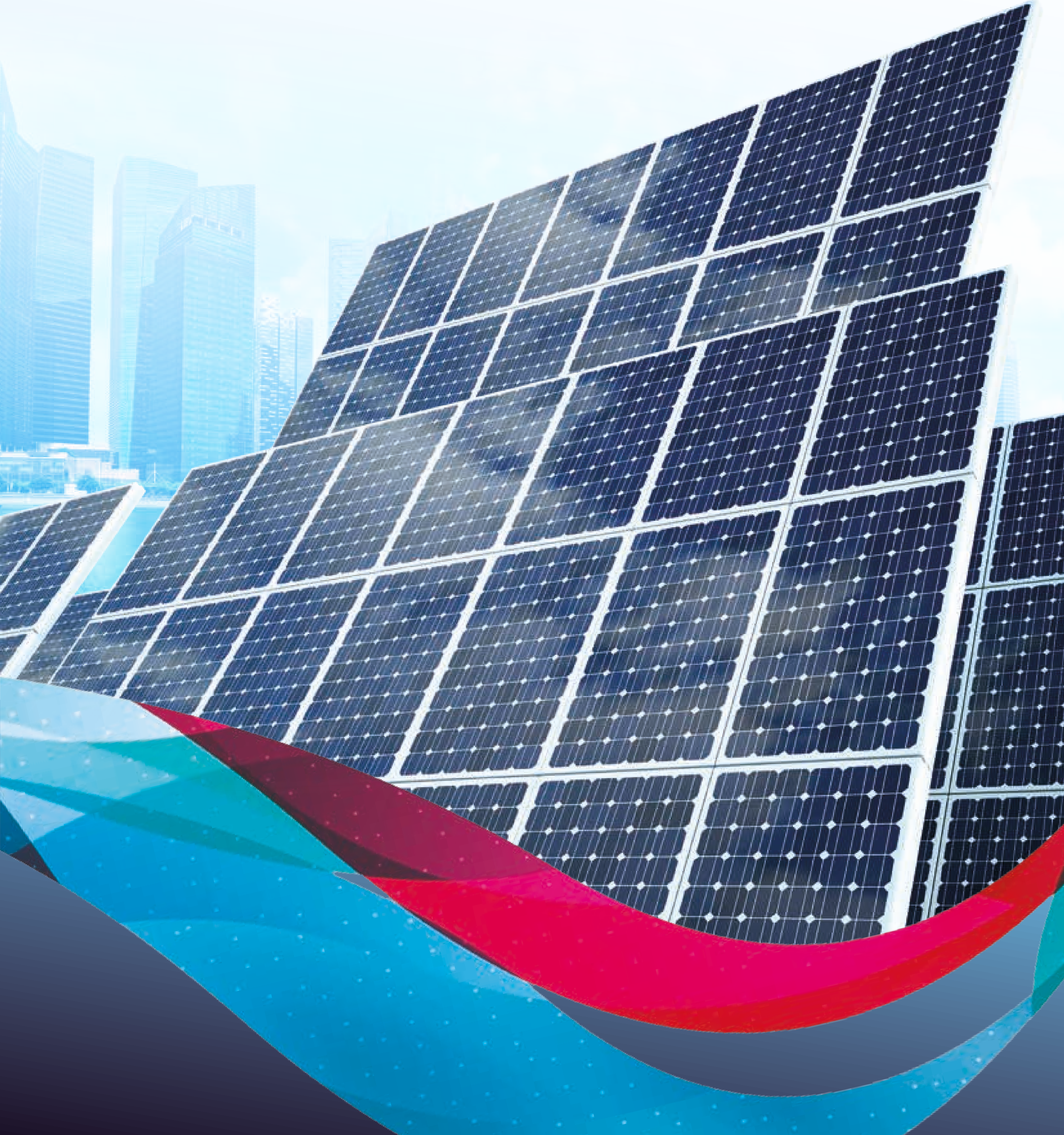
PHOTOVOLTAIC (PV) Roadmap for Singapore (A Summary)



Solar Photovoltaic (PV) Roadmap for Singapore (A Summary)

Prepared for

Singapore Economic Development Board (EDB) and

Energy Market Authority (EMA)

by

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The information given in this roadmap are mainly based on data available in June 2013.

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EXECUTIVE SUMMARY

Roadmaps are designed to help to meet specific goals. The goals of the roadmap at hand are aligned with Singapore's energy policy in terms of increasing the sustainability of Singapore's energy supply system and meeting the following objectives:

- Cost effective electricity supply
- Increased security of energy supply
- Ecological sustainability

Scenarios are helpful tools in formulating concrete goals that will lead to the realisation of such future-compliant energy systems. The advantage of the scenario approach is that a variety of approaches can be analysed. From these, policy-makers and government bodies may choose goals that are consistent with their overall political strategy.

Based on two scenarios and assessments of the energy supply system in 2050, the PV roadmap for Singapore presents paths into the future of Singapore's energy supply; it displays in particular different maps leading to different (increased) contributions of solar electricity to Singapore's electricity supply.

Solar power can contribute considerably to a sustainable electricity supply of Singapore and to a reduction of CO_2 emissions in Singapore.

The development of photovoltaic scenarios for Singapore is most importantly influenced by:

- Availability of space for PV installations
- Technological advancements leading to cost reduction of PV electricity
- Reliable integration of the variable solar power generation into the electric grid

Different assumptions on these parameters will result in different scenarios. Thus a plethora of scenarios and roadmaps are conceivable. The authors hope that the scenarios chosen will be suggestive of possible pathways towards a future-compliant electricity supply of Singapore[1]:

Baseline scenario (BAS):

- An effective area of 27 km^2 is used for PV installation in Singapore (partial use of the available space in Singapore) [2]
- An evolutionary growth in PV area efficiency and yield is assumed, in-line with global technological developments

[1] On the basis of such scenarios, precise goal setting can be done in an iterative process between policy makers, government bodies and experts working on scenarios.
[2] The relevant agencies have been part of the stakeholder involvement of the PV roadmap and participated in two workshops held. The detailed area data have not been endorsed by the various agencies.

- PV electricity costs are calculated according to a moderate reduction in cost.

Accelerated scenario (ACC):

- Full utilisation of the effective area that is available for PV installations in Singapore (45 km^2) [2]
- An accelerated growth in PV area efficiency and yield (through enhanced R&D) is assumed, in-line with global technological developments
- PV electricity costs are calculated according to an accelerated reduction in cost

Assessment of the future energy supply system in 2050:

The BAS and ACC scenarios would lead to a gradual, but incremental addition of solar PV to the current electricity supply system with a penetration of annual solar energy in the order of 20% by 2050 (see also Table A3 later). To address the issue of what would be required to substantially go beyond that level, a third possibility with more disruptive changes was evaluated. It requires fundamental changes to Singapore's energy supply system by 2050 and is therefore referred to as a "paradigm shift". Despite uncertainties for technological developments over ~35 years, this could result in the solar contribution to Singapore's electricity supply in 2050 being higher than in the ACC scenario. This, however, would require alternative deployment strategies as outlined in section 4.2.2, which includes off-shore floating PV systems and importing solar power through a future SE-Asian or even Pan-Asian power grid. For this "paradigm shift" to be possible, deliberate decisions would need to be made, carefully weighing geopolitical considerations, competing use of space and transmission requirements.

The two quantifiable scenarios will lead to annual PV electricity generation as shown in Table A1 and associated CO_2 emission reductions as shown in Table A2 (assuming 2012's grid emission factor[1]).

Table A1: Potential annual electricity generation from PV in TWh[2] under the BAS and ACC scenarios.

Year	2012	2020	2030	2050
BAS	0.01	0.8	4	7
ACC	0.01	1.2	6	15

Table A2: Potential annual CO_2 emission reductions in Megatons CO_2 per year under the BAS and ACC scenarios.

Year	2012	2020	2030	2050
BAS	0.007	0.40	2.0	3.5
ACC	0.007	0.60	3.0	7.5

[1] 0.50 kg CO_2/kWh [EMA6].

[2] As reference: the 2012 electricity demand of Singapore, measured by overall electricity sales, was 42.6 TWh [EMA].

The values given in Table A1 can be compared with scenarios assessing the future electricity demand of Singapore in 2050 in order to calculate the contribution of PV electricity, relative to Singapore's electricity demand. Three largely different scenarios are considered here:

- E 1: Energy demand growing at a constant rate of 2.5% p.a., proportional to expected long-term average GDP growth (110 TWh by 2050)
- E 2: Energy consumption under additional energy efficiency measures (80 TWh)
- E 3: Energy demand following strong energy efficiency efforts (50 TWh)[4]

The derived relative contribution of PV electricity to Singapore's electricity demand in 2050 for the different combinations of scenarios (energy demand and PV deployment) can be seen in Table A3.

The PV roadmap for Singapore has been designed in a way that it is in line with the scenarios characterised above.

Table A3: Potential relative contribution of PV electricity to the electricity demand in 2050 in [%] under the BAS and ACC scenarios.

Year	E1, 110 TWh	E2, 80 TWh	E3, 50 TWh
BAS, 7 TWh	6%	9%	14%
ACC, 15 TWh	14%	19%	30%

Assuming improvement in the yield of PV systems and reduction of turnkey system cost over time, the cost[1] of solar electricity (levelised cost of electricity, LCOE[2]) at a cost of capital of 4%, 20 years system lifetime and no rent to be paid (i.e. for building owners) will likely gradually come down[3] over the time horizon of this roadmap[4]:

- 2012:
  0.19 SGD/kWh
- 2020:
  0.11-0.12 SGD/kWh
- 2030:
  0.08-0.10 SGD/kWh
- 2050:
  0.07-0.08 SGD/kWh

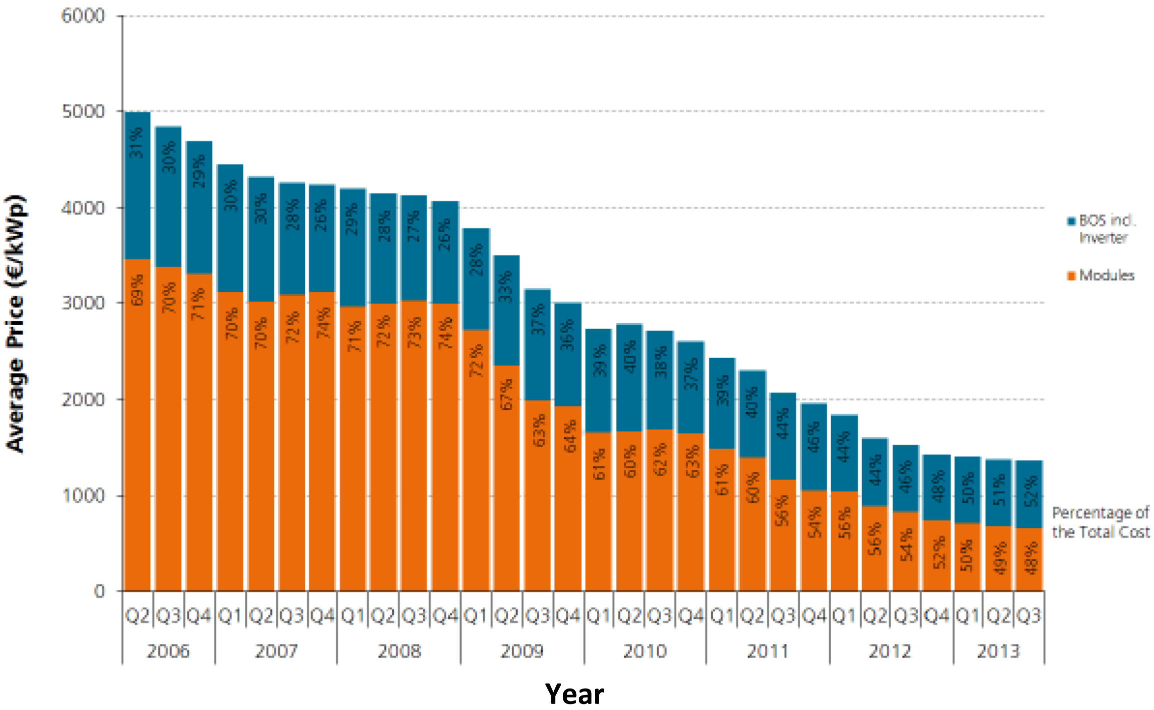
The authors of this PV roadmap would like to highlight some caveats: The recommendations in the roadmap were made as specific as possible given the long time horizon and the time available for

[1] Not including subsidies and profits.
[2] The concept of LCOE (see also section 4.4.1) is a figure of merit for the generation cost at the point of interconnection to the grid, and does not include external costs such as grid integration costs. In order to accommodate an increasing share of variable solar electricity into Singapore's electric power system, a detailed study of the positive and negative influences (incl. costs) on typical power grid parameters has to be carried out, which is beyond the scope of this roadmap.
[3] The different numbers for one year apply to different technology scenarios.
[4] For detailed assumptions, see sections 4.4.1 and 4.4.2.

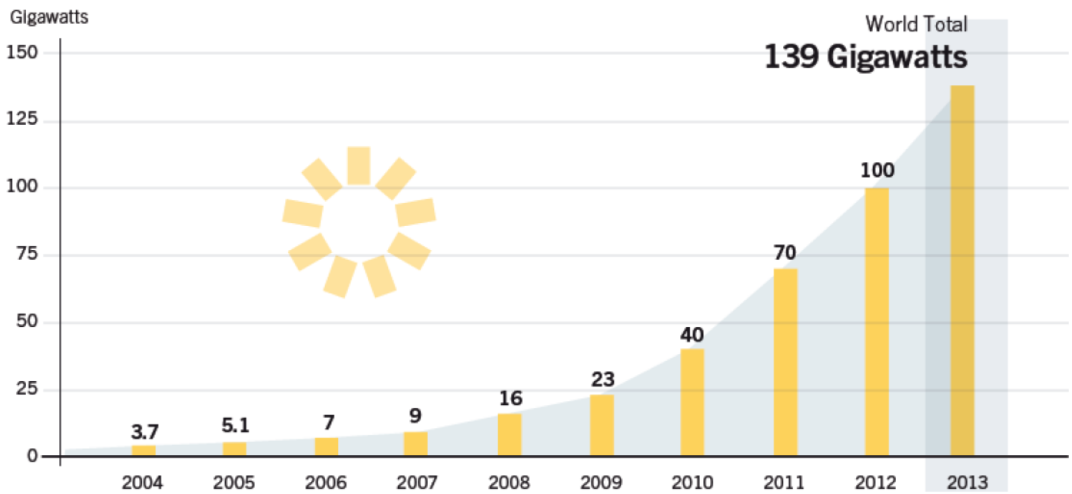
drafting the roadmap. Several ways to reduce the cost of PV modules, to increase the efficiency of PV devices, to reduce the amount of costly / rare materials, etc. have been discussed. By today it is not clear which precise path will lead eventually with certainty to much lower PV electricity cost compared to current values. A much more extensive study on this topic could of course reduce - to a certain extent - the uncertainty with respect to this topic. In that regard, the numbers given for the characterisation of the scenarios in the roadmap look at a first glance precise, but they are of course assessments only.

1. INTRODUCTION

The cost of solar electricity generation declined dramatically during the last three years (Figure 1.1 (a)). This reduction was mainly due to the strong increase in global PV installations (economy of scale, Figures 1.1(b) and (c)) and market answers to overcapacities in photovoltaic (PV) module production. In Q1 2013, the levelised cost of electricity (LCOE)[1] generated via PV energy conversion in Singapore is in the range of 0.19 and 0.27 SGD/kWh depending on financial and technological assumptions made. (see section 4.4.1).

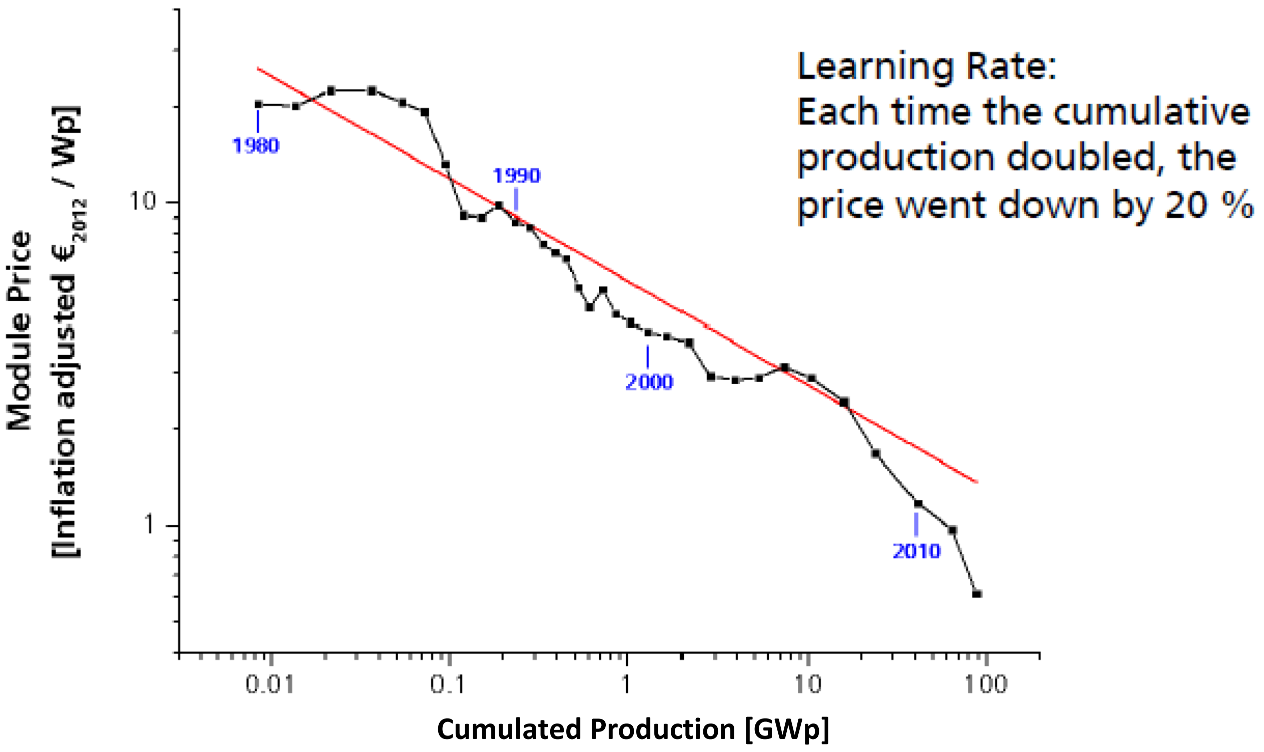


(a)



(b)

[1] The scheme of LCOE is introduced in section 4.4.1



(c)

Figure 1.1: (a) Cost curve for a PV rooftop system in Germany (10-100 kW_p) over the last 6-7 years [ISE], (b) development of the total installed world PV capacity [REN21], and (c) price experience curve for silicon PV modules [Ris, ISE].

Most likely the reduction of cost of PV electricity will continue, albeit at a slower rate: consolidation in industry, growing markets and on-going technological progress will be the main reason. The roadmap assesses that LCOE's around 2020 will be in the range of 0.11 – 0.15 SGD/kWh in Singapore. This cost reduction facilitates the transformation of today's energy systems towards sustainability[1]; solar electricity will be one of the main energy sources of a future sustainable energy supply.

The transformation of the global energy system towards sustainability is high on the political agenda in some countries. Compared to today's energy supply which is mainly based on fossil fuels, a global sustainable energy system would combine, amongst other things, the following advantages:

- Protection of the natural life support system – in particular, fighting climate change[2],
- Reduction of energy poverty in developing countries, and

[1] The concept of sustainability as developed and adopted by the United Nations Conferences on Environment and Development, Rio de Janeiro 1992 is as follows: Decision-making and implementation processes should promote development that is ecologically, economically and socially sustainable, and should take into account the needs of future generations.
[2] Reducing the emission of greenhouse gasses, in particular CO_2.

- Minimising energy-related conflicts, by reducing dependencies on regionally concentrated energy resources.

The transformation of the global energy systems towards sustainability will be mainly based on energy efficiency measures and the sustainable use of renewable energy sources such as solar, wind, biomass, hydro and other renewable sources.

For many countries such a switch to locally available renewable energy sources would create additional benefits such as[1] [Gra]:

- Increasing the security of energy supply,
- Reducing uncertainties in the cost of energy supply, and
- Promotion of future compliant industries, jobs and know-how.

These benefits also apply to Singapore. Furthermore, a sustainable energy supply system would contribute to Singapore's strategy of becoming a model green megacity in Asia.

The only abundantly[2] available renewable energy source of Singapore is solar energy. Because of the building and energy demand structure of Singapore, the direct conversion of sunlight into electricity (PV energy conversion) will be the main route[3] of solar energy harvesting. The total annual yield of solar electricity generation in Singapore depends mainly on the space being available for PV systems installations and the system efficiency values of the energy conversion units.

Of course transformation of an energy system towards sustainability (like in the case Singapore) is by no means an easy task. It will ask for major restructuring of the whole electricity supply structure and significant investments. The authors of this roadmap do not underestimate the necessary efforts, both in the technical and economic realm.

The technological challenges are mostly in the area of the integration of variable, non-dispatchable solar electricity into the Nation's electricity grid. Compared to larger countries the statistical levelling out of fluctuations over the small area of Singapore is not very pronounced [Lut]. Furthermore the tropical weather[4] is characterised by particularly strong fluctuations in solar

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1 For many countries the possibility to create an environmentally benign, reliable and cost effective electricity supply for regions not connected to a reliable public grid could be advantageous.

2 The average wind speed in Singapore is below 2 m/s and thus too low for large-scale wind energy harvesting; biomass, in particular in the form of waste constitutes a useful but small source of energy; the utilisation of ocean currents is very limited due to the shipping activities in the straits of Singapore.

3 For the generation of domestic hot water, process heat for industry and solar powered air-conditioning the deployment of solar thermal collectors may be considered as well. Most probably this will not reduce the space being available for PV installations considerably. Furthermore heat and cold will be generated in the future also via PV powered heat transformers.

4 The high fraction of diffuse radiation in the tropics has little influence on the electricity generation via flat plate PV modules. I.e. the efficiency of non-concentration photovoltaic energy conversion does not depend strongly on the ratio of diffuse to total (global) solar radiation.

radiation. This calls for highly sophisticated smart grids and, in the mid-term, for the integration of demand-side management and of storage systems. Essential technological measures are:

- Optimisation of Singapore’s electricity transmission and distribution system,
- Introduction of centralised and decentralised energy storage systems,
- Extensive demand side management,
- Active PV grid interactions (making distributed PV systems an active part of the grid)
- Highly sophisticated solar radiation forecast.

The challenge of coping with the solar radiation variations could be alleviated if Singapore’s electricity grid would be part of a strong South East Asian electricity distribution grid [Bla]. Such an extension of the supply structure could also increase the above mentioned contributions of PV electricity to Singapore’s energy demand.

A roadmap is, of course, only a map. While industry and academia can make important contributions through the drafting of roadmaps, the government plays a key role in the eventual adoption of the provided recommendations. The authors of this roadmap are convinced that solar energy has to, and will, make a decisive contribution to the global energy supply of the future. But they are well aware that there is not only a single road leading into the future and that uncertainties increase considerably when making assessments concerning the remote future.

As for the development of the domestic PV market, Singapore has embarked on an early integration of PV into its energy matrix. Figure 1.2 below illustrates that the market growth for PV in Singapore for the years 2008 to 2013 has been considerable although on very low levels.

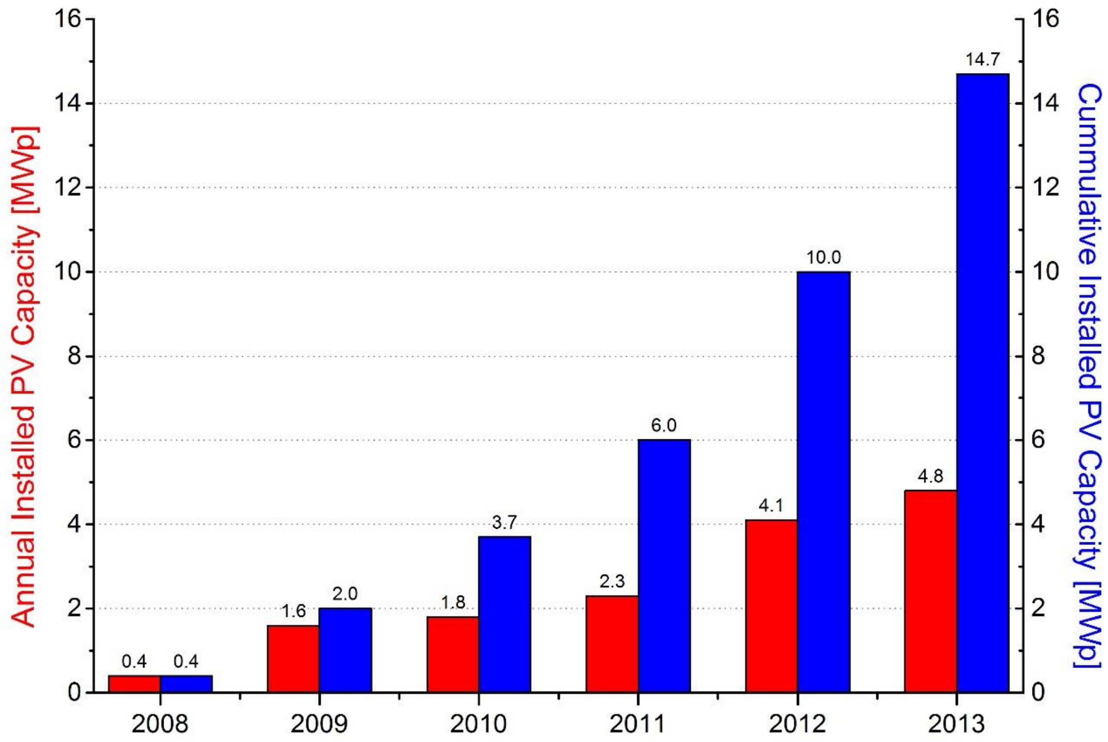


Figure 1.2: Annual market growth and cumulative installed capacity of solar PV electricity generation in Singapore for the years 2008 to 2013 [NSR].

Under the enhanced regulations, contestable[1] consumers who want to sell excess PV electricity to the grid, depending on the size of the system, can either register with SP Services (SPS) or the Energy Market Company (EMC) to participate in the wholesale electricity market. For the non-contestable consumers, they can apply for simplified credit treatment and will be paid the energy component of the regulated electricity tariff for the export of electricity into the grid. More details of the regulations of connecting a PV system to the Singapore power grid can be found in the determination paper issued by EMA. There is no preferential feed-in tariff regime available in Singapore.

The remaining chapters discuss the current and future PV technologies, key learnings from international PV Roadmaps, the potential for PV in Singapore, its implementation challenges and how to overcome those with targeted RD&D measures.

[1] A contestable consumer is free to procure electricity from the retailer, SP Services or from the wholesale generation market directly. A non-contestable consumer will have his/her electricity demand supplied by either SP Services or the winning generation companies in the bidding of vesting tender for its electrical demand.

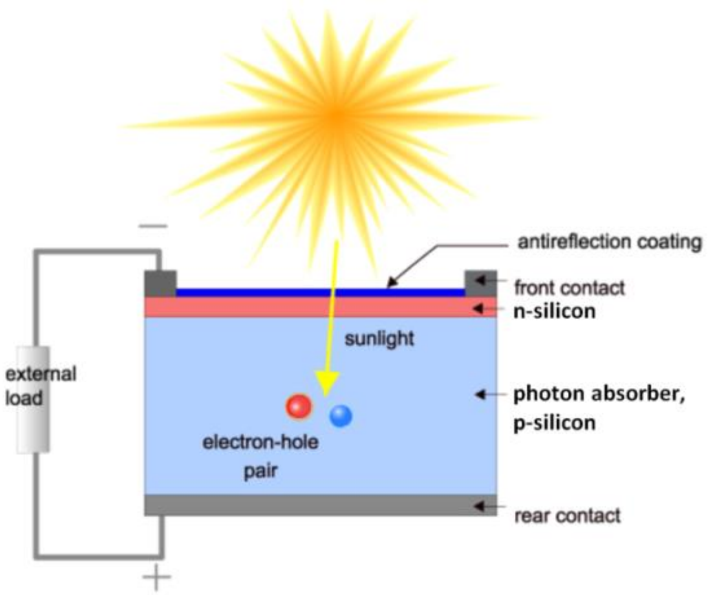
2. TECHNICAL AND ECONOMIC BACKGROUND OF TODAY'S AND FUTURE PV AND RELATED TECHNOLOGIES

2.1 TECHNOLOGIES FOR PV ELECTRICITY GENERATION

2.1.1 Basics of the PV energy conversion process

Photovoltaics is the direct conversion of solar energy into electrical energy using devices called solar cells. Almost all solar cells being on the market today use semiconductor materials to harness solar energy using the photovoltaic (PV) effect, whereby silicon wafer based technologies dominate today's market. Sunlight can be considered as a flux of particles called photons, whereas electric current is a flux of free (i.e. unbound) electrons. In essence, solar cells convert the energy of a photon flux into energy of an electron flux (see Figure 2.1 (a)).

Due to the huge density of photons in sunlight, single solar cells generate very large electric currents (of the order of hundreds of Amperes per m^2). To reduce the ohmic losses associated with such currents solar cells are limited in size (presently to less than 300 cm^2). Since solar cells generate relatively low voltages (typically below one Volt) they are generally connected in series to build up voltage. To ensure a long life in outdoor operations, the series-connected solar cells are laminated into a durable package, the so-called PV module (see Figure 2.1(b)). In PV systems, a number of PV modules are connected together (in series and/or in parallel) to realise the required current and voltage values.



(a)

(b)

Figure 2.1: (a) Schematic drawing (cross section) of a standard silicon wafer based solar cell. The asymmetric structure of the device (utilisation of p-type doped (p) and n-type doped (n) silicon) causes the selective transport of negative charge carriers (electrons) to the front contact and the transport of positive charge carriers to the rear contact. The typical thickness of such a cell is below 200 µm, the width is approximately 15 cm (square); (b) Photo showing a roof-mounted silicon wafer based PV module.

2.1.2 Technology, efficiencies and prices of market-leading PV technologies

Today's market leading terrestrial PV technologies are based on silicon (Si) wafers ("crystalline Si PV" or c-Si PV) and on thin-film cells made from the semiconductor materials amorphous silicon (a-Si), cadmium telluride (CdTe) and copper indium gallium (di)selenide (CIGS) (see Figure 2.2).

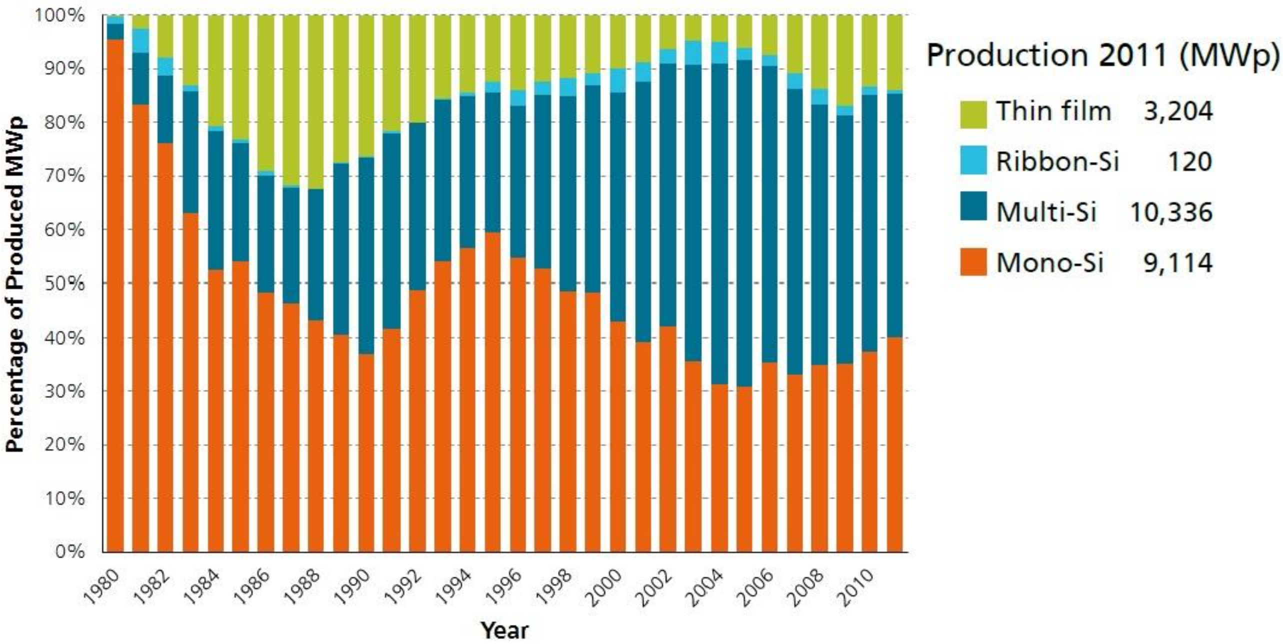


Figure 2.2: Chronological evolution of relative market shares of the major PV technologies (from [ISE])

Si wafer based PV modules: The processing sequence of today's silicon wafer based solar cells (at least until the next decade) starts with high-purity silicon feedstock ("polysilicon"), which is melted and solidified using different techniques to produce crystalline ingots or ribbons with variable degrees of crystal perfection[1]. The ingots are then shaped into bricks and sliced into thin wafers (~180 microns thick) by wire-sawing. Cut wafers and ribbons are processed into solar cells. Small-area lab cells achieve efficiencies of up to 25% under standard test conditions (STC)[2] [Gre]. Commercial PV module efficiencies at STC are presently in the 14-21.5% range.

Amorphous Si thin-film PV: Silicon can also be formed as a thin film of amorphous silicon (a-Si) material for solar cell applications[3]. Amorphous silicon is cheaper than crystalline silicon, but at the expense of a much lower electronic quality. Small-area amorphous Si laboratory cells achieve efficiencies at STC of up to 10%. The reason why a-Si has not been able to conquer a large share of the global PV market is the comparatively low stable efficiency of 5-7% at STC for large-area a-Si PV modules[4]. The so-called 'micromorph' technology is an advanced thin-film silicon solar cell consisting of a stack of two solar cells. The top cell is a conventional amorphous silicon solar cell, while the bottom cell consists of microcrystalline silicon (μc-Si). The different light absorption characteristics of the two solar cells give a better utilisation of the solar spectrum and hence a higher PV efficiency. The record micromorph cell efficiency in the laboratory is 12% at STC, while the best commercial modules are about 10% efficient at STC. An advantage of the thin-film silicon PV technology is that established large-area processing equipment from the display industry can be used.

CdTe PV modules: STC efficiencies of almost 19% have been achieved with small-area cells, while leading commercial modules (company First Solar) now have an efficiency of 12-13% at STC. One main issue of the CdTe PV technology is the toxicity of cadmium.

CIGS PV modules: The CIGS technology is the star performer amongst the thin film PV technologies in the laboratory, with STC efficiencies of over 20% for small cells. However, the technology has proved challenging to commercialise. The best commercially available modules are presently 13-15% efficient at STC. The main technical issue of the CIGS technology is associated with the complexity of the CIGS absorber layer (a multi-element system), which imposes significant challenges for the realisation of uniform film properties across large-area substrates using high-throughput equipment. Other issues are the use of the scarce element indium and, in some commercial PV modules, the use of cadmium.

Besides wafer and thin-film technologies which use natural sunlight for energy conversion, PV conversion schemes that are based on the optical concentration of sun light have entered the market [ART2]. In this optically-concentrated schemes, low optical concentration (up to x = 10)[5] may be applied everywhere while the application of high concentration PV systems (today

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[1] Monocrystalline wafers have higher electronic quality than multicrystalline wafers. This results in slight differences in solar cell efficiency.

[2] STC: Irradiance spectrum of AM1.5 Global, irradiance intensity of 1000 W/m^2, device/module temperature of 25 ^{o}C. (AM1.5 Global is a standard solar spectrum)

[3] For details see e.g. the books [Luq, Wür].

[4] The efficiency figures apply to single-junction cells.

[5] X is the optical concentration factor. E.g. X= 10 means 10 000 W/m^2 maximum solar irradiation. High optical concentration requires high precision mechanical tracking of the PV converters. Tracking adds additional cost to the systems.

typically x = 500) are restricted to regions characterised by a very high fraction of beam (direct, not diffuse) radiation. High concentration PV (HCPV) systems are not suitable in Singapore's context because of the high fraction of diffuse solar radiation in the tropics.

A compilation of the 2012 efficiency values at STC of the market-leading PV technologies is given in Table 2.1. For all these PV technologies most manufacturers give a power output warranty of 20 or even 25 years. This means that it is warranted that, after 20 (or 25) years, depending on the length of the warranty, of operation, the module's actual power at STC is still at least 80% of the module's factory rated power.

At the end of 2012, despite the strongly differing module efficiencies, the spot market prices of all PV module technologies shown in Table 2.1 were approximately the same (about 0.65 USD/W_p[1] for the silicon wafer based modules and about 0.62 USD/W_p for the thin-film modules) [MER]. For a land-limited country such as Singapore, this favours the use of high-efficiency PV module technologies[2].

[1] W_p means "Watt peak", the nominal output power under STC conditions. USD/W_p means "US dollars per Watt peak".

[2] This situation may be different for countries where space is abundantly available and cheap. It should be noted though that with decreasing efficiency the area-related costs (e.g. land use, support structure, cabling) become more prominent and could in the worst case be prohibitively high for an economic operation of a PV system.

Table 2.1: Efficiencies, area specific yields, and temperature coefficients[1] of PV market technologies, for power applications (data at STC).

Technology	Best efficiency in laboratory (cells)[2]	Efficiency in industry (modules)[3]	Area specific power yield (modules)	Temperature coefficient of output power at MPP[4]	Remarks
Mono-Si	25.0%	14-21.5%	140-215 W/m^2	-0.38%/°C	Pseudo-square wafers (125 mm)
Multi-Si	20.4%	14-18%	140-180 W/m^2	-0.40%/°C	Square wafers (156 mm)
CIS (CIGS)	20.3%	11-15%	110-150 W/m^2	-0.31%/°C	Uses indium (scarce)
CdTe	18.7%	12-13%	120-130 W/m^2	-0.25%/°C	Uses tellurium (scarce) and cadmium (toxic)
Micromorph Si	11.9%	8-10%	80-100 W/m^2	-0.28%/°C	Tandem cell (a-Si/µc-Si)
Amorphous Si	10.1%	5-7%	50-70 W/m^2	-0.27%/°C	Very thin cells (Si~300 nm)

2.1.3 Efficiency and technology roadmaps of market-leading PV technologies

2.1.3.1 Short term goals (2015)

Si wafer technologies: Over the coming years the Si wafer PV community[5] is expected to continue driving down the costs, both via the implementation of improved solar cell manufacturing equipment and via the realisation of improved solar cell efficiencies, manufacturing processes and device architectures. For the top manufacturers the short-term industrial efficiency targets (at STC) for the five major Si wafer PV technologies are approximately 18-19% for multi-Si cells, 20-21% for p-type standard mono-Si cells, 21-22% for n-type standard mono-Si cells, 22-23% for heterojunction mono-Si cells [Abe], and 23-25% for all-back-contact mono-Si cells [Glu]. The goal of the R&D efforts is to realise these cell efficiency gains in a cost-effective way, thereby leading to reductions of the USD/W_p cost of the PV modules.

Amorphous Si thin-film PV: The key issue of this technology is the low stable efficiency (STC) of 5-7% of standard industrial modules. To reduce the USD/W_p cost of the technology, this efficiency

[1] The temperature coefficient gives information on the efficiency reduction of solar cells with increased operation temperatures (compared to the STC temperature).
[2] Martin A. Green, Keith Emery, Yoshihiro Hishikawa, Wilhelm Warta and Ewan D. Dunlop, Solar cell efficiency tables (version 39), Progress in Photovoltaics: Research and Applications, 2012; 20: p. 12-20; regularly updated from solar news in PV Magazine, Photon, Solarbuzz.
[3] From manufacturers' data sheets
[4] MPP = maximum power point.
[5] Industry, and research and development institutions.

needs to be significantly increased in the coming years. Ambitious but achievable efficiency targets for 2015 are 8% for single-junction modules and 9% for a-Si:H/a-Si:H[1] double-junction[2] modules. Today's best industrial micromorph modules are about 10% efficient at STC. To bring down the USD/W_p cost, this efficiency must be significantly increased in the coming years. For 2015, an ambitious but achievable efficiency target for industry-size micromorph modules is 12%.

CdTe thin-film PV: The market leader in the CdTe PV sector is US company First Solar who produces single-junction CdTe thin-film PV modules with efficiencies (STC) of up to 13% and is one of the cost leaders in the global PV industry. A realistic module efficiency target for the mass market for 2015 is 14%[3].

CIGS thin-film PV: Given the difficulties with obtaining uniform CIGS properties over large areas, there is no consensus in the industry about which of the different CIGS technology path to favour. The best industry-size CIGS modules made thus far have an efficiency at STC of about 15.5%. By 2015, the efficiency targets for industry-size single-junction CIGS modules are about 13-14% for monolithic[4] modules and 17-18% for non-monolithic modules.

2.1.3.2 Efficiency goals for 2020, 2030 and 2050

While the efficiency progress in PV energy conversion in the near future can be assessed relatively accurately, efficiency prognoses for the decades to come are subject to high and increasingly higher uncertainties. This applies in particular to totally new technologies that are currently hardly seen on the horizon.

An upper limit of PV efficiency can be derived from a fundamental thermodynamic analysis of the terrestrial conversion of sunlight into electricity (Figure 2.3) [Siz]. As can been seen from Figure 2.3 the efficiency of today's best industrial silicon wafer based solar cell (efficiency ~ 20%, blue dot) is still far below the theoretically possible PV efficiency of 31% for single junction solar cells[5], leaving much room for further efficiency improvements via technological innovations. The gain in PV efficiency with increasing optical concentration of solar radiation is also shown in Figure 2.3. It can be harvested in concentrating PV (CPV) as discussed at the end of chapter 2.2. However because of the high fraction of diffuse radiation such technologies are not applicable for Singapore[6].

[1] a-Si:H is hydrogenated amorphous silicon, all a-Si solar cells use a-Si:H material.
[2] Double junction solar cells are a type of tandem (or multi-junction) solar cells. Tandem solar cells consist of a stack of solar cells that have different spectral sensitivities in different parts of the solar spectrum. By this concept different parts of the solar spectrum are separately converted into electricity. This increases the overall efficiency of PV converters relative to single-junction solar cells.
[3] In spring 2013 First Solar has announced that it has produce modules with efficiency values of 16.1%.
[4] Monolithic is defined as constituting or acting as a single, uniform whole. In semiconductor and PV devices, a monolithic (integrated) device refers to one in which all sub-devices or multiple devices are all grown and formed together on the same single base.
[5] This limit of 31% is frequently called Shockley-Queisser limit.
[6] For principle physical reasons it is impossible to concentrate diffuse radiation under the boundary of photon energy conservation.

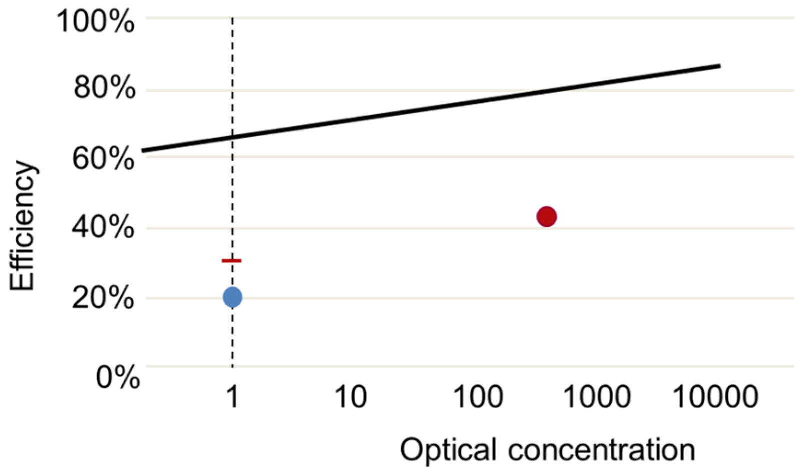


Figure 2.3: Thermodynamic limits of PV energy conversion. The theoretically maximum efficiency (black line) depends on the optical concentration of the solar radiation and the device architecture[1] of the solar energy converter. The blue dot and the red bar at concentration one indicate the efficiency of today's best silicon wafer solar industrial solar cell and the theoretical limit of such single-junction solar cells respectively. The red dot on the right side refers to the best laboratory efficiency value for concentration PV using highly sophisticated space technology solar cells. Concentration 1 means no optical concentration equivalent to 1000 W/m^2 (or standard test conditions), concentration 1000 is equivalent to 1 MW solar radiation per m^2 on the front surface of the PV cell. For these calculations, the sun's radiation is approximated as the radiation of a black body radiator having a temperature of 5777 K; the solar cell temperature is assumed to be 300 K [Siz].

An assessment of the long-term technically achievable PV efficiency values has been performed by a number of groups [REF][2]. These findings have been consolidated with recent scientific results and evaluations by the authors of this roadmap report.

The efficiency values given in the tables below are for industrially manufactured PV cells (wafer based and thin-film based). In order to have corresponding values for PV-modules the values given in the tables have to be reduced by about 10% (relative) whereby the resulting number includes the slight degradation of the module efficiency over its technical lifetime.

Silicon wafer-based solar cells:

From today's perspective, Si wafer-based industrial types of solar cells will continue to have the highest efficiency values for PV application in tropical[3] climates[4]. Thus they are most suited if Singapore embarks on a strategy that fully exhausts its space-limited potential for solar energy conversion. Efficiency assessments for this class of solar cells are compiled in Table 2.2.

1 The device architecture is not specified in such a thermodynamic analysis. Efficiency values beyond the red bar may be achieved e.g. via the tandem concept. The efficiency value of the red dot is e.g. achieved by applying triple-junction solar cells and optical concentration.

2 Due to the fast progress in PV performance studies older than two years are generally outdated (too conservative).

3 This statement does not change qualitatively if the higher negative temperature coefficient of Si-wafer solar cells is taken into account. See Table 2.1.

4 This statement assumes that no paradigm shift in PV energy conversion occurs in the next future. Solar cells for optical concentration are not considered here. Such small area cells show under high optical concentrations efficiency values of more than 40% [ART2]; values beyond 50% are realistic assumptions for the future.

Alternatives with respect to technical progress are given in the form of different scenarios: baseline progress (BAS), accelerated development (ACC) in the applied PV energy conversion principles and architectures.

Table 2.2: Assessment of future Si wafer-based PV cell efficiency values at STC. Large-scale industrial manufacture is assumed. Alternatives with respect to technical progress are given in the form of different scenarios: baseline progress (BAS), accelerated development (ACC) in the applied PV energy conversion principles and architectures[1]. Technical lifetime averaged[2] module efficiency values will be slightly lower (~ 10% relative). It should be noted that there are fundamental limits to the efficiency of PV energy conversion (Figure 2.5). The values for 2020 are based on detailed technological analyses; the values for 2030 and 2050 are estimates (characterised by increasing uncertainties with advancing time, hence shown in smaller font size).

Power conversion efficiency of future Si wafer-based PV cells at STC			
Year	**2020**	**2030**	**2050**
BAS	23%	25%	26%
ACC	24%	30%[3]	35%[3]

The efficiency values under the BAS scenario assume incremental progress of today's known technologies. The ACC scenarios for 2030 and 2050 are based on novel concepts for wafer-based solar cells such as low-cost tandem structures (multi-junction cell devices).

Thin-film solar cells:

Thin-film photovoltaic energy converters will most likely continue to have lower efficiency compared with silicon wafer-based solar cells. On the other hand, these energy converters consume less material and are characterised by lower cost per Watt. Favourable applications will thus in particular be in areas where the availability of space is not a key issue and where area-related system cost will not be too high. Furthermore in building integrated PV (BIPV) applications thin-film technologies may have an advantage with respect to the aesthetical appearance (in particular for facade integration). Efficiency assessments for this class of solar cells are compiled in Table 2.3. It should be noted that there are fundamental upper limits to the efficiency of PV energy conversion (Figure 2.3)

Table 2.3: Assessment of future thin-film PV cell efficiency values at STC (numbers e.g. for CIGS). For further information on the assumptions, see Table 2.2.

Power conversion efficiency of future thin-film PV cells at STC			
Year	**2020**	**2030**	**2050**
BAS	16%	18%	20%
ACC	17%	22%	28%

[1] The 2020 values are weighted averages over different technologies (see section 2.3.1 first paragraph).
[2] See footnote 4 of this page.
[3] Efficiency values of 30% and higher assume Si-wafer based tandem technologies. NEDO assessed an efficiency of 40%.

The efficiency values under the BAS scenario assume incremental progress of today's known technologies. The ACC scenarios for 2030 and 2050 are based on radically new concepts for thin-film photovoltaics.

2.1.3.3 Cost goals for 2020, 2030 and 2050

Table 2.4 summarises the cost[1] assessments for photovoltaic modules. These numbers are based on several external studies [ITR, REF] and on evaluations of the authors of this roadmap report. Price reductions in the past have been displayed in the introduction of this roadmap in the form of a price-experience curve (see Figure 1.1(c)). Probably price reductions will follow such a heuristic curve also for the near future[2]. The cost reduction assessment until 2020 is based on detailed analyses of industry and R&D institutes [ITR].

For simplicity, and because of the large margins of error we only give cost assessments for silicon wafer-based technologies; the cost of thin-film based modules may be 10 to 20% lower. It should be highlighted that for the calculation of the levelised cost of electricity, the full cost of turn-key systems are decisive and not only the cost of the PV modules.

Table 2.4: Assessment of future costs of PV modules. For further information on the assumptions, see Table 2.2.

Cost in USD/W_p, Si wafer-based modules			
Year	**2020**	**2030**	**2050**
BAS	0.40	0.35	0.30
ACC	0.35	0.30	0.25

2.1.3.4 Technical lifetime of PV modules

For the amortisation of PV modules and for the calculation of levelised cost of electricity (see sections 4.4.1 and 4.4.2) the technical lifetime of PV modules is an important parameter. The numbers given in Table 2.5 are based on several external studies [REF] and on evaluations of the authors of this roadmap report. It should be noted, that too long technical lifetimes of PV modules do not favour the repowering of PV systems if higher-efficiency modules become available. Such a repowering of PV systems will be particularly important if space availability is the limiting factor for increased generation of PV electricity.

[1] These are the full costs of manufacture (i.e. "cost of ownership). The data given do not include subsidies. The market prices will generally be higher than the full costs of manufacture .The difference between prices and costs are the profit margins of the companies.

[2] An average learning factor of 20% may be applicable. This means that for each doubling of the global shipment, prices will decline by 20%.

The technical lifetime of silicon wafer based modules is limited by the applied encapsulation technology[1] and not by the technical lifetime of the solar cells. The same applies to most thin-film technologies. Some PV energy conversion technologies show small[2] or even considerable[3] initial degradations but the efficiency values stabilise after a well-known time span. Name plate efficiency values account for this effect.

Table 2.5: Assessment of the technical lifetime of Si wafer based PV modules. For further information on the assumptions, see Table 2.2.

Technical lifetime in years, Si wafer-based modules			
Year	**2020**	**2030**	**2050**
BAS	30	35	35
ACC	35	40	40

2.1.3.5 Recycling of PV modules

Because of the low spatial energy density of solar radiation PV energy conversion is a large area technology. Thus for a sustainable mass deployment of PV electricity converter recycling of the PV modules is essential. The principle feasibility of the recycling of silicon based PV modules has been demonstrated at the pilot plant scale. No fundamental problems have been identified [Ebe]. Because of the technical lifetime of Si wafer based modules of more than 20 years mass scale recycling of such modules will only start in 10 to 15 years. The feasibility of the recycling of thin-film modules has also been proven [Goo]. The goal of the recycling of these modules is not only the recovery of expensive[4], rare[5] and energy-intensive[6] materials but also the prevention of environmental contamination with toxic materials[7].

2.2 PV SYSTEM TECHNOLOGIES AND PV GRID INTEGRATION

2.2.1 Technologies

Photovoltaic modules generate direct current (DC) electricity at relatively low voltages (e.g. ~30 V for a standard 250 W_p panel). In most applications[8] such modules are series connected in order to generate higher voltages and parallel connected for higher currents. Such an arrangement of PV modules is called a PV array or if larger PV power plant.

[1] The technical lifetime of PV modules depends mostly on the polymer encapsulates applied, the encapsulation process and the rim isolation of the model. Highly sophistic module technologies increase the technical life time of modules but will be more costly.
[2] E.g. Silicon solar cells based on p-type Cz material [Pin].
[3] E.g. amorphous silicon based solar cells [Kol].
[4] E.g. silver from the front contacts of crystalline wafer-based modules.
[5] E.g. Indium or Tellurium from thin-film modules.
[6] E.g. Aluminum from the frames.
[7] E.g. cadmium in CdTe thin-film PV modules.
[8] In many off-grid applications just one module is applied.

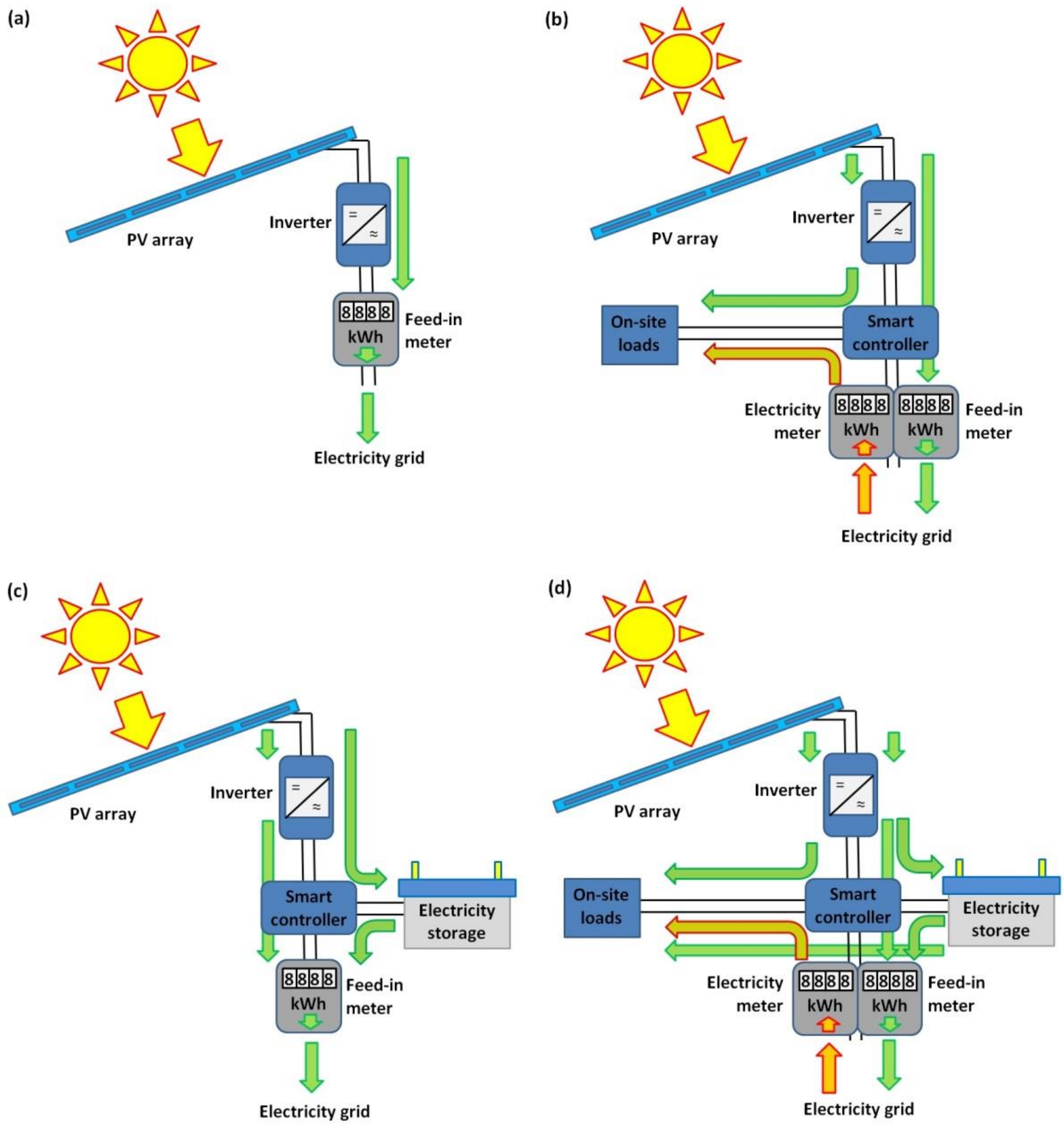


Figure 2.4: Schematic of grid connected medium power PV systems. (a) PV installation without on-site consumption of electricity; (b) System serving in addition on-site loads, (c) PV system without on-site consumption but additional electricity storage capability, (d) system as (c) with additional on-site loads.

PV arrays or PV power plants are interconnected with the external electricity grid via power electronic devices (Figure 2.4(a)). Such devices include safety facilities. The main function of such power electronic units is the conversion of the PV DC power into alternating current (AC) which can be fed into a standard electricity supply grid. These power electronic devices are called "inverters". Low power PV systems are connected to the low voltage distribution grid, while PV power plants are usually connected to the medium voltage grid system. The energy conversion efficiency (DC to AC) of high standard inverters is in the range of 98%.

Power electronic systems of PV installations may incorporate smart controllers, which - in addition to the two-way interaction with the grid - control the electricity flux between the system and on-site loads (Figure 2.4(b)). More advanced systems may incorporate batteries (electricity storage) in order to achieve a better time matching between PV electricity generation and the demand pattern of the on-site loads (Figure 2.4(d)). Such batteries may also be uses to store PV electricity and feed it with some delay into the grid in times when the electricity demand is particularly high (Figure 2.4(c)). This could constitute a novel type of business for the system owner, effectively participating in the market as "independent power producer".

In modern PV applications – in particular in the case of high penetration[1] of the grid with PV electricity – smart inverters and smart controllers (see Figure 2.3) will incorporate several features that are important for an optimal operation of the electricity grid. Characteristics of such sophisticated PV power electronics are summarised in the following. Not all of the features are already available in today’s market products; these features are labelled “experimental” below.

Guaranteeing the safety of operation

- In the case of a relevant failure of the external supply grid: switching off the PV electricity supply (avoiding islanding) or, as an upcoming alternative (if applicable);
- Provide grid stability support during normal as well as critical grid conditions, as long as it is safe to do so. Instead of suddenly dis-connecting, the PV inverter will be providing active grid support until the normal conditions have been restored (so-called "fault ride through capability") – the latter often asks for sophisticated communication between dispersed PV-grid interface units and the grid operator.

Increasing the quality of electricity supply

- Provision of reactive power (this asks for a certain local storage capacity);
- Active compensation of harmonic distortions in the grid;
- Connection to the grid without a transformer interface (reduction of cost);
- Controlling of the PV electricity flow into the grid in situations of oversupply (reducing the PV feed-in on the request of the grid operator[3]);
- Local, detailed monitoring of the supply grid and forwarding of such data to the grid operator (experimental);

[1] Grid penetration is defined as the ratio between the (annual) average PV electricity generation fed into the grid and the average load of the grid. In general the PV energy fed into the grid will originate from many spatially dispersed PV installations.

Measuring PV supply and electricity demand, fault detection

- Metering of load and PV generation;
- Compiling time resolved statistics of PV production, PV system efficiency and load;
- Fault detection and detection of reduced performance in PV systems;
- Automatic information to PV systems operators about faulty or underperforming systems.

Managing local storage

- Charging and discharging of local electricity storage according to a local strategy – based on external and local information on energy flow and tariffs; in the future this may include batteries of the e-mobility sector (experimental);
- Forced charging and discharging of local electricity storage as requested by the grid operator (type and extend of the influence has to be negotiated between the consumer and the grid operator (experimental);
- Charging of local non-electricity product storage (e.g. cold, heat, desalinated water) in order to utilise excess PV electricity (experimental).

Load management

- Control of loads on the basis of externally available information (e.g. actual tariff information) and internal algorithms (priorities set by the local consumer);
- Forced control of loads as a response to signals issued by the grid operator (type and extend of the influence has to be negotiated between the user and the grid operator - available on industrial level, experimental on consumer level).

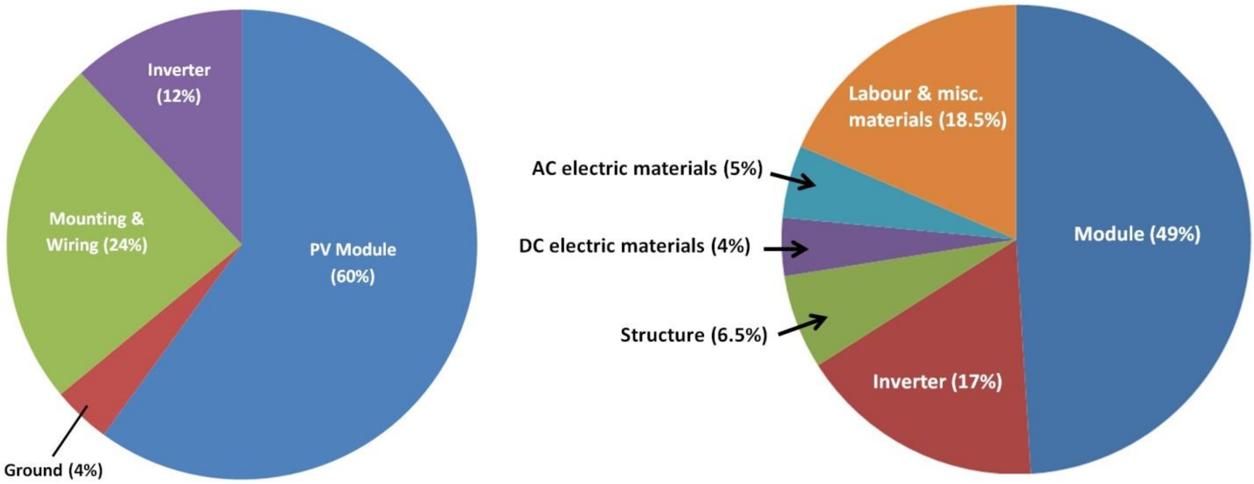
2.2.2 Present PV system cost

A cost break-down of typical PV installation in large European markets is given in Figure 2.4(a) together with a comparison to a similar system in Singapore, see Figure 2.4(b).

In 2013, net retail prices of PV power electronic (DC to AC inverter) are in the order of 0.18–0.20 USD/W_p[1]. Lowest turnkey systems prices in 2013 are found in the market with the largest installed capacity, Germany, and are in the order of 1.2 USD/W_p[2] for MW_p systems and 1.9 USD/W_p for 10 kW_p systems inclusive of profits, equivalent to 1.5 SGD/W_p and 2.4 SGD/W_p respectively.

Local prices in Singapore are only for rooftops systems due to space constraints for ground-mounted installations, and are in the range of 2.2 SGD/W_p (for 1 MWp systems, currently the largest size) to 2.5 SGD/W_p (for typical ~10-50 kWp systems). Those numbers are also used for the calculation of the cost of electricity in section 4.4.1.

[1] These inverters do not have all the smart features mentioned above.
[2] Prices for the German market for end of 2012, acquired through phone interviews of PV system integration companies.



(a) (b)

Figure 2.4: Break down of the full investment cost of a state of the art >100 kW_p PV system in (a) Europe [ITR] and in (b) Singapore [REF3]. The non-module costs are called BOS cost. "Ground" refers to "space" for PV installations.

2.2.3 Development of total cost of PV systems

It can be seen from Figure 2.4 that almost 40% of the costs of a PV system can be allocated to BOS cost. These costs have to be reduced in parallel to cost reductions in PV modules. Table 2.6 gives the anticipated values for total PV systems. These costs are the base for the LCOE calculations for the deployment in Singapore (see section 4.4.1). It should be noted that the numbers given here are cost, whereas in section 2.2.2 it was prices for 2012 that include profits.

The anticipated cost reduction between 2012 and 2020 of approximately a factor of 2 is the result of detailed analyses of leading industry experts. The main causes of this reduction are economy of scale, improved manufacturing technologies and the more efficient use of materials. The anticipated additional cost reductions for 2030 and 2050 are relatively low. This is a conservative assessment. Nevertheless the cost reduction after 2020 will be slower than in the time before due to the fact that the area related cost of total system cost will become increasingly more important; this applies in particular to the cost of transparent covers for PV modules, installation cost, and ground (space) cost or rent (see the pie chart in Figure 2.4).

Table 2.6: Assessment of future costs of total PV system cost (power range: 10–100 kW_p). For further information on the assumptions, see Table 2.2.

Full cost of PV systems in USD/W_p			
Year	**2020**	**2030**	**2050**
BAS	0.90	0.80	0.70
ACC	0.80	0.70	0.60

2.2.4 Energy payback of PV systems

As part of the EPIA Sustainability Working Group and the IEA PVPS Task 12, the Energy Research Centre of the Netherlands (ECN) has conducted a detailed study with various parameters and assumptions. The results show that the energy payback times on PV system levels are between 0.8 and 1.5 years, depending on the PV technology) [Wil]. Given the lifetime expectations of PV systems of ~30 years, backed-up by a 20-25 year power output warranty from the manufacturers, the energy pay-back time is relatively short compared to the technical lifetime of the systems.

3. PV ROADMAPS FROM OTHER REGIONS

The goal of this project was to develop a solar PV technology roadmap for Singapore with a long term perspective of up to year 2050. It is thus essential to achieve a good understanding of how other parts of the world plan to include solar PV into their energy mix by reviewing existing solar PV technology and/or energy-related policy roadmaps around the world. To this end, 16 roadmaps, papers and articles were reviewed and summarised in this section. The lessons learned from global, regional and national roadmaps on solar PV can be distinguished into three areas: policy-, technology- and R&D-related learning. Those are summarised in Table 3.1 below.

Table 3.1: Summary of key learning from global, regional and national PV roadmaps.

Policy-related learning	Technology-related learning	R&D-related learning
Pro-actively plan & steer the shift towards renewables	Strongly combine and interlink renewable energy deployment with energy efficiency measures	Increase R&D on BOS components and (sub-)systems
Provide clear and binding long-term deployment targets	Strengthen the role of natural gas in general and gas-fired power plants for fast-reacting reserves in particular	Increase R&D on smart grid technologies
Introduce effective and cost-efficient incentive schemes (that gradually phase out over time)	Use of Information and Communication Technologies (ICT) for smart grids, load management and PV grid interaction (e.g. balancing generation and demand)	Continue R&D on cost reduction of PV technologies (lower manufacturing cost, higher efficiencies)
Set the framework for the private sector to adopt efficient financing schemes	Demand-side management and distributed storage will be critical for larger shares of non-dispatchable renewables	Increase R&D on improved systems performance, reliability and lifetime
Develop new energy market and business models for both, incumbents and new entrants	PV has to play an active role in grid support / stability measures	Develop further and broadly demonstrate innovative technologies such as BIPV
Provide priority access for renewable energies	Smart and interactive meters will play a crucial role in making optimised local energy choices	Increase R&D energy output forecasting and optimisation of storage technologies

4. A PV ROADMAP FOR SINGAPORE

4.1 OVERVIEW OF MAIN FOCUS AREAS FOR THE CASE OF SINGAPORE

Based on the understanding of the current and future developments in photovoltaic (PV) and relevant ancillary technologies gained in the previous sections, this chapter applies those findings on the specific case of Singapore. Evaluations are made on the maximum potential of solar PV - especially also looking into over-coming the obvious space constraint - and on the challenges an increasing share of distributed variable generation from solar PV will impose on the power grid operation. The chapter will also assess the levelised cost of electricity (LCOE) of various deployment scenarios within the main island of Singapore and beyond. Finally, possible RD&D strategies for PV in Singapore are discussed.

4.2 SPACE CHALLENGE

4.2.1 Space potential in Singapore

4.2.1.1 Available roof-top area

This section is based on a top-down estimation of the available space area for Singapore. It has to be updated in the future to take into account a more detailed analysis of the actual solar space potential in Singapore using e.g. aerial view data, as well as agencies' policy/planning considerations and potential competing uses of rooftop space.

This assessment for suitable space for PV installations excludes ground-mounted systems on the main island. The indication given so far suggests that land leasing cost near to industrial market rates would have to be borne by the system owner, which makes solar PV installations economically un-viable.

A manual analysis of the build-up area of Singapore revealed that 8% of the total land area is covered with buildings, i.e. the total building footprint area is ~56 km^2, out of which 25% are HDB blocks (~14 km^2). Based on that, studies at NUS [Won] in co-operation with SERIS give an estimation of the relative portion that is suitable for PV installations[1] on HDB building blocks, as well as on other building types (especially: residential, industrial and commercial buildings). For a conservative approach, an area utilisation factor of 0.5 for HDB blocks and 0.6 for other building types was applied to the available gross building footprint area.

[1] i.e. no shading and installation is feasible with reasonable effort.

4.2.1.2 Possible facade areas

Due to the high sun path in Singapore (lowest angle at solar noon is 65° from the normal), facades in Singapore only receive an average of ~43% of the annual irradiance on a horizontal surface[1].

Taking mutual shading between buildings into account, however, only the upper part of high-rise buildings should be considered for PV installations. The number of buildings in Singapore, taken from manual count and extrapolations, is in the order of 38,000. Given the 40% lower sun irradiance factor this area is hence equivalent to ~16 km^2 of roof-top area facing the sun with optimum angle[2].

Further analysis and discussions with various stakeholders (building owners, architects, HDB representatives) showed that there is a risk of non-acceptance of the "alternative visual impact" on one hand, and a serious concern about sabotage and mis-handling of the PV modules, if installed within the reach of tenants or building owners. Owing to the typical building structure in Singapore, this would reduce the installations mostly to East-West facades where less or no windows are present. Due to the diurnal cycle, this will then also reduce the overall power generation as typically only one of the facades would be widely exposed to sun at a time. As a consequence, the potential derived above is reduced to 1/4 of the theoretical value; i.e. equivalent to ~4 km^2 of roof-top area facing the sun with optimum angle.

4.2.1.3 Infrastructure areas

Note:
The figures mentioned below are based on SERIS' analysis. The authors of the roadmap recognise that the future use of all infrastructure areas will be subject to further discussions with the relevant authorities, to verify these figures and de-conflict competing space usage requirements.

Singapore has a number of infrastructure areas that potentially could be used for PV installations. While the width of roads and expressways will make an economic installation difficult, covering the railway tracks of the Mass Rapid Transport (MRT) system seems to be suitable due to its small width and the elevated (and exposed) construction, subject to economic viability, meeting safety requirements, and approval of the relevant authorities, especially the Singapore Land Transport Authority (LTA). A first analysis showed that there are 56 km of exposed railway tracks above ground[3]. The width of 3.5 m per track per direction adds up to a usable area of ~0.5 km^2.
It is a conservative approach to only take the MRT tracks into account for the PV potential estimations. Recent technological developments in the area of PV canopies offer much more opportunities to utilise open spaces such as car parks, highways or even the space between building blocks.

[1] Called "Global Horizontal Irradiance" (GHI).
[2] i.e. a roof-top system with 10° tilt angle.
[3] Excluding tracks in train stations and dispatch lines to depots.

4.2.1.4 Singapore's islets

Apart from the mainland, Singapore consists of more than 60 smaller islands; many of them could possibly be used for solar PV installations and connected via sub-marine cables to the main island. The most prominent island for such usage would be Pulau Semakau (Singapore's landfill), which could gradually, after each of the sealed basins is filled-up, be covered with PV systems. An estimated 20%, or 10 km^2 of all those areas could in-principle be useful for PV installations, subject to economic viability and approval of the relevant authorities.

From a policy point-of-view, a deliberate decision is certainly required to make use of any of the islets for solar PV. This decision-making process will then also take opportunity costs such as potential competing uses and the environmental impact into consideration. Therefore this roadmap makes the assumption that possibly only 1/4 of the theoretical potential may eventually be used for solar PV installations; i.e. 2.5 km^2.

4.2.1.5 Floating PV systems[1]

After having closed most of the lagoons facing the sea, Singapore has now a total area of ~20 km^2 of inland water surfaces[2]. An estimated 20% of that area would be usable for floating PV installations, subject to economic viability and approval of the relevant authorities. Higher percentages would possibly restrict current recreational use or potentially affect flora and fauna of the reservoirs. The latter impact has to be studied in detail before venturing in such technology, which will be part of an upcoming test bedding project that also involves the "owner" of the inland waters, the Public Utility Board (PUB).

4.2.1.6 Summary of potential space for PV installation in Singapore[3]

Based on SERIS' assessment above, Table 4.1 summarises the possible areas for PV installations in Singapore with a maximum available space of around 45 km^2. Further discussions will be needed with the relevant authorities to verify these figures and de-conflict competing space usage requirements, taking into account site suitability, economic viability, as well as agencies' policy/planning considerations. The possible area for urban PV canopies cannot be assessed at the moment.

Excluding tracks in train stations and dispatch lines to depots.
the roadmap recognise that the future use of all infrastructure areas will be subject to further discussions with the relevant authorities, to verify these figures and de-conflict competing space usage requirements.

[2] Based on analysis from satellite data carried out by SERIS

[3] The authors of the roadmap recognise that the future use of all infrastructure areas will be subject to further discussions with the relevant authorities, to verify these figures and de-conflict competing space usage requirements.

Table 4.1: Overview of possible areas for PV installations in Singapore, based on the discussion above.

Space type	Area used	Total area (km^2)	Area utilisation factor[1]	Net-usable area (km^2)
Roof-top[1)]	HDB blocks	14	0.5[2)]	7
	Other buildings	42	0.6[3)]	27
Facades[1)]	Top-5 stories	10	0.40	4
Infrastructure	MRT tracks	0.5	1.00	0.5
Islets	Ground-mounted	50	0.05	2.5
Inland waters	Floating PV (mainland only)	20	0.20	4
TOTAL				**45**

1) based on existing building stock in 2011, and conservatively projecting the same building stock for the timeframe under consideration in this roadmap.
2) based on the lowest value for possible un-shaded installations on HDB blocks from studies at NUS [Won]
3) based on the lowest value for possible un-shaded installations on other buildings from studies at NUS [Won]

4.2.2 Alternative deployment strategies

This section looks into alternatives of large-scale PV electricity generation outside the Singapore land territory. These are based on SERIS' analysis, and would require carefully weighing geopolitical considerations, competing use of space and transmission requirements. There are generally two main alternatives: off-shore floating PV systems and import of solar electricity through a SE-Asian or even Pan-Asian power grid.

4.2.2.1 Off-shore floating PV systems

Off-shore floating PV platforms are a possible option to increase the suitable area for deployment of solar PV installations in land-restricted urban countries with coastal access like Singapore. In order to maintain security of electricity supply, it is envisaged that the off-shore floating platforms would be located within the maritime territory of Singapore. International waters bear the risk of disputable ownership or sabotage and hence would require a higher protection mechanisms, e.g. through the Singapore Navy.

4.2.2.2 PV system deployment in neighbouring countries

The variability of solar PV installations levels out over distance (see also section 4.3.2.1). So effectively enlarging the area used for the deployment of PV will not only help to generate more solar energy, but is in-principle also beneficial for reducing the variable lumped output of solar PV and could counter-balance effects on the main island.

[1] "Area utilisation factor" refers to the percentage of gross area that can be used for PV installations, given the irradiance, reasonable installation efforts and balancing with alternative usage for different purposes.

In order to keep investment cost in a reasonable range, the closest proximity to Singapore should be considered for such installations.

4.2.2.3 Pan-Asian power grid interconnection

One additional possibility to add significantly more PV power to Singapore's energy mix and level out variability over larger distances is to explore the feasibility of stronger interconnecting the Singapore power grid with those in its neighbouring countries. This could, in the long term considerably increase the contribution of renewables (not only solar) to Singapore’s electricity supply.

There are visions for trans-national super grids that would foster the large scale utilisation of renewable energy sources beyond regional co-operations. Most advanced is the DESERTEC project between Europe and Africa [Zic], but Asia-Pacific Super Grids have been proposed as well [Bla, Mat]. Such super grids would bring renewable electricity generation, storage and distribution to a new level. Though only a vision today such super grids could form a basis for a qualitatively novel sustainable global energy supply system by the mid of this century.

4.3 EFFECTIVE PV GRID INTEGRATION OF SOLAR PV IN SINGAPORE

4.3.1 PV contribution to Singapore's electricity supply

4.3.1.1 Development of the installed capacity in Singapore

The potentially installed capacity over time depends on the area efficiency of the solar modules and the expected technological advancements until 2020, 2030 and 2050, respectively. With today’s standard silicon wafer based module technology an area factor of 0.12 kW_p/m^2 of net-usable area can be assumed. This is a realistic value that is based on an optimum 10° tilt angle[1], a standard 250 W_p solar module of 1 m x 1.65 m area and a 30 cm spacing between every two rows of solar modules to allow access for installation and maintenance purposes. With improving efficiencies and in-line with section 2.1, it is expected that this factor will improve as indicated in Table 4.2:

[1] "Optimum angle" refers a compromise between the tilt angle, which mathematically should be zero (flat installation) close to the equator and the fact that only from ~10° tilt onwards rain would wash off the dust accumulated on the module surface, which otherwise would reduce the light transmission to the solar cells (so-called "self-cleaning effect").

Table 4.2: Assessment of future area factors in kW_p/m^2 for high efficiency PV modules, based on Table 2.2 and gradually decreasing cell-to-module losses. For further information on the assumptions, see Table 2.2.

Future area factors in [kW_p/m^2] for high efficiency PV systems			
Year	**2020**	**2030**	**2050**
BAS	0.19	0.21	0.22
ACC	0.20	0.25	0.30

Based on these area factors, the different PV deployment scenarios are shown in Table 4.3. All scenarios assume significant growth rates, starting with an installed capacity of 10 MW_p in 2012 (as per Figure 1.2). The increased area factors are only applied to newly installed PV systems after the indicated point in time.

Table 4.3: Assessment of cumulative future solar PV installations in GW_p, based on the area factors given in Table 4.2, starting with an existing area factor of 0.12 kW_p/m^2 today. For further information on the assumptions, see Table 2.2.

Future cumulative solar PV installations in [GW_p]				
Year	**2012**	**2020**	**2030**	**2050**
BAS	0.01	0.65	3	5
ACC	0.01	0.90	4	10

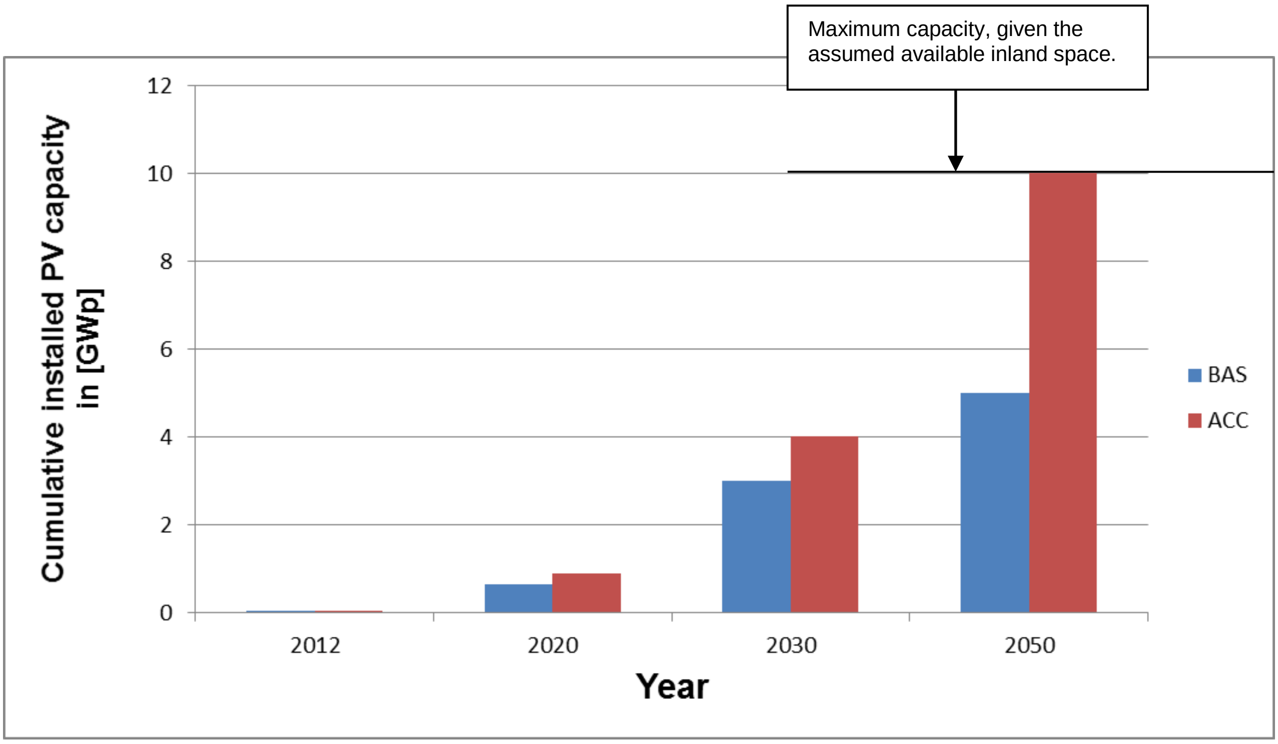


Figure 4.1: Growth scenarios for Singapore's solar PV deployment. Values are in GW_p and identical with Table 4.3. The graph also indicates the space limitations in Singapore on its inland space.

Figure 4.1 visualises these scenarios in graphical format and also indicates the approximate, maximum possible installations given the 45 km^2 limitations of usable area in Singapore, as derived in section 4.2.1. Anything beyond would require substantial PV electricity import from outside the land area of Singapore.

4.3.1.2 Contribution of PV electricity to the Singapore energy mix

As for the PV electricity generation of the various scenarios in section 4.3.1.1, the expected yield improvements are indicated in Table 4.4.

Table 4.4: Assessment of future energy yields in [MWh / (kW_p * year)] and performance ratios (PR) [%] for high efficiency PV modules, based on the long-term average irradiance for Singapore of 1,636 kWh/(m^2 * year) [Met]. For further information on the assumptions, see Table 2.2.

Future energy yields in [MWh / (kW_p * year)] and performance ratios (PR) [%] for high efficiency PV modules						
Year	**2020**		**2030**		**2050**	
BAS	1.36	83%	1.39	85%	1.43	87%
ACC	1.41	86%	1.44	88%	1.47	90%

Based on that, the installed capacities in the various scenarios would allow the generation of solar electricity values as shown in Table 4.5. The yield factors are only applied to newly installed PV systems in the respective time period, using the arithmetic averages between the higher and the lower values. These values have to be compared to today's electricity demand, measured by overall electricity sales, of 42.6 TWh (2012) [EMA].

Table 4.5: Assessment of the annual generated solar electricity in [TWh] for high efficiency PV modules[1], applying the area factors given in Table 4.2, the cumulative installed capacity values given in Table 4.3 and the yield factors given in Table 4.4, starting with an existing area factor of 0.12 kW_p/m^2 and a yield factor of 1.25 MWh / (kW_p year) (equivalent to the mean PR of 76% of today's' installations [NSR]). For further information on the assumptions, see Table 2.2.

Annual generated solar electricity in [TWh] for high efficiency PV modules				
Year	**2012**	**2020**	**2030**	**2050**
BAS	0.01	0.8	4	7
ACC	0.01	1.2	6	15

Referring to the three different demand scenarios outlined in the summary (see Executive Summary), Table 4.6 shows the possible share of PV contribution to Singapore's electricity supply.

[1] Based on crystalline silicon wafer-based solar cells.

Note on the assessment of the future energy supply system in 2050:
The BAS and ACC scenarios would lead to a gradual, but incremental addition of solar PV to the current electricity supply system with a penetration of annual solar energy in the order of 20% by 2050 (see Table 4.6). To address the issue of what would be required to substantially go beyond that level, a third possibility with more disruptive changes was evaluated. It requires fundamental changes to Singapore's energy supply system by 2050 and is therefore referred to as a "paradigm shift". Despite uncertainties for technological developments over ~35 years, this could result in the solar contribution to Singapore's electricity supply in 2050 being higher than in the ACC scenario. This, however, would require alternative deployment strategies as outlined in section 4.2.2, which includes off-shore floating PV systems and importing solar power through a future SE-Asian or even Pan-Asian power grid. For this "paradigm shift" to be possible, deliberate decisions would need to be made, carefully weighing geopolitical considerations, competing use of space and transmission requirements.

Table 4.6: Assessment of the relative contribution of PV electricity to the electricity demand in 2050 in [%], based on the generated energy from Table 4.5 and the energy scenarios outlined in the summary (see Executive Summary).

Relative contribution of PV electricity to the electricity demand in 2050 in [%]			
	E1 110 TWh	**E2 80 TWh**	**E3 50 TWh**
BAS	6%	9%	14%
ACC	14%	19%	30%

In addition to that, applying the 2012 grid emission factor of 0.50 kg CO_2/kWh for all years until 2050 [EMA6], Table 4.7 lists the potential CO_2 emission savings that can be derived from the scenarios given in Table 4.5. These values have to be compared to the current annual CO_2 emissions in Singapore of 45 Mt in 2011 [EMA6].

Table 4.7: Assessment of the annual CO_2 emission saving potential in Mt CO_2 for Si wafer-based PV modules, based on the solar electricity generation scenarios given in Table 4.5. For further information on the assumptions, see Table 2.2.

Annual CO_2 emission saving potential in [Mt, mega-tons] for Si wafer-based PV modules				
Year	**2012**	**2020**	**2030**	**2050**
BAS	0.007	0.40	2.0	3.5
ACC	0.007	0.60	3.0	7.5

4.3.2 Technical grid integration of PV electricity in Singapore

This roadmap focuses on grid-connected PV systems, which is expected to represent the vast majority of future PV installations in Singapore. The roadmap does not consider stand-alone, “off-grid” or hybrid systems that typically operate in an autonomous mode, but may also be connected to the main grid.

Managing the variable, non-dispatchable nature of the solar power output, finding the right mix of mitigation measures and estimating the associated cost is the most complex topic for a large-scale deployment of solar PV in Singapore. In this context, EMA issued the following assessment[1]: “the amount of intermittent generation that the system can accommodate based on the existing amount of reserves procured is the ‘Intermittent Generation Threshold’ (or IGT). In October 2013, EMA has raised the IGT from 350 MW to 600 MW. The IGT will be regularly reviewed and could be further increased in the future. Above the IGT, additional reserves capacity may also be procured to support the deployment of intermittent generation, up to the ‘Intermittent Generation Limit’ (IGL), which is still being studied and determined by EMA.”[2]

4.3.2.1 The solar resource in Singapore and its variable nature

One main characteristic of the solar resource is its availability during day-time with a typical peak at solar noon and, especially in the tropics, the high share of diffuse radiation (~55%) and the high level of variability due to frequently changing cloud coverage. Singapore's location close to the equator leads to very little seasonality over the course of a full year. In total, the annual irradiation is 1636 kWh / (m^2·a) [Met].

Figure 4.2 shows the irradiance profiles of a typical day with high variability in Singapore, as well as of a rare day with no cloud coverage. On a single location (here: SERIS' meteorological station), these perfectly clear-sky days happen on less than 5 days per year. The red curve is close to the extra-terrestrial "quasi sinusoidal-curve", which one could expect on a clear-sky day.

There are two crucial learnings for the interaction of the solar systems with the electric power grid:

- The irradiance, even at highest levels of variability, never goes down to zero during the day.
- Due to the statistical fluctuations throughout the day, the average irradiance is much lower than the peak irradiance.

[1] http://www.ema.gov.sg/media/com_consultations/attachments/526a1e95d104b-Consultation_Paper_-_Enhancements_to_the_Regulatory_Framework_for_Intermittent_Generation_28_October_2013_FINAL.pdf
[2] Information in parentheses given by EMA

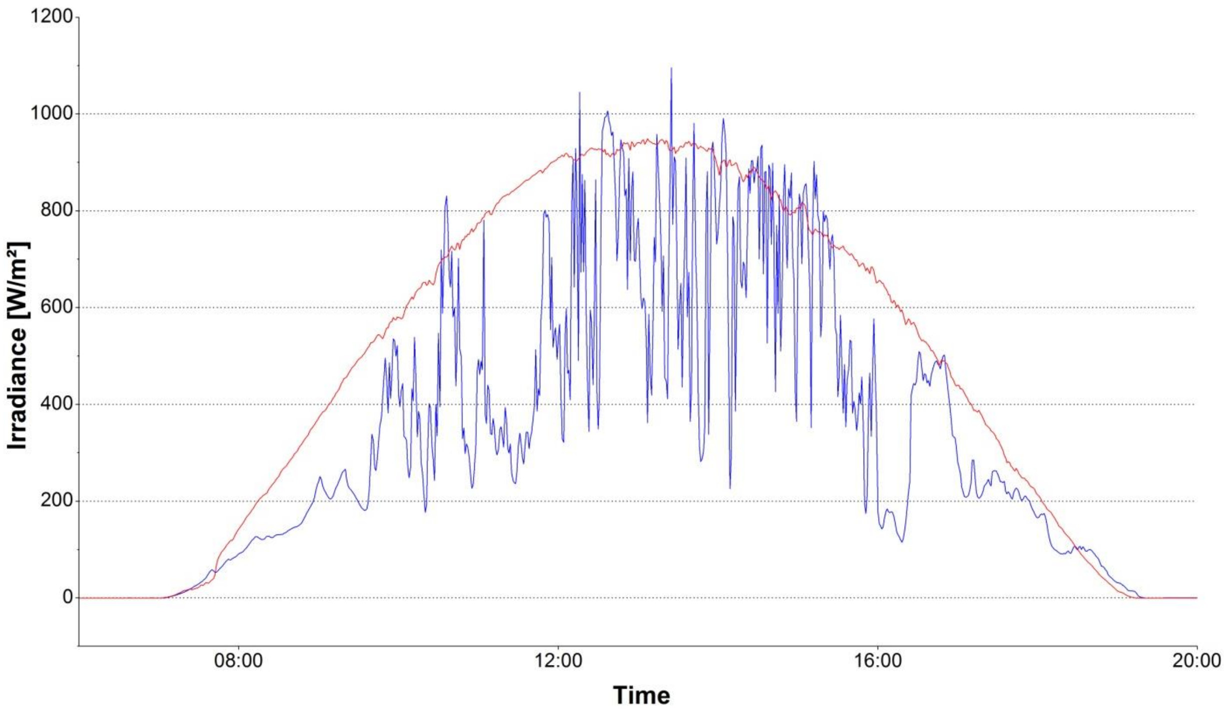
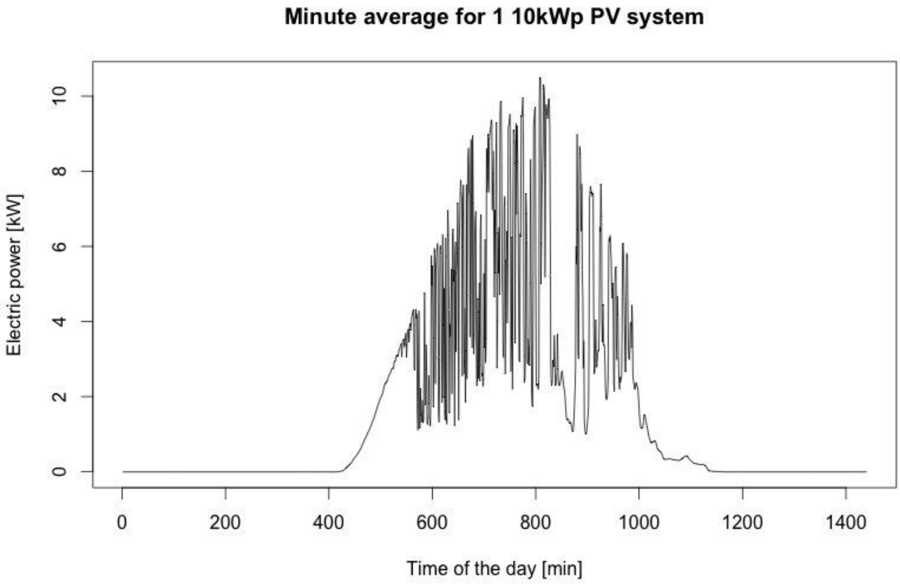


Figure 4.2: Irradiance profile of a single radiometer during a typical day with high variability in tropical Singapore (blue curve) and of a rare day with clear-sky conditions (red curve); Source: SERIS meteorological station, 1-min data.

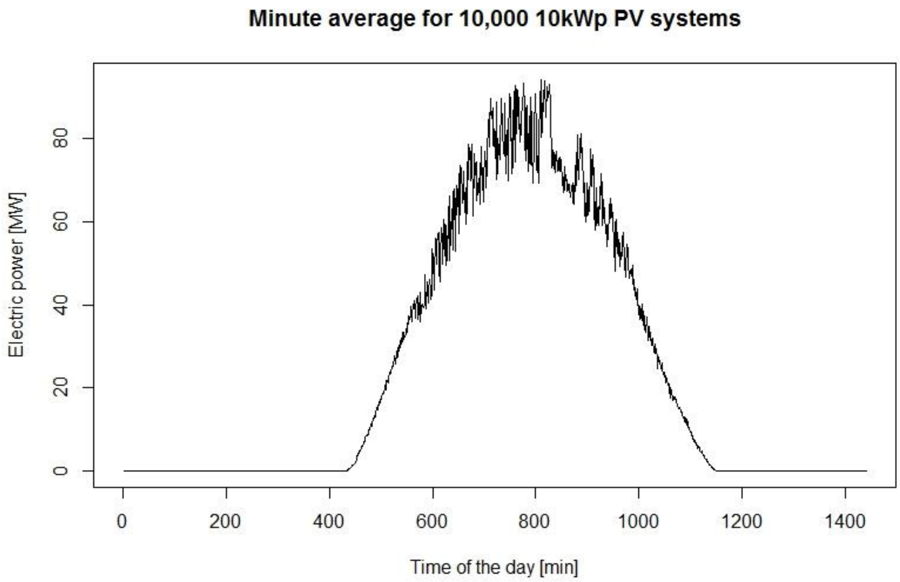
The temporal variations in solar energy fluxes have two components: a trend pattern (daily and seasonal), and a random (or stochastic) component. The stochastic component is characterized by a spatial coherence that decays approximately exponentially with increasing distance between the sites. That is, the power fluctuations of two combined solar power systems situated nearby at the same site are considerably larger than the fluctuations of the lumped power output of two systems when installed further apart (e.g., 10 km). The 'decay constant' mentioned above is roughly inversely proportional to the frequency of the power fluctuations. In other words, high-frequency fluctuations (in the range of seconds to minutes) are evened out much more effectively than low-frequency fluctuations (in the range of hours) [Bey, Lut].

Solar power systems, especially in urban environments like Singapore, are not deployed in a few locations with large-scale ground-mounted systems in the multi-megawatt range due to the shortage of available land space, but rather in a widely dispersed fashion on roof-tops or on facades (building-integrated PV, BIPV). It is therefore more relevant for Singapore to understand the combined output of a larger sample of smaller systems distributed across the main island e.g. hundreds and thousands of roof-tops.

This smoothening effect can be observed for the power output curve in Singapore for 10,000 PV systems of 10 kW_p rated power, compared to a single PV system with 10 kW rated power output station, greatly reducing the variability (see Figure 4.3). Further, the general shape of the curve (outside the fluctuations) comes close to the expected quasi sinusoidal shape for the clear-sky conditions, which will allow for output forecasts that should be acceptable for power systems operation. The maximum variability as a percentage of the total power output according to the Figure 4.3 (b) is in the range of 20%. This value is important for evaluating suitable counter measures to support the seamless grid integration into the electric power grid.



(a)



(b)

Figure 4.3: Smoothening of the lumped PV power output with the number of equally distributed 10 kW_p PV systems across Singapore: (a) Measured irradiance for a single system, and (b) Simulated solar power output for 10,000 PV systems), based on 25 actual irradiance measurement stations with 1-min data logging across Singapore and 2D-simulation of the irradiance variations [SER].

4.3.2.2 Possible measures to facilitate PV grid integration

The significant temporal variability of the solar power generation in Singapore, as shown above, poses two different types of challenges to an electric power grid operator:

1. Managing excess solar power during times of high irradiance;
2. Grid stability and conventional generation management issues during times of high variability of solar power generation.

Those two topics will be discussed separately in the following sections.

4.3.2.2.1 Shifting of excess solar power

Excess energy shifting on power system level will only be required once the actual solar power generation exceeds the demand over a certain time frame. This phenomenon is different from the fact that the instantaneous solar power generation will quite often be larger than the load on very short time scales (seconds, minutes), which is discussed below in the variability section. With a current annual peak demand in Singapore during week-day afternoons of ~6,700 MW, this case is not expected before the cumulative PV installations have reached ~13 GW_p. As mentioned earlier, long-term monitoring of PV systems in Singapore shows that the 1-hour averaged solar power generation is about ~50% of the rated installed capacity [SER].

Given the large amount of solar PV capacity that is necessary to exceed the current load demand and taking into account that the load is expected to go up over time (see Executive Summary), the scenario that there will be storage required in large scale for load shifting will not happen in Singapore for many years to come.

This can be different for individual isolated PV system operators who have little demand during the day when peak irradiance occurs. In that case in order not to forego the generated solar electricity, it would be necessary to store the solar energy locally or use the grid as “storage” by feeding-in excess solar power and draw it back at other times, e.g. at night.

4.3.2.2.2 Measures to manage variable solar generation

The seamless integration of an increasing share of variable solar power generation into electricity supply structures is intrinsically tied to the topic of how the future grid structure is envisaged. Globally there is no clear solution yet as to what is the best way to integrate so-called "distributed generation" (DG) into current power grid structures, since this strongly depends on the local boundary conditions, especially also the existing flexibility of the electricity generation technologies. In all cases, the complexity of the grid control becomes larger compared to today where uncertainty predominantly arises from the variability in demand and contingencies in supply. Consequently, there will be a need for greater flexibility, faster response times and reaction capabilities. The wider diversity in interactive measures that have to be implemented for effective grid control will include:

- Forecasting of irradiance and PV power output
- Active PV-grid interactions (making PV systems an active part of the grid)
- Demand response and demand-side management
- Storage technologies

They will be discussed in detail in the following.

4.3.2.2.2.1 Irradiance and PV power output forecasting

Spatially-resolved forecasting of the solar electricity generation over different time horizons will be very critical for the efficient and stable operation of the electric power grid in Singapore with an increasing share of variable PV.

Live irradiance data have to be collected and then processed and bundled with other meteorological inputs, such as satellite and numerical weather prediction model data, to generate spatially-resolved irradiance forecasts that are eventually converted into solar electricity generation forecasts. The different timescales deliver results for different stakeholders:

- Short-term (minutes to hours): for grid control and dispatch
- Intra-day: for ramping up or down demand-side response activities and/or conventional flexible generators (such as gas-fired power plants)
- Day-ahead: for activities at the electricity futures market

4.3.2.2.2.2 Active PV-grid interactions

Arising from regulations in Germany, the largest PV market globally with ~ 35 GW_p installed capacity, PV inverters for systems larger than 30 kW_p have to provide active and reactive grid support. The requirements range from provision of reactive power, frequency control to fault-ride through capabilities. In addition, all such systems have to have a device that allows for curtailing the power output through a signal from the utility grid control centre (down to 60%, 30% or 0% of maximum capacity). Following the developments in Germany, these grid support services are currently being included more and more in the European grid codes where there is no distinction anymore between central conventional and distributed renewable generators, e.g. in the new draft of the European "Requirements for Generators" code developed by the European Association of Electricity Transmission System Operators, ENTSOE-E [ENT]. Aim is to define suitable network codes that govern the solar PV systems' behaviour in a way that they show a *known* and *defined* reaction to certain grid conditions. In contrast to the belief some 5-8 years ago, PV system should now remain connected to the grid as long as it is safe to do so and support grid stability during normal as well as critical grid conditions.

As PV inverters installed today will remain connected to the grid over the whole lifetime of the PV system, it is important to ensure that today's requirements are compatible with and not compromising grid stability in a future scenario with high share of PV. Therefore, strong efforts need to be put on developing (or adopting) appropriate regulations and grid codes.

Through interactive inverters and provided that the inverter follows a known and pre-defined behaviour (according to suitable rules and regulations), it can be achieved that the ensemble of solar PV systems may not require additional primary spinning reserves anymore. Especially in Singapore that generates most of its electricity with relatively flexible gas turbines.

4.3.2.2.2.3 Demand response and demand-side management

Adjusting the demand to the available power in a dynamic process is a very powerful tool to address the variability of solar PV. It can be managed on micro- (household) and on macro- (industry, commercial) level. In that context, *demand response* (DR) refers to an immediate triggered action to an actual or anticipated drop / raise in solar PV output under a so-called "direct load control" (DLC) regime. It requires an instant communication link between the sender (typically a grid control centre and/or in future the power electronics of a disperse PV installation) and the recipient (a manageable load). *Demand-side management* (DSM) describes the scheduling of certain flexible loads at times with abundant (or anticipated excess) electricity generation. It has a longer time horizon, typically 30 minutes to hours in advance and hence does not necessarily need a direct line of communication. It can be accompanied by an adjustable pricing structure, for example to allow for lower electricity prices during times of abundant sunshine. This works even on private household level, and allows non-time critical loads to be run during those periods (e.g. washing machines).

DR and DSM can work in both directions: increase or reduction of loads. While very often, they are applied for the reduction of loads, it works equally well with increase of demand, which has a similar effect on the grid as storage. The absorbed energy, however, will then not be available as electricity anymore (unlike in a storage system, such as a battery). In the case of Singapore, there are at least two industrial applications that are highly suited for DR technologies: (i) chilled water production for air conditioning and (ii) desalination of seawater. The "stored" electricity will eventually reduce the demand at another time of the day, hence effectively works like excess energy shifting (see also below).

4.3.2.2.2.4 Storage technologies

The introduction of variable, non-dispatchable renewable energy sources (such as solar and wind) in electric power systems will eventually (at high levels of penetration) lead to the requirement for an efficient electrical energy storage system on different regional scales (central, distributed), at different capacities (small, medium, large) and on different timescales (ms to hours and days) to moderate supply-demand mismatches. PV-generated electricity is inherently variable and characterised by the diurnal cycle. Although the diversification of PV systems across Singapore will go some way to reducing the variability of the lumped PV electricity generation, the limited spatial extent of Singapore implies that variability will be a permanent consideration[1]. The desirability of dispatchable power, together with the need to maintain grid stability and the multiple benefits of time-shifting of the produced PV electricity, will likely make electrical storage an essential component of future smart grids.

Apart from the more “classical storage technologies, such as various types of batteries (e.g. lead acid, lithium ion, redox-flow), capacitors or mechanical storages (e.g. flywheels, pumped hydro, compressed air), the RD&D focus for Singapore should also focus on alternative storage technologies. Such alternatives would not necessarily convert the energy back to electricity, but use it for generation of fuel (e.g. by generating hydrogen through electrolysis) or potable water (e.g. through reverse osmosis in desalination plants).

One special case in Singapore could arise from a mass deployment of electric vehicles, which - from a utility perspective - can be seen as "moving batteries". While they can be a drain to the power grid during charging, they can also be considered as potential distributed energy source for grid stability support and balancing supply and demand [Hub]. Although the technology is reasonably well understood, the main challenge there will be the unknown "user behaviour" that cannot easily be planned or influenced.

4.3.2.2.2.5 Spinning reserves

Apart from the integration measures discussed above, the more traditional alternative is to increase the operating reserves of the electric power system. These are in part the so-called "spinning" reserves, which are idle running generators that are synchronised with the grid frequency and ready to instantly absorb any surges in demand. The other type are the "non-spinning" reserves that can be ramped up within a pre-defined time frame (e.g. 5, 10 min or longer). The behaviour of such reserves can also be emulated by power electronics with short-term storage devices (such as batteries), even in a very distributed fashion as it is expected for PV deployment. Alternatively, system reserves can also be provided by capacities under a Demand response (DR) and Demand-side management (DSM) regime.

[1] Off-shore PV systems have been proposed which may eventually mitigate the limitations of spatial distribution inherent in mainland-based PV systems in Singapore.

Experiences from other countries may not be representative for the specific case of Singapore though, especially when taking into account the high levels of output fluctuation due to the tropical climate conditions and the limited distances for levelling out this variability. Eventually, the total amount of system reserves required (spinning, non-spinning) depends on the "net variability" in the power system, i.e. the delta between the load variability and the resource variability (here: from solar PV systems). Therefore system simulation studies (such as the current NRF 9^{th} Competitive Research Programme (CRP-9) project of SERIS with various relevant stakeholders on “Power grid stability with an increasing share of intermittent renewables (such as solar PV) in Singapore”) that include both irradiance mapping and actual load data with high time resolution are key for a full understanding of the reserve requirements and mitigation measures here.

Given the fact that the majority of Singapore's conventional generation uses combined-cycle gas turbines, which are more flexible than coal-fired or nuclear power plants, the power system could be considered as well suited for the accommodation of an increasing share of PV electricity (eventually supported by any of the mitigation measures mentioned above).

4.4 ECONOMICS OF ROOF-TOP SOLAR PV IN SINGAPORE

4.4.1 Current roof-top PV electricity cost (LCOE)

The levelised cost of electricity (LCOE) is a well-established method in energy finance and policy for the calculation of the cost of electricity generation at the point of connection (to a load or the electric power grid). It factors in all costs over the lifetime of the generating system such as the initial capital, fuel (where applicable), capacity factors, operational costs, financing costs, periodic replacements and any other relevant costs, while considering the time value of money. For details and formulations, see Appendix C.

While a LCOE gives a monetary value per unit of electric energy generated by a certain technology, external factors or costs associated with grid integration are not taken into account and must be considered separately. In the case of PV, such external factors can be “negative" costs (e.g. reduced conventional capacity required due to matching peak generation with peak demand) or "real" costs (e.g. potential need for energy storage to bridge sudden generation losses caused by cloud-reduced solar irradiance).

The current LCOE of roof-top PV systems in Singapore can be calculated, based on the assumptions in Table 4.8. The resulting LCOE values range from 18-27 SGD-cents/kWh (see Tables 4.9 and 4.10), mainly depending on the turnkey system price and the assumed cost of capital.

Table 4.8: Assumptions for the calculation of the "Levelised Cost of Electricity" (LCOE) of solar PV systems in Singapore installed in Q1 2013.

System assumptions:	
Average annual yield:	1,250 kWh / (kW_p year) This is a conservative value based on 76% Performance Ratio (PR) as the actual values for installed PV systems in Singapore [NSR] and the long-term irradiance data. Using a PR of 83% (as observed in some systems in Singapore), then the annual yield would even be 1,350 kWh / kW_p.
Annual decrease of production:	-0.5% p.a.; This is in-line with international literature reviews. [Jor]
Financial assumptions:	
Turnkey systems price:	Two alternatives: 2,200 SGD/(kW_p installed capacity) and 2,500 SGD/(kW_p installed capacity). Those prices are taken from actual roof-top projects in Singapore for MW-scale (2,200) or smaller roofs of ~10 kW_p (2,500)
Leverage ratio:	100% debt-financed.
Cost of capital (using the "weighted average cost of capital, WACC):	Two alternatives: 4% p.a. (annuity); fixed interest rate; and 8% p.a. (annuity); fixed interest rate.
Tenure of loan:	20 years.
Annual operating expenses: (maintenance, repair, administrative cost, insurance)	2% of turnkey system price (with a split of 1/3 for insurance and 2/3 for operating cost).
Annual rent / lease of space (to the building owner):	Two alternatives: No rent (for building owners); and 3% of revenue[1]. This is equivalent to ~ 1 SGD/m^2.
Inflation on operations and insurance:	4% p.a.
Operation period:	20 years.
Depreciation:	Linear over 20 years.
Taxation:	Zero, i.e. calculation is excluding any taxes.
Salvage value after 20 years:	Zero; typically identical with dismantling cost.
Grid utilisation charges	Zero, i.e. no feed-in to the national power grid.
Resulting LCOE:	See Tables 4.9 and 4.10.

[1] The building owner will receive this amount in compensation for allowing the PV system owner to use his/her roof.

Table 4.9: Results of the "Levelised Cost of Electricity" (LCOE) calculations for solar PV systems in Singapore in SGD-cents/kWh as a function of "Turnkey systems price" and whether or not rent has to be paid. Assuming cost of capital of 8% and PV system prices of Q1 2013.

	Turnkey system price of 2,200 SGD/kW$_p$	Turnkey system price of 2,500 SGD/kW$_p$
Cost of Capital: 8%, rent to be paid	24	27.5
Cost of Capital: 8% no rent to be paid (i.e. for building owners)	23.5	27

Table 4.10: Results of the "Levelised Cost of Electricity" (LCOE) calculations for solar PV systems in Singapore in SGD-cents/kWh as a function of "Turnkey systems price" and whether or not rent has to be paid. Assuming cost of capital of 4% and PV system prices of Q1 2013.

	Turnkey system price of 2,200 SGD/kW$_p$	Turnkey system price of 2,500 SGD/kW$_p$
Cost of Capital: 4%, rent to be paid	19	22
Cost of Capital: 4% no rent to be paid (i.e. for building owners)	18.5	21.5

4.4.2 PV electricity cost reduction over time (LCOE)

Table 2.6 has given the expected cost development for medium- to large-scale PV systems, clearly moving below the 1 USD/kW$_p$ threshold by 2020.

For the case of Singapore, there are generic obstacles for achieving this low global cost levels due to the urban nature where PV systems will predominantly be built on roof-tops that in many cases also have obstructions such as chimneys, elevator shafts or water tanks. Therefore, for the future LCOE calculations, an additional 20% are added for the higher complexity of system installations. This top-up is phased out over time to reflect innovations in the integration of PV into buildings (+ 10% in 2030; +0% in 2050). On top of this, a generic systems integrator margin of 10% of sales is added to accommodate for turnkey *prices* (to the end user) rather than *cost* of the components. Table 4.11 reflects these additions. The values given there are then used for the future LCOE calculations.

Table 4.11: Assessment of future prices of total PV system cost (power range: 10–100 kW_p). Large scale industrial manufacture is assumed. Data are given in SGD/W_p. For further information on the assumptions, see Table 2.2.

Prices of PV systems in SGD/W_p			
Year	**2020**	**2030**	**2050**
BAS	1.45	1.2	1.0
ACC	1.35	1.1	0.9

Given the improvements of the yield factor over time (see Table 4.4) and the reduction of turnkey system cost (see Table 4.11), Tables 4.12 and 4.13 show the development of the LCOE of PV systems in Singapore over the time horizon of this roadmap using the baseline (BAS) and accelerated (ACC) scenarios, each for two different assumed cost of capital (4% and 8%). Only the case where rent has to be paid is considered. This is a more likely scenario and also allows for investor or solar leasing models.

Table 4.12: Assessment of future "Levelised Cost of Electricity" (LCOE) of solar PV systems in Singapore in SGD-cents/kWh. Assumed cost of capital is 8%. Calculations consider improvements of the yield factor over time (see Table 4.4) and reduction of turnkey system prices (see Table 4.11). For further information on the assumptions, see Table 2.2.

Future LCOE of solar PV systems in Singapore in [SGD-cents/kWh], with 8% cost of capital			
Year	**2020**	**2030**	**2050**
BAS	15	12	10
ACC	13	11	9

Table 4.13: Assessment of future "Levelised Cost of Electricity" (LCOE) of solar PV systems in Singapore in SGD-cents/kWh. Assumed cost of capital is 4%. Calculations consider improvements of the yield factor over time (see Table 4.4) and reduction of turnkey system cost (see Table 4.11). For further information on the assumptions, see Table 2.2.

Future LCOE of solar PV systems in Singapore in [SGD-cents/kWh], with 4% cost of capital			
Year	**2020**	**2030**	**2050**
BAS	12	10	8
ACC	10.5	8	7

These calculations show that there is a medium-term perspective to reach LCOE's in Singapore for PV system on its land area of approximately or even below 10 SGD-cents/kWh, excluding external factors, such as grid integration costs.

4.4.3 Assessment of the full cost implications of PV electricity in Singapore

As mentioned in section 4.4.1, the "levelised cost of electricity" (LCOE) is a figure of merit to compare the cost of electricity generated by different technologies at the connection point to the grid point. It helps to compare various generation technologies, but does not include any external factors. Those external cost could arise from the variable, non-dispatchable nature of the solar power generation, which potentially poses a challenge to traditional electric power systems that are structured into generation, transmission and distribution. In addition, solar systems, especially in urban areas, tend to be installed in smaller systems sizes (10-100 kW_p) on roof-tops and are therefore "distributed generators", for which the original grid architecture has not been designed for.

There are, however, also positive effects from distributed generation using photovoltaic, which have to be considered as well when trying to perform an evaluation of the full cost of solar electricity.

4.4.3.1 Examples of grid integration cost

There are various cost items for the power system operator to consider when envisaging the large-scale integration of solar PV systems into the power grid. It is noted though that the degree of such measures (and associated costs) depends on the penetration levels with variable, distributed generation (such as PV) and the need for such measures increases gradually with the continuous deployment of solar systems. Some of the anticipated measures could be:

- Forecasting of irradiance and PV power output:
  This is crucial for the generation operations in the time frame of 10-15 min (dispatch cycle) up to intra-day and even day ahead, and greatly helps managing the generation side.
- Active PV-grid interactions:
  This is critical for the transmission operations. Especially during grid disturbances or overload situations, the codes must prescribe a known and pre-defined behaviour to avoid any unforeseen events.
- System reserves:
  For balancing the variable output from solar PV systems, using system reserves, there are two cost aspects to be considered: addition of (highly flexible) generation capacity and of ramping requirements, which possibly could lead to higher wear and tear, and lower operational efficiency.

- Grid reinforcements:
  The most trivial approach to avoid over-voltage situations is simply to reinforce the grid and/or add controllable transformers.
- Storage solutions for power applications:
  As outlined in previous sections, storage is a possible option for various types of use within an electric power system. Storage is typically distinguished by its use for power (e.g. instant grid stability support) or energy (e.g. load shifting). As large-scale load shifting (over days or seasons) will most probably not be required in Singapore, hence the focus is more on power-related (most critical time frame is the "minutes to 1 hour") and small-scale energy applications, such as power quality or bridging power [Den]:

The integration costs largely differ depending on the environmental conditions, such as climate, density of PV deployment (especially concentration on individual distribution lines) and power grid area / topology for possibly levelling out of variability with distance. In one such analysis, for example, a study from Colorado/USA calculates grid integration cost for 800 MW_p in a 6,922 MW peaking system of 3.51 - 7.14 USD/MWh, equivalent to 0.004 - 0.009 SGD/kWh [ENC]. Other studies in Europe for penetration levels of up to 18% on energy level [Pud] project cost of 5-26 EUR/MWh (equivalent to 0.0085 – 0.044 SGD/kWh), depending on the country, its current grid conditions and the PV capacity factor.

It shall be noted that these studies can only give a very rough assessment for the case of Singapore, as the actual impact on the power system has to be simulated and modelled in detail in order to understand the best technical and economical way of managing the system in the future.

4.4.3.2 Positive cost factors

There are a number of positive influences from the large-scale deployment of solar PV system in Singapore. Those will be only discussed qualitatively, as a detailed quantitative analysis would require complex macro-economic calculations, which were beyond the scope of this roadmap.

Electric power system-related effects:

- Cost savings from peak shaving (conventional electricity generation) during times of maximum electricity demand (e.g. air conditioning), which is often generated by highly flexible, but rarely used generation capacity and is hence associated with highest generation cost.

Energy policy-related effects:

- Stability of electricity cost due to the fact that most cost of a PV system have to be borne upfront at the time of installation. This, however, has the advantage that the electricity cost is basically logged-in for the entire lifetime of the system. And even after the warranty has expired (typically 20-25 years) the electricity generation continues at marginal cost, which prevails as long as the generated electricity cost has a value greater than the annual operation & maintenance cost.

- Independence from importing resources. Gradually becoming in part energy-autonomous has a value associated with it. This also reduces cost for storage of conventional energy resources for interims periods, should the energy supply be interrupted - be it for technical reasons, acts of terrorism or political tensions between countries.

Environment-related effects

- Carbon emission reductions, which will have a positive impact on human mankind, but also on the possible reduction of raising sea levels, which on the long term could affect Singapore as well. Depending on current international negotiations of carbon trading, there will also be a $-value associated with the reduction of CO_2 emissions in the future.

4.5 INDUSTRY, DEPLOYMENT AND RD&D STRATEGIES FOR SOLAR PV IN SINGAPORE

Strategies are measures to reach a goal. Thus strategies generally depend strongly on the setting of such goals. In the context of a sustainable PV electricity supply for Singapore three main goals should be targeted:

- scientific excellence in PV materials, cells and modules research
- increased and optimised deployment of PV in Singapore and
- fostering of industrial activities.

This will also lead to education and training of experts in those areas on different academic levels to gradually build a renewable and solar expert cohort in Singapore.

4.5.1 Increasing scientific excellence in PV materials, cells and modules research

Achieving this goal would increase the international reputation and ranking of Singapore's universities and research institutions. In this context the authors of this roadmap recommend to focus on novel very-high-efficiency, low material consuming and low cost energy conversion paths. In particular materials research could contribute substantially to the realisation such novel devices. It is important that these devices are in principle compatible with a sustainable industrial mass production. Thus application oriented R&D should be done in close cooperation with industry. Detailed activities should be:

Short-term (before 2020):

- Development of very high-efficiency c-Si cells (hetero-junction, all-back contact cells).
- Development in particular of high efficiency multi-crystalline solar cells (industry type).
- Start the development of multi-junction cells consisting of silicon wafers and III/V and/or II/VI thin films.
- Continue the development of epitaxial crystalline silicon thin-film solar cells.
- Further development of CIGS[1] and CZTS[2] thin-films (and other thin-film cells that have the potential for very low cost production and which are based on ecologically acceptable materials).
- Research on improved optical management in solar cells.
- Research on fundamentally novel PV energy conversion concepts (e.g. tandem concepts for Si wafer based cells).
- Develop efficient module manufacturing technologies for new types of solar cells that are near to market introduction.
- Enter material-related research for crystalline silicon wafers.
- Develop improved block-cast silicon ingots and wafers.
- R&D on reducing rare, costly and environmentally non-benign materials in the manufacture of solar cells and modules (e.g. Silver, lead).
- Optimise manufacturing processes including real-time process analyses and recycling of process materials.

Medium-term (2020 - 2030):

- Continue working in the R&D areas mentioned above.
- Increase research activities on the development of fundamentally novel photovoltaic energy conversion concepts (donor acceptor solar cells, self-organisation of PV structures, tandem concepts, etc).
- Start R&D on high efficiency concentrating PV (optics, cells and systems) in a strategic way addressing the international market.
- Design and establish R&D pilot productions line for full-size high-efficiency thin-film on modules.
- Identify new earth abundant materials for thin-film solar cells for low-cost mass manufacture.

Long-term (2030 - 2050):

- Continue working in the R&D areas mentioned above, increase efforts where promising

[1] Copper Indium Gallium Diselenide.
[2] Copper Zinc Tin Sulfide.

4.5.2 Facilitating the deployment of PV in Singapore through RD&D

There are three major challenges for the large-scale dissemination of solar PV in Singapore: PV grid integration, limited space and the tropical climate. Singapore's RD&D community has the unique chance to take on these challenges and turn them into opportunities. For all three areas Singapore has the great potential to become a global know-how and knowledge hub:

PV grid integration challenge:

The main challenge for a large-scale deployment of PV energy conversion in Singapore is the integration of PV electricity into the nation's electricity grid. Having one of the most reliable power systems in the world, the opportunity is to keep this benchmark and to master the reliable integration of a sizeable share of solar PV, despite the high variability and the limited spatial distribution of the system installations. This can be a role model for other megacities and upcoming "solar districts" in other parts of the world.

Short-term (before 2020):

- Enhance spatially- and time-resolved irradiance and PV output forecasting for Singapore ("energy meteorology").
- Conduct entire power system simulation study for Singapore's power grid in real-time and add both load and PV output data (actual, forecasting) to assess true impact of an increasing share of solar PV on the power system.
- Develop grid integration devices that interact between the PV system and grid control centre.
- Develop and roll-out suitable communication infrastructure and protocols for real-time interaction between PV systems and the grid control centre.
- Assess potential for demand response and demand-side management in Singapore and develop control electronics for his purpose.
- Develop demand response devices (industrial, consumers) that react to grid signals and are optimised for flexibility with less wear & tear (e.g. industrial air conditioners with cooling reservoirs).
- Develop technical solutions for the support of the "energy market model" for PV in Singapore as defined by the market regulators (e.g. home energy management).
- Develop products and system designs for "virtual power plant" and "dispatchable" solar power.
- Develop advanced electrochemical storage solutions optimised for PV grid integration for both power and energy applications.

Medium-term (2020 - 2030):

- Address PV integration issues associated with the large-scale introduction of electro-mobility.

Accompany the possible establishment of "power-to-gas" with all technical aspects along the value chain (if desirable).

Long-term (2030 - 2050):

- Continue working in the R&D areas mentioned above, increase efforts where promising.

Space challenge:

Singapore is an Asian mega-city characterised by a high population density and a large share of high-rise buildings. The large-scale deployment of solar PV in Singapore requires a more fundamental approach of how and where PV system could possibly installed. A concerted effort is required from architects, government agencies, academia and industry alike to overcome the challenge in an effective way.

Short-term (before 2020):

- Conjointly with architects, government agencies and industry address the issue of space utilisation and increasing space for PV use, whilst preserving the necessary urban green space.
- Create and test innovative solutions for system deployment (e.g. inland floating PV, building-integrated PV (BIPV), PV canopies, and extremely light weight movable PV canopy construction).
- Conduct a comprehensive solar potential analysis based on 3D models from aerial view data.
- Start analyses on the utilisation of space for renewable energy applications outside of Singapore’s main island, in consultation with the relevant authorities.
- Address and develop solutions for suitable infrastructure areas (e.g. MRT lines).
- Develop comprehensive concepts for "solar districts", test-bed and implement it.
- Leverage local marine platform industry to explore suitable expansion into off-shore PV.

Medium-term (2020 - 2030):

- Develop comprehensive concepts for energy supply outside of Singapore’s main island (e.g. "energy islands"[1]), possibly even combined with off-shore industries (e.g. fish farms) or human habitats.
- Start analyses on future SE-Asian or even Pan-Asian power grids.

Long-term (2030 - 2050):

- Continue working in the R&D areas mentioned above, increase efforts where promising.

[1] “Energy islands" refer to energy generating units that are floating off-shore, leveraging various technologies such as solar PV, wind or ocean waves. They can be connected to an adjacent or the main island, but may as well function as autonomous energy supply units to future floating off-shore industrial estates (the simplest ones being fish farms) or for future habitats as an alternative to land reclamation.

Tropical climate challenge:
The tropical climate is characterised by constantly high air temperatures and high air humidity values, which leads to higher wear & tear of PV system installations. Long-term durability and reliability of PV systems over 20-30 years or more will become key for a sustainable energy supply, but also to gain investors' confidence. Scientific excellence in this area will be crucial and transferable also to other tropical countries that have embarked on a journey of large-scale PV deployment (e.g. Thailand, Philippines or Brazil).

Short-term (before 2020):

- Develop "Singapore modules" with high energy yield and durability in the tropics.
- Create new and innovative solutions for system mounting on existing roof-tops (e.g. on HDB blocks).
- Run extensive testing and quality assurance programs for PV module and system component in the tropics to assess the suitability and develop mathematical models for the system reliability over time.
- Enter research into PV module recycling, provided promising business case, including waste-treatment aspects.
- Together with PV module and balance-of-systems manufacturer, establish solutions for higher automation and lower cost in PV system deployments (e.g. though pre-fabrication of whole strings).
- Develop components and PV system designs for off-shore marine environments.
- Develop off-grid applications and large-scale solar hybrid systems for the Asia-Pacific region (e.g. diesel replacement with solar PV).

Medium-term (2020 - 2030):
- Establish R&D pilot lines for PV module recycling, provided promising R&D results.
- Find technical necessity and possible solutions for "re-powering" of existing PV installations with new low-cost, high-efficiency technologies.

Long-term (2030 - 2050):
- Continue working in the R&D areas mentioned above, increase efforts where promising.

4.5.3 Fostering industrial activities and development in PV

Increased industrial activities in Singapore through R&D and manufacturing of PV materials, solar cells, modules and potentially power electronic units directly contributes to the nation's GDP and employment of its skilled work-force. According to data from 2012, the PV value chain in Europe creates 30-60 jobs per MW_p installed [EPI]. This includes both, direct and indirect jobs. Typically half of those are industrial jobs in manufacturing[1], with the other half being localised for system design, installation and financing of solar PV systems, but also supporting functions in the economy. By just taking only half of the lower end of the band as an example, for every 1 GW_p of PV installations, about 15,000 jobs (direct and indirect) would be created locally.

Consider research and industrial production of equipment for solar cell and module manufacture like laser structuring, deposition of thin films, equipment for the forming of electrical contacts, etc.

Doing R&D for industries in other countries and developing exportable solutions should create additional income to R&D institutions in Singapore and should also help in further building up a PV-relevant high-quality resource base of scientists and engineers. In order to create an additional return on Singapore's investment in R&D, a focus in applied PV research should be on creating marketable intellectual property rights.

As for *PV materials, cells and modules*, one of the globally largest and most advanced silicon wafer PV cell and module companies is based in Singapore. Several of Singapore's R&D institutions closely cooperate with this manufacturing plant. It is essential that the expected technological progress in silicon wafer PV technologies (see section 3.1.3) is at least partly generated in Singapore.

Generally, a focus on industry oriented R&D - in close cooperation with industry - is a prerequisite for further strong reductions of the cost of PV electricity and further significant increases in the performance of mass-produced PV technologies.

For *PV grid integration*, since Singapore is both industry-wise and research-wise strong in electronics and IT technologies it is recommended to increase industry and R&D activities on components and software for smart grids. The same applies to the harvesting of Singapore's strengths in materials science and in battery technologies.

As for overcoming the *space challenge*, the building and construction industry is one of the focus areas of Singapore's economy. Developing fully building-integrated PV structures and design tools could create a unique position for this industry in Singapore.

In terms of *PV system for the tropics*, in addition to the grid-connected technologies discussed above, Singapore should also leverage its location, being surrounded by many countries with large areas that lack access to modern electricity supply. In many neighbouring countries there is a huge demand in rural and industrial[2] off-grid PV applications, including PV hybrid systems. Singapore's

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[1] i.e. at the country of origin of the solar modules, inverters and components.

[2] Powering telecommunication systems, sensors, cooling systems in agriculture, etc.

R&D institutions – in close cooperation with industry – should develop power electronics[1] and complete PV electricity supply systems for off-grid applications in tropical climates.

4.5.4 General Recommendations

The following recommendations show the critical decisions and strategies for the adoption and the large-scale deployment of solar PV in Singapore:

Short-term (before 2020):

- Stay at the forefront of solar material, cell and module research and selectively expand the activities where scientific excellence is given in Singapore and/or industry partners can be attracted.
- Pro-actively address the major challenges for large-scale application of PV in Singapore and turn them into opportunities; here especially the grid integration, the space and the tropical climate challenges. This will have a signalling effect globally in establishing Singapore as *the* knowledge and know-how hub for PV system deployment in the tropics.
- Pass relevant laws and codes that facilitate the wide-spread adoption of PV in Singapore as long as it is in line with government policies.

Medium-term (2020 - 2030):

- Start "out of the box" thinking when it comes to possible space to be used for solar PV installations. Deliberate decisions on space allocations will have to be carefully considered, in view of the potential opportunity cost (e.g. for the use of islets).

Long-term (2030 - 2050):

- Assess the feasibility of future SE-Asian or even Pan-Asian power grids.
- Explore the generic concept of floating “off-shore” islands for energy generation, and in the future possibly for industrial use or even habitats.

The authors sincerely see a great potential for the large-scale adoption of solar PV in Singapore and the future lighthouse role of Singapore in the global PV community as *the* Centre of Excellence for PV worldwide and particular in the tropics.

[1] Including electricity storage adapted to tropical conditions.

5. APPENDICES

APPENDIX A

Literature

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APPENDIX B

Acronyms and abbreviations

AC	Alternative current
ACC	Accelerated development
a-Si	Amorphous silicon
a-Si:H	Hydrogenated amorphous silicon
BAS	Baseline progress
BIPV	Building-integrated photovoltaics
BOP	Balance of plant
CAES	Compressed air energy storage
CAPEX	Capital expenditure
CCGT	Combined-cycle gas turbine
CCS	Carbon capture and storage/sequestration
CIGS	Copper indium gallium diselenide
CdTe	Cadmium telluride
CNREC	China National Renewable Energy Centre
CO_2	Carbon dioxide
COP	Coefficient of performance
CPV	Concentrator photovoltaics
CSP	Concentrated solar power
DC	Direct current
DR	Demand response
DSCR	Debt service coverage ratio
DSM	Demand-side management
EDB	Economic development board, Singapore
E^2PO	Energy efficiency programme office, Singapore
EMA	Energy market authority, Singapore
EMC	Energy market company, Singapore
EPIA	European photovoltaic industry association
EU	European Union
EVA	Ethylene vinyl acetate (photovoltaic module encapsulant material)
FIT	Feed-in tariff
GenCo	Power generation company
GHG	Greenhouse gas
GT	Gas turbine
HVAC	Heating, ventilation and air-conditioning
HCPV	High concentration photovoltaic
IDR	Iskandar development region, Malaysia
IEA	International energy agency
IEC	International electrotechnical commission
IM	Iskandar Malaysia
IPCC	Intergovernmental panel on climate change
IPPs	Independent power producers
IRDA	Iskandar regional development authority, Malaysia

ISE	Fraunhofer Institute for Solar Energy Systems (Fraunhofer ISE)
JNNSM	Jawaharlal nehru national solar mission, India
kWh/MWh/GWh	Kilowatt-hour/megawatt-hour/gigawatt-hour
KeTTHA	Ministry of energy, green technology and water, Malaysia
LCOE	Levelised cost of electricity
Mtoe	Million tonnes of oil equivalent
Mtpa	Million tonnes per annum
NCCS	National climate change secretariat, Singapore
NDRC	National development and reform commission, China
NEDO	New energy and industrial technology development organization, Japan
NEMS	National electricity market of Singapore
NREL	National renewable energy laboratory, USA
OPEX	Operating expenditure
O&M	Operation and maintenance
PAS	Paradigm shift
PCS	Power conversion system
PLN	Perusahaan listrik negara ("state electricity company" in Indonesia)
PSOD	Power system operation division
PV	Photovoltaic(s)
PVPS	Photovoltaic power systems
R&D	Research and development
RD&D	Research, development and demonstration
RES	Renewable energy sources
SEDA	Sustainable energy development authority, Malaysia
SEII	Solar Europe industry initiative
SEMI	Semiconductor equipment and materials international
SERIS	Solar energy research institute of Singapore
Si	Silicon
ST	Steam turbine
STC	Standard testing condition
T&D	Transmission & distribution
TCO	Transparent conducting oxide
TNB	Tenaga Nasional Berhad, Malaysia (National power grid operator in Malaysia)
TPC	Total project cost
TSO	Transmission and system operator
W_p/kW_p/MW_p	Watt-peak/kilowatt-peak/megawatt-peak
WACC	Weighted average cost of capital
WBGU	Wissenschaftlicher Beirat der Bundesregierung globale Umweltveränderungen (German Advisory Council on Global Change)

Glossary

Anti-Islanding: Islanding refers to the condition in which a distributed generator continues to supply electrical power to a sub-section of a grid even though electricity is no longer supplied by the utility. Islanding can be dangerous to utility workers who may not be aware that a circuit in the above-mentioned location is still powered. To prevent this problem, distributed generators must detect islanding and immediately stop producing power. This is referred to as anti-islanding. A common example is a grid that has solar panels that act as a distributed generator attached to it. In the case of a blackout, solar panels will continue to supply power to the grid as long as the illumination condition is appropriate, thereby potentially inducing an islanding effect. Being the PV feed-in interface between the PV supply circuit and the utility grid, inverters are expected to have some sort of anti-islanding mechanism.

Biomass: The total organic mass of the biotic environment, either as living or dead biomass or organic wastes (e.g. fuel wood, charcoal and dung). Important conversion products of biomass include biogas and biofuel. In several developing countries, traditional biomass use is the dominant form of energy supply.

Black-start: A black start is the process of restoring a power station to operation without relying on the external electric power transmission network. Normally, the electric power used within the plant is provided from the station's own generators. If all of the plant's main generators are shut down, station service power is provided by drawing power from the grid through the plant's transmission line. However, during a wide-area outage, off-site power supply from the grid will not be available. In the absence of grid power, a so-called black start needs to be performed to bootstrap the power grid into operation. To provide a black start, some power stations have small diesel generators which can be used to start larger generators (of several megawatts capacity), which in turn can be used to start the main power station generators.

Capacity factor: The capacity factor of a power generating system is the ratio of the actual energy output of the system over a period of time and the system's potential output if it had operated at full nameplate capacity over the entire time.

Captive power: Captive power is electrical power that is generated by any entity primarily for its own consumption (not for sale).

Carbon Capture and Storage/Sequestration: This is a process of removing generated carbon dioxide from large point sources such as coal-based power plants, transporting the gas to a storage site, usually an underground geological formation, to be kept so that it will not re-enter the atmosphere. The objective of this process is to prevent greenhouse gas emission to the atmosphere so as to reduce the impact of global warming and climate change.

Coefficient of performance (COP): This is the ratio of work or useful output of an energy conversion unit to the amount of work or energy input. The COP is e.g. used as a measure of the energy-efficiency of air conditioners, space heaters and other cooling and heating devices.

Contestable consumers: These are electricity consumers in Singapore who uses, on average, > 10,000 kWh of electricity per month. Non-contestable consumers use < 10,000 kWh of electricity per month.

Decarbonisation: The process of removing carbon from the energy cycle. In the context of this roadmap, carbon-based gases are to be removed from the atmosphere. In October 2009, the European Council set an economy-wide greenhouse gas abatement ("decarbonisation") objective of 80–95% below 1990 levels by 2050.

Demand-side management: Demand-side management describes the scheduling of certain flexible loads at times with abundant (or anticipated excess) electricity generation. It has a longer time horizon, typically 30 minutes to hours in advance and hence does not necessarily need a direct line of communication[1] to the electricity supply utility. It can be accompanied by an adjustable pricing structure, for example to allow for lower electricity prices during times of abundant sunshine.

Demand response: Demand response refers to an immediate triggered action to an actual or anticipated drop /rise e.g. in solar PV output. It requires an instant communication link between the sender (typically a grid control center and/or in future the power electronics of a disperse PV installation) and the recipient (a manageable load).

Dispatchable: Dispatchable generation refers to sources of electricity where the power generation output can be adjusted at the request of power grid operators by turning power plants on or off to match demand. This is in contrast to variable/intermittent renewable energy sources such as wind and solar power in which the power output is dependent on environmental conditions and cannot be controlled by operators. Therefore, these renewable energy sources are non-dispatchable.

Energy efficiency: This refers to the use of energy in an efficient manner so that energy demand needed for energy services can be minimized. Energy efficiency is often considered the energy demand-side solution towards sustainable development. The supply-side solution can be achieved through the use of renewable energy.

Feed-in tariff: This is a government incentive scheme in the form of a fixed, guaranteed price, usually above those of the existing retail electricity price, over a stated fixed-term period when renewable power can be sold to the utility by feeding into the electricity network.

[1] SERIS has just signed a CRP-9 project in collaboration with EMA (PSOD) and Singapore PowerGrid to simulate the entire Singapore power grid in real time. This project will also evaluate the possibilities of demand response in greater detail.

Final energy: Final energy is energy that is available in an utilisable form after conversion of primary energy to secondary energy and after transportation and distribution to the final consumer (e.g. electricity from the socket, or petrol at the petrol pump). Final energy is the third stage in the energy flow chain from primary over secondary to useful energy.

Fossil fuels: These are carbon-based fuels from fossil carbon deposits, including coal, oil and natural gas. Their combustion releases carbon dioxide, which is the main driver of human-induced global warming.

Grid emission factor: The grid emission factor refers to the amount (grams, kg, etc) of carbon dioxide released per unit (Wh, kWh, etc) of electricity produced.

PV Grid penetration/penetration level: This is defined as the ratio between the (annual) average PV electricity generation fed into the grid to the average load of the grid. In general the PV energy fed into the grid will originate from many PV installations.

Inverters: Inverters are devices that convert electric energy from direct current (DC) generated e.g. by the solar panel to alternating current (AC) for feeding into the grid.

Junction in semiconductors: A junction is the interface region between semiconductors of different composition. In PV a p-n homo-junction is the interface region between positively and negatively doped semiconductors of the same material (e.g. silicon). Hetero-junctions are composed of different materials

Kilowatt-peak (kW_p): This is the physical unit of the output of a PV module under standard test conditions, i.e. global radiation 1000 W/m^2, device/module temperature 25 °C and AM1.5G irradiance spectrum.

Kilowatt-hour (kWh): The kWh is a commonly used measure of energy. For larger installations, energy is often stated in megawatt-hours (MWh) per year.

Levelised cost of electricity/electrical energy (LCOE): The LCOE is defined as the ratio of the sum of net present value of all related costs over the lifetime of the system, divided by the total electricity output over the system's operational lifetime. LCOE calculations give a cost per unit of energy by considering the initial capital, fuel, capacity factors, operational costs, financing costs, periodic replacements, depreciation, taxes and any other relevant costs. Such calculations allow strategic inter-comparisons of differing technologies.

Load shifting: This is a process of shifting electricity that is generated in excess of the demand in a location/time of the day to another location/time of the day where/when the energy demand is not met by the generated output at that location/time.

Micromorph solar cell: This is a double-junction silicon tandem solar cell where two solar cells are series connected in one device. One cell is made of amorphous silicon, the other consists of microcrystalline silicon material.

PV Peak shaving: This is the process of capping the (usually fluctuating) power output of a PV generator. Peak shaving can be used to reduce the variability of PV output so as to enhance grid stability.

Penetration: Penetration is defined in the context of power grid penetration, which is defined as the ratio between the (annual) average PV electricity generation fed into the grid and the average load of the grid.

Performance ratio of PV systems: The performance ratio of a PV system is the ratio of the systems annual energy yield (total annual energy output divided by the nameplate direct current power rating) to the reference yield (total annual in-plane irradiance divided by the reference 1 Sun (see "Sun") irradiance at standard testing conditions STC (see "standard testing conditions")). This value is a useful way of quantifying the overall effect of losses in a PV system due to inverter, wiring, module mismatch, and other losses such as PV module temperature, optical reflection, soiling and system downtime. The performance ratio is a dimensionless quantity.

Power electronics/power control systems: Refer to "Inverters".

Primary energy: The energy content of natural energy carriers such as coal, oil, natural gas or natural uranium. It is the input parameter of energy flows, which characterise energy use by humankind. Primary energy is the first link in the energy flow chain and is converted, e.g. in power plants, into secondary energy.

Renewable Portfolio Standard: This is a regulation that requires the increased production of energy from renewable energy sources such as wind and solar. This mechanism generally places an obligation on electricity supply companies to produce a specified fraction of their electricity supply from renewable energy sources.

Smart grid: A smart grid is an electricity network that uses digital technology to monitor and manage the transportation of electricity from all generation sources to meet the varying electricity demands of end users. Such grids will be able to co-ordinate the needs and capabilities of all generators, grid operators, end users and electricity market stakeholders in such a way that it can optimize asset utilisation and operation and, in the process, minimize both costs and environmental impacts while maintaining system reliability, resilience and stability. (IEA)

Solar tracking): Refer to "Tracking".

Spinning reserve: This refers to the extra generating capacity in a power generation system that is immediately available by increasing the power output of generators that are already connected to the power system.

Standard testing conditions (STC): The STC is a standardized condition to test the power conversion efficiency of PV cell devices and modules. This efficiency value is quoted as the power rating of the device/module. This testing condition is: irradiance spectrum of Air Mass (AM) 1.5 Global, irradiance intensity of 1000 W/m^2, device/module temperature of 25^o C.

Storage: Storage generally refers to energy storage devices. Electricity storage will become increasingly important to a smart grid system as renewable energy penetration level increases so as to moderate the supply-demand mismatches due to the intermittency of the renewable energy sources.

Sun: The light intensity on a solar cell is called the number of Suns, where 1 Sun corresponds to standard illumination at Air Mass (AM) 1.5, or 1000 W/m^2. For example a system with 10 kW/m^2 incident on the solar cell would be operating at 10 Suns.

Sustainable development: The concept implies that democratic decision-making and implementation processes should promote development that is ecologically, economically and socially responsible and sustainable, and should take into account the needs of future generations.

Tracking (solar tracking): Solar tracking in a PV setup is a process that orientates various payloads towards the sun. Payloads can be photovoltaic panels, reflectors, lenses or other optical devices. This tracking process is carried out with mechanical solar trackers. In flat-panel photovoltaic (PV) applications, tracking is used to minimize the angle of incidence between the incoming light and a photovoltaic panel. This increases the amount of energy produced from a fixed amount of installed power generating capacity. In concentrated photovoltaic (CPV) applications, the optical components in the CPV systems can only accept the direct component of sunlight for optimal conversion of energy by the PV device. Therefore, tracking is carried out to orientate the optics appropriately to maximise the collection of solar irradiation by the PV device in the CPV setup. Tracking systems are found in all CPV applications because such systems do not produce energy efficiently unless oriented closely toward the sun.

Watt-peak (W_p): A measure of rated electrical power equivalent to generated power of 1 watt under a 1 Sun (peak) standard testing condition of 1000 W/m^2, 25 ^{o}C and an AM1.5 Global irradiance spectrum.

Zero energy building: A zero energy building, also known as a net-zero energy building, or net zero building, is a building with zero net energy consumption and zero carbon emissions annually. This means that the energy generated by this building is sufficient to match the energy consumed by this building and the activities in this building. These buildings are generally grid connected. The electric energy generated by the building and fed to the grid balances with the electric energy drawn from the grid (over a year).

6. MAIN CONTRIBUTORS

This roadmap was produced by a group of seven researchers at the Solar Energy Research Institute of Singapore (SERIS) with feedback from a network of government agencies, institutes of higher learning (universities and polytechnics) and research institutes in Singapore. The report also incorporates opinions and views from a select group of local and international photovoltaic (PV) science and technology experts who were interviewed by the authors of this roadmap. This roadmap was commissioned by the National Climate Change Secretariat (NCCS) and the National Research Foundation (NRF) under of the Singapore government through the two lead agencies: the Economic Development Board (EDB), and the Energy Market Authority (EMA).

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Mr	James BOULDER	Principal, Cybele Capital Limited
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Housing Development Board (HDB), Building Research Institute

Agency for Science, Technology and Research (A*STAR), Experimental Power Grid Centre

Urban Redevelopment Authority (URA)

Government agencies (other than the lead agencies), institutes of higher learning, research institutes and companies that participated in the stakeholder workshops:

National Research Foundation (NRF)
Agency for Science, Technology and Research (A*STAR)
Building and Construction Authority (BCA)
Housing Development Board (HDB)
Ministry for the Environment and Water Resources (MEWR)
Ministry of Trade and the Industry (MTI)
National Climate Change Secretariat (NCCS)
National Environment Agency (NEA)
SPRING Singapore
Urban Redevelopment Authority (URA)
Jurong Town Corporation (JTC)

Canadian Solar
K-Green Trust
Phoenix Solar
REC
SolarGy
Sunseap Enterprises
Trina Solar

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Lead Agencies

EDB singapore

Energy Market Authority
Smart Energy, Sustainable Future

Commissioning Agencies

NCCS
National Climate Change Secretariat
Prime Minister's Office Singapore

National Research Foundation
Prime Minister's Office
Singapore