IALA GUIDELINE

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SOLAR MODULES FOR A MARINE ENVIRONMENT

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1. INTRODUCTION

The use of solar modules on Marine Aids to Navigation (AtoN) dates back to the mid-1980s, where the aim was to adopt a clean renewable energy source. This new source of energy allowed the powering of remote and afloat AtoN, removing the need for the delivery of acetylene gas, or diesel, to power light source.

Since these early days, the development of solar modules has made significant strides, moving from niche areas such as small DC systems, to mainstream power production, in the form of grid connected “solar farms”. This has delivered great enhancement in the performance of solar cell and a reduction in manufacturing costs, but it has resulted in manufacturers focussing their products on this high-volume market.

Naturally, the demands and requirements for such high volume “solar farm” modules, differ to that required in a remote marine location. This has resulted in the challenge of trying to identify the qualities that make a good marine solar module, from that presented in a data sheet of the more mainstream solar module. This guideline hopes to present the areas that are important to obtaining a reliable marine solar module.

2. SCOPE

This guideline has been developed to assist AtoN manufacturers and authorities, when selecting and applying solar modules to a power system, in a marine environment. It is intended to inform the reader about factors influencing performance and reliability, as well as considering aspect of selection, application and purchasing. In addition, a sample specification is presented in Annex A, capturing some of the key factors to consider when engaging with the market.

3. THE USE OF SOLAR ENERGY AS A POWER SOURCE FOR ATON

Although the first solar cell was created in 1881 by Charles Fritts, it was not until 1957 that the first commercial solar cells became available. This technology was first adopted on AtoN in the mid-1980s, generally as trials, leading to adoption as a mainstream power source, in the 1990s. This technology initially allowed the replacement of small acetylene gas AtoN but has since been adopted on all forms on AtoN.

The efficiency of solar cells has slowly improved through the expansion of commercial mainstream solar modules for such things as domestic and industrial solar generation. This has allowed solar to be adopted on significantly higher energy demanding systems at one end of the power spectrum, with the development of small self-contained AtoN, often referred to as an integrated power system lantern (IPSL) (see Guideline *G1064 Integrated Power System Lanterns* [1]) at the other.

To meet the increasing power budget for the larger solar systems, the number of cells, modules and arrays have expanded. To aid in how these different components of a system are referred to, figure 1 has been developed, starting from solar cells used on an IPSL, to solar arrays used on a larger lighthouse installation.

When developing the design of a solar power system, IALA provides Guideline *G1039 Designing Solar Power Systems for Marine Aids to Navigation (Solar Sizing Tool)* [2] to help in this task.

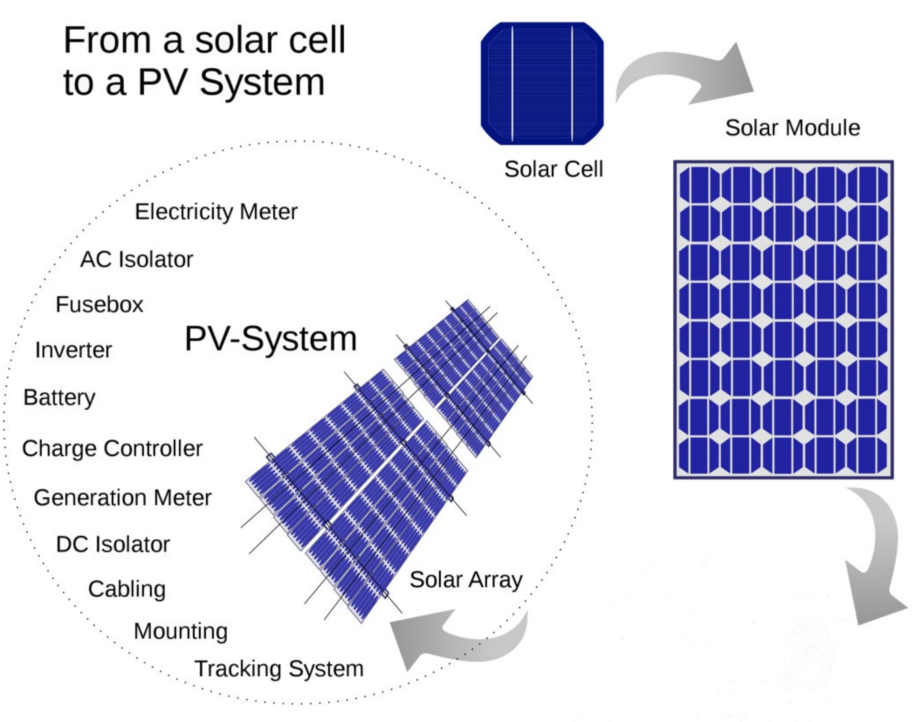


Figure 1 Component of a solar system by Rfassbind - Own work, Public Domain,

3.1. HOW TO RECOGNIZE THE BEST SOLAR MODULES ON THE MARKET?

It is difficult for even a specialist to verify the quality of a solar module by only checking the visual aspect. Indeed, several criteria, such as standards and technical specifications will have to be assessed to ensure the reliability. Even then, it is only time in the operational environment that will deliver this confidence.

4. TECHNOLOGY

There are several solar cell technologies available, with many enhancements and variation being progressed in development laboratories around the world, but those commonly available are described below.

4.1. MONOCRYSTALLINE

Monocrystalline is made from the mineral "silicon", which is found in abundance in sand. A single "grown" crystal is gradually formed into a block. The cells are then cut into thin slices from 250 to 350µm. The efficiency limit of the crystalline cell is around 35%. Currently this type of cell achieves efficiencies of up to 21%. These can be recognized by their dark colour and uniform structure.

4.2. POLYCRYSTALLINE

Polycrystalline is made from molten silicon glass that is formed in a mould. It is cheaper than the monocrystalline cells, but its efficiency is limited to 32%. Currently this type of cell achieves efficiencies up to 19%. It is recognized because its colour is irregular and clearer than the monocrystalline and has a rectangular shape without cuts at the edges.

4.3. THIN FILM / FLEXIBLE MODULES

This uses a new technology consisting of a thin film of pure silicon glass on a glass or ceramic substrate. This layer does not exceed 20µm. The thickness of the entire cell is between 300 to 800µm. The substrate may also be plastic, which allows the production of flexible modules.

Currently, the efficiency of these cells is around 13%, although, in laboratories, efficiency levels of 15% have been reached. The advantage of this technology is that it is much cheaper to produce than the crystalline cells, it allows the formation of flexible modules and in the manufacturing process, no polluting elements are used. However, they have a performance less than half that of the crystalline type cells.

Cell type	Max cell efficiency (lab)	Max cell efficiency commercial
Monocrystalline	35%	21% (23% back contacts)
Poly/multi-crystalline	32%	19%
Amorphous thin film	15%	13%

Figure 2 Types of solar cells

4.4. MONOCRYSTALLINE VS POLYCRYSTALLINE MODULES

Crystalline silicon solar cells are the most popular solar cells on the market today and provide the highest energy conversion efficiencies of all commercial solar cells and modules. Silicon is safe for the environment and one of the most abundant resources on Earth. Monocrystalline modules, as the name suggests, are made from a higher-grade silicon and their single-cell structure creates minimal resistance to the flow of electricity once the electrons are excited by the sun. Solar modules are constructed using a collection of these cells interlinked to achieve the desired voltage and power. It was once the case that polycrystalline solar modules were 20-30% cheaper than monocrystalline solar modules, because producing monocrystalline cells was a more expensive process than producing polycrystalline cells, this, however, is no longer the case, with the price difference between the technologies being negligible.

With all solar cells, electricity production falls as the temperature goes up. Studies have shown that in the summer months with high temperatures, polycrystalline and monocrystalline modules perform similar however, in non-summer months, when the photon energy is lower, even with similar irradiance levels, monocrystalline modules perform better than polycrystalline modules. The choice between monocrystalline and polycrystalline solar modules is not considered a critical factor when purchasing solar modules unless modules are susceptible to long periods of low irradiance, in which case, monocrystalline modules would be recommended over polycrystalline.

5. MODULE DESIGN

This section looks at some of the important factors in the design of a reliable marine solar module. When considering the design of a solar system, then Guideline *G1039* on *designing solar power systems for marine aids to navigation (Solar sizing tool)* [2] should be used.

5.1. NUMBER OF CELLS

Each solar cell within a solar module produces about 0.5 V, under standard test conditions (STC). Where STC are with the module at a temperature of 25 °C, the level of irradiance is 1000 W/m^2 and an air mass of 1.5 spectrum. As such, the solar cells within a module are interconnected in a series and parallel arrangement, to achieve the desired output voltage and power. Typically, for a 12 V module, this is 36 cells in series to allow a suitable output voltage to charge a 12 V battery system across different operating temperatures.

Modules designed for domestic grid connected purposes, will have a higher output voltage and more solar cells in series, typically 72, as this provides a module that maximizes the voltage and efficiency.

5.2. INTERCELL CONNECTIONS

The series / parallel connectivity of the solar cells within a module are achieved using solder coated ribbon strip, typically soldered to a front and rear printed electrodes, on the solar cell. Although, in high efficiency modules this interconnectivity will be achieved with just rear connected electrodes. The series solar cell groups are also connected in parallel by busbar ribbons at the top and bottom of a module. These busbar ribbons are then brought out to a junction box, often on the rear of the module.

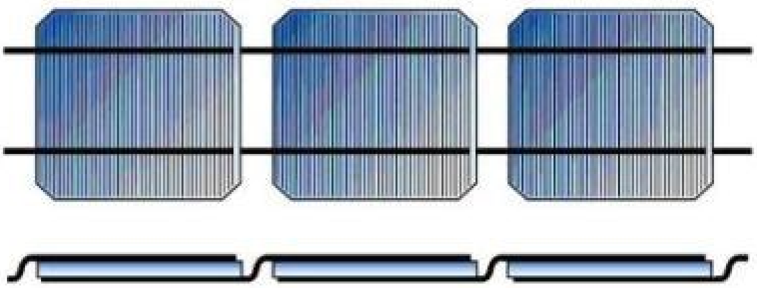


Figure 3 Intercell connectivity

The joining of the ribbons, both on the solar cells and to the busbars, is achieved through a soldering process that can induce thermo-mechanical stresses. The ribbons are also bent over the cell edges, which can cause mechanical stresses.

In striving to maximize the output of solar modules, thinner tapes are used to minimize the impact of shadowing on each cell. These tapes are subject to thermal stresses on a day-to-day basis which can lead cracking and premature failure. This is most likely in location where high daytime and low nighttime temperatures occur, resulting in the widest thermal stress window.

The design of the intercell connectivity can impact on how well the solar systems perform. On paper, it looks as if striving for modules with the greatest efficiency is best, but in a marine environment, these modules are often fitted where small amounts of shading may occur, due to supporting structures or hand railing within in the vicinity.

Shading can therefore lead to a period of reduce or no output from a module or part of a module. Given this, it is worth considering a less efficient module overall, but one with greater parallel sections. This will then ensure some output from a module during periods of partial shade, probably leading to a more effective solar system as a whole.

When fitting the modules, consideration should be given to orientating the parallel section in line with the possible source of shading, to minimize any impact.

Figure 4 An example of a module with 6 parallel sections

5.3. COLOUR

The colour of solar modules is generally dark blue or black to maximize the energy capture, see figure 5. This, however, can have a detrimental impact on the look of the daymark, as such the solar modules need to be located carefully, with the daymark in mind.

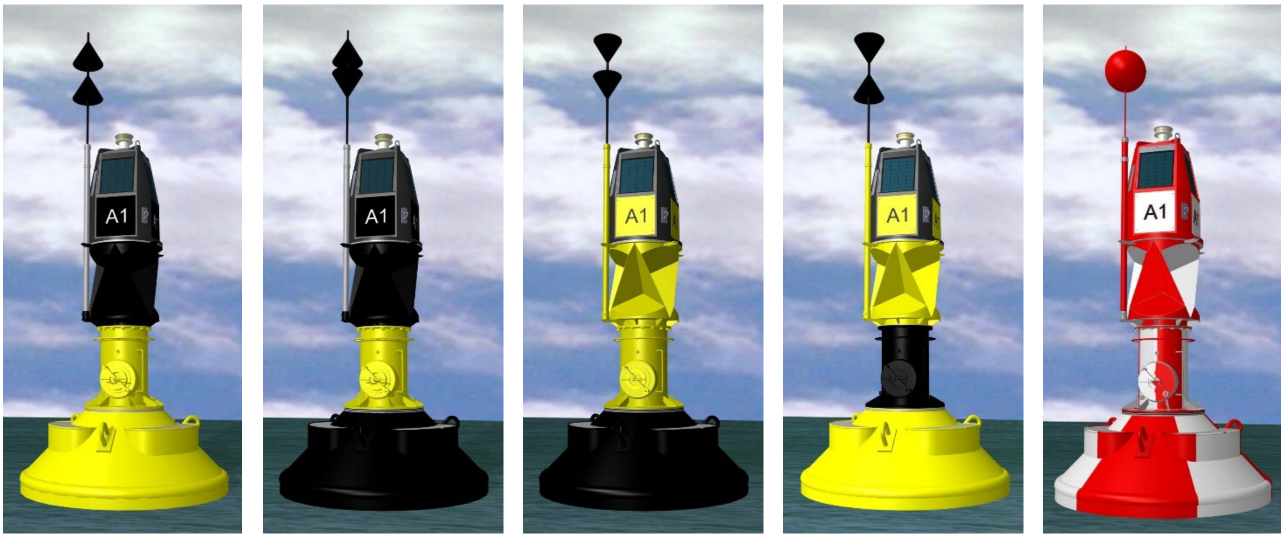


Figure 5 Example from WSV showing the solar modules within dark sections of the daymark

The use of coloured solar modules on AtoN is a new area of development, predominantly driven by architectural building pressures, but is slowly becoming more readily available. This possibility has not generally been considered as an option on AtoN, but with the efficiency of conventional AtoN resulting in a reduction in the energy demand, and solar modules having significantly improved in their output, there is now not the need to maximize the available space for energy generation. This now potentially allows the option to adopt coloured modules of a lesser efficiency to improve the daymark. An example of this has been tried on the Norwegian lighthouse of Domberskjera as can be seen in figure 6.

Figure 6 Domberskjera lighthouse with white solar modules

There are a number of approached to achieving a coloured module, including colouring the solar cells, colouring the glass, but one of the most effective methods is through the use of digital, ceramic printing of small coloured dots on the glass. This option provides the highest number of colour choices, along with a stable colour for a >20-year life, but with approximately 20 % reduction in the solar module performance.

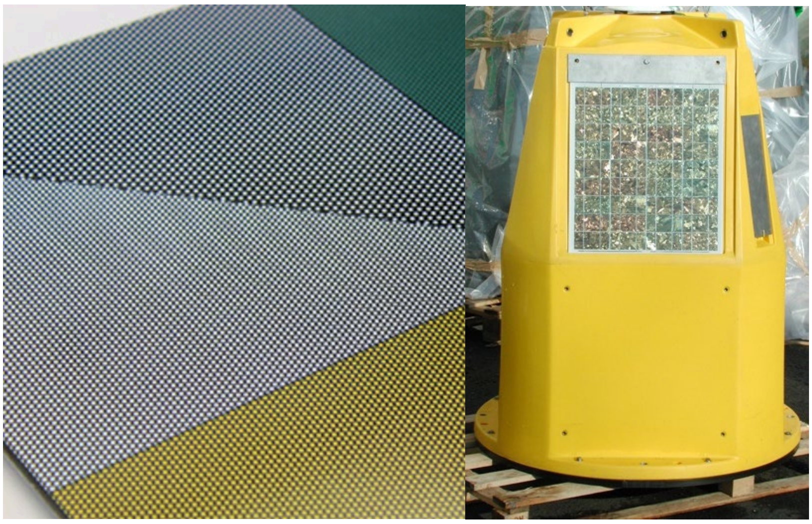


Figure 7 An example of digital, ceramic printing on glass (left) and a yellow solar cell (right)

5.4. SHOCK AND VIBRATION

The impact of shock and vibration is generally not an issue for the design of the solar modules due to the bonded sandwich construction. This can also generally be mitigated if the module has a supporting rear structure and by the design of this supporting structure. The design does need to consider the handling and environmental conditions, and as such, should be consider "rugged" for a marine application.

5.5. MODULE EFFICIENCY

Solar module efficiency is determined as the proportion of sunlight energy that can be converted into electrical energy, via the photovoltaics solar cells. For example: a solar module with 15% efficiency and an area of 1m² will produce 150 W under STC.

The overall efficiency of a module, and the efficiency of the cells will be different, with the efficiency of the module being lower. This is because of spaces needed between the cells, the boarder of the frame and the inter cell connections, all having an impact on available silicon area being exposed to the sunlight. Generally, modules can be obtained with an efficiency between 12 % and 20 %.

It should be note that the efficiency of the solar module is just one factor in the efficiency of the power generation system, and that it is important not to just focus on the module efficiency but consider the efficiency of the system as a whole, with consideration to the transfer of power across the system.

5.6. DIODES

A solar module will ideally have diodes fitted either within the module junction box, or somewhere within the module laminate. These diodes have two different purposes, and are known either as a bypass diode, or a blocking diode.

The bypass diodes limit the impact shading has on a module. These are physically fitted within the laminate but can be fitted in a junction box attached to the solar module. The bypass diodes allow a section of series cells to continue to provide power at a reduced voltage, if part of the series string is shaded, rather than no power. Ideally, one diode would be fitted across each cell, but this would be very expensive, so generally they are fitted to series section within a module.

The blocking diodes, however, are used to prevent a shaded module acting as a load, when modules are in parallel. These are usually fitted within the junction box on the back of the module. Where there is diffused light, perhaps from a module pointing in a northerly direction, these diodes need not be adopted, as the diffused light will generally provide some output from each of the modules.

As an alternative approach to the fitting of blocking diodes, each module can have a regulator fitted, such that the power output from the module is managed by the regulator based on the irradiance level. This provides excellent levels of redundancy but can be expensive.

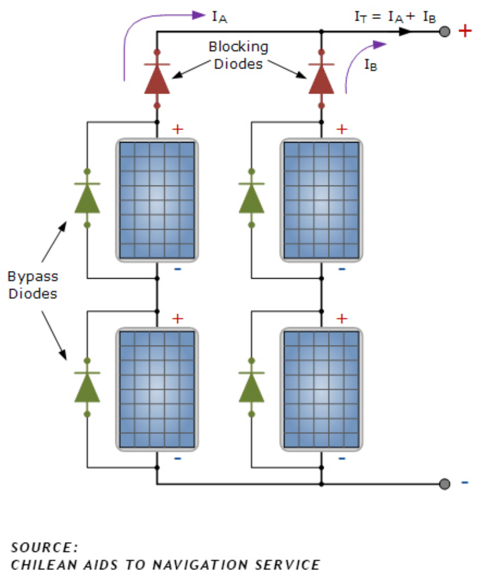


Figure 8 Details of the diode arrangement within a solar module.

5.7. MODULE CONSTRUCTION

A solar module is typically made from a three-part laminate, essentially sealing the selected solar cell technology between two other supporting materials and using ethylene-vinyl acetate (EVA) sheet, as a waterproof bonding layer for the laminate. For flexible solar modules, thin film solar cells are used within a flexible plastic laminate, but for rigid solar modules, the monocrystalline and polycrystalline cells can be used with a supporting stiffening material as part of the laminate as show in Figure 9.

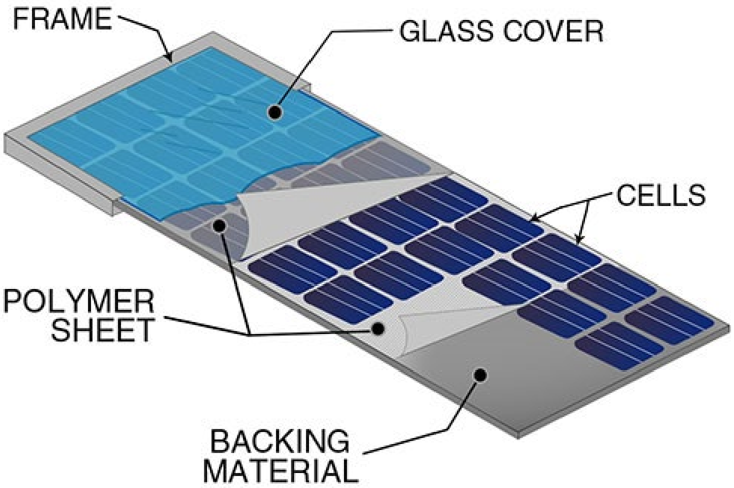


Figure 9 Figure showing the construction of a solar module from www.sunnectsolar.com

5.7.1. GLAZING MATERIAL

Both toughened glass and acrylic can be used as the glazing section. The use of acrylic allows a small degree of flexing during impact, without damage to the module. It also reduces the weight, which benefits handling. The transmissivity of acrylic can also be better than toughened glass, improving the module's overall performance. However, acrylic is more prone to scratches and high temperature, which would not be suitable for dusty and hot environments.

5.7.2. BACKING MATERIAL

Various types of backing materials have proven to be successful in a marine environment. One example of these being polyvinyl fluoride foil in a frameless arrangement, where it is supported within a structure, such as marine grade aluminium backing where structural support is needed or stainless steel frame for a standalone arrangement.

Where the solar modules are land based and protected from direct action by the sea, a glass / glass structures within a frame, have also proven to be effective.

The use of rigged solar modules, with a crystalline solar cell, has to-date been more popular than that of flexible thin film solar modules. This has generally been driven by the demand to maximize power generated; however, the adoption of flexible modules, generally on buoys, is now starting to be used. Examples of these are shown in figure 10.

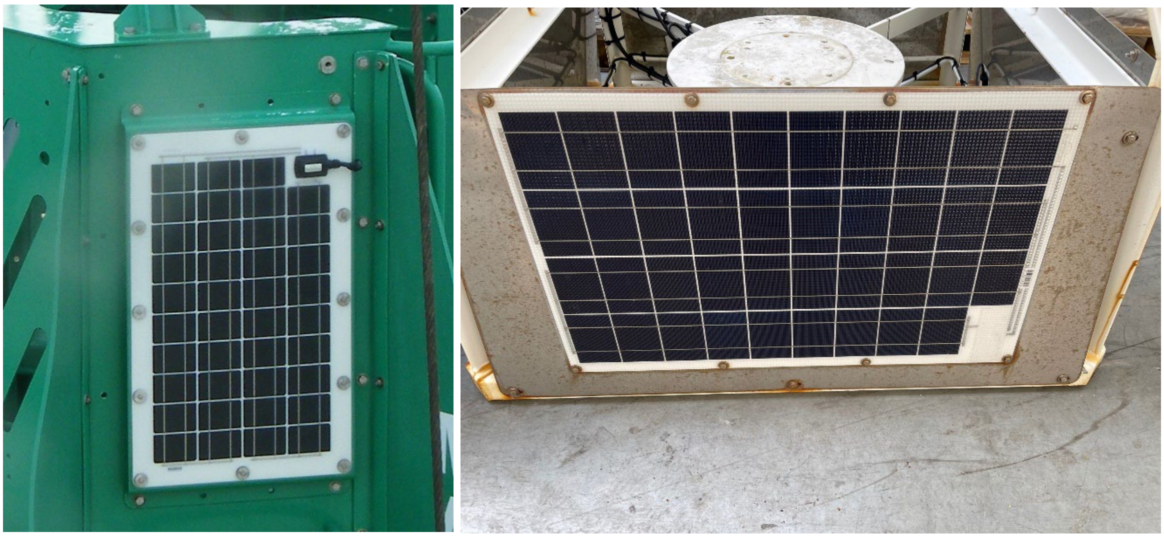


Figure 10   Showing the application of flexible solar module from Trinity House and Rijkswaterstaat

5.8. QUALITY

The quality of a solar module is an important factor to consider for any marine solar power system. Indeed, the quality of the chosen solar modules will determine the reliability, operational life, and output performance in the long term.

At the core of any high-quality modules, is firstly consistency and control within the production process, supported by manufacturing quality control tests, minimizing the variation of the products produced. This is especially important for the bonding phase of the laminate, to ensure all moisture is prevented from penetrating. Secondly, the design of the product, accounting for all the physical and environmental stress that are experienced in the production, transportation, and operational environments. Thirdly, the quality of the materials used and especially ensuring they are correct for the planned operational environment.

If the above points are accounted for in the module design and production, then this should ensure a consistent performance and a reliable life from each module. It is also important that during the production of the solar modules, the output performance for each module is checked, ensuring the final product meets the required performance.

There are many standards that are relevant to the production of solar cells and modules, some of which are listed in the references section.

5.9. INGRESS PROTECTION

This is a critical aspect to the long-term, reliable operation of a module, in a marine environment. It is not just critical for the module itself, but also for the junction box.

The junction box ideally needs to be bonded to the back of modules with the option of potting being added to prevent water ingress. The bonding between the module and the junction box needs to be secure both to avoid any water ingress, but to withstand the physical effects of handling that could result in the ingress protection failing.

It is also important to ensure that during the production process, there are no voids or gaps crated within the solar module laminate, or the junction box, where moisture can penetrate.

5.10. HUMIDITY AND CONDENSATION

Humidity in a high temperature environment can cause similar effects to that of direct water, through the build-up condensation. To limit the impact of condensation, some modules provide an anti-condensation heater within the junction box, giving low level background heating to the module.

5.11. WIND LOADING

When considering and selecting a solar module for an application on an AtoN, another key factor to survivability is understanding the modules maximum wind loading. The impact of this is covered in two parts; the first being the static pressure the module is designed to tolerate and still operate without issue. This is covered here, with the second being associated with the mounting and protection methods, which is detailed in the installation section.

Information on maximum gust wind speeds in different locations, especially remote locations, can be difficult to obtain and certainly varies. For example, a typical maximum for Germany is 40m/s, but for China, this can increase to 70 m/s during a super typhoon. As such, the build and materials used, may need to be different to meet the differing levels of performance.

To assess the forces involved, the wind loading pressure can be calculated as expressed in Equation (1):

$$Wp = \frac{0.5rv^2}{g} \tag{1}$$

where:

Wp is wind pressure (kN/m^2);

r is air mass (kg/m^3);

v is wind speed (m/s); and

g is gravity acceleration (m/s^2).

This formula is a general formula for estimating wind pressure by wind speed. It should be noted that the air mass (r) and the gravity acceleration (g), vary with latitude and altitude. Generally speaking, r/g is smaller on the plateaus than on the plains, that is, under the same wind speed and the same temperature, its wind pressure is smaller on the plateaus than on the plains. Because AtoN are generally located on the sea or rivers, the air mass and gravity acceleration are less affected by the height.

Given the above, and assuming the following standard conditions:

Pressure = 1013 hPa;

temperature = 15 °C;

air volumetric weight (r) = 0.01225 kg/m^3; and

gravity (g) = 9.81 m/s^2 at a latitude of 45 °.

The above formula (equation 1) can be simplified to

$$Wp = \frac{v^2}{1600} \tag{2}$$

As an example, in table 1 below, this formula is then used to calculate the force being applied to a typical solar module of a size 0.6 m x 0.3 m.

Table 1 Sample wind loadings for a given module

Wind speed (m/s)	Module stress (N)	Wind speed (m/s)	Module stress (N)
0.0 - 0.2	0.00	24.5 - 28.4	90.74
0.3 - 1.5	0.25	28.5 - 32.6	119.56
1.6 - 3.3	1.23	32.7 - 36.9	154.01
3.4 - 5.4	3.28	37 - 41	192.82
5.5 - 7.9	7.02	42 - 45	239.09
8.0 - 10.7	12.88	46 - 51	291.47
10.8 - 13.8	21.42	52 - 59	352.80
13.9 - 17.1	32.90	60 - 61.2	421.36
17.2 - 20.7	48.21	>61.2	>422.74
20.8 - 24.4	66.98		

5.12. ELECTRICAL PERFORMANCE

The operational life for which a solar module can generate power can be many decades. During this period, the module's power output slowly reduces over time from its initial 100 % performance. Generally, manufacturers provide a guaranteed output performance over a given time frame. This is often represented in a graphical form as shown in figure 11.

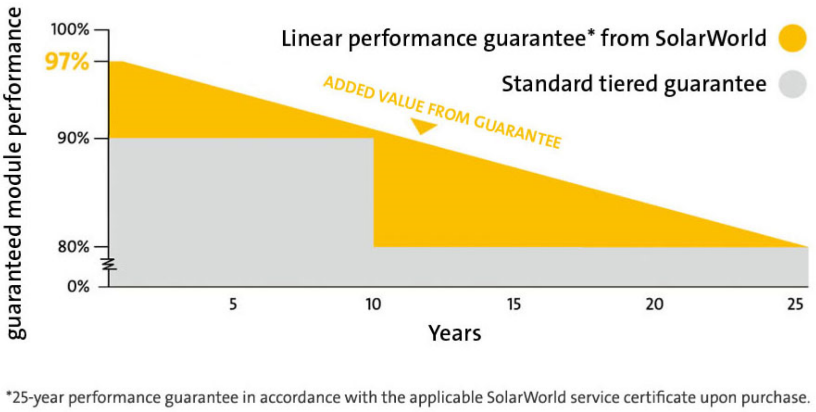


Figure 11 Typical example of performance over time from SolarWorld.

A solar module will typically continue to produce power at a reduced level beyond the guarantee period, until total failure occurs. This is often referred to as the operational life of a module. This reduction in output, can be caused by many things including cell damage, contact corrosion and anti-reflective coating deterioration. Ultimately total or partial output is lost generally due to one of the causes captured in section 9.

When designing a solar system, the minimum generated power requirement for end of life should be specified and considered when selecting the modules. If using the IALA solar model, Guideline *G1039 Designing Solar Power Systems for Marine Aids to Navigation (Solar Sizing Tool)* [2], then it should be noted that this is based upon a minimum solar module output of 80 %. This is usually considered the performance life of a module.

Current available modules typically provide a performance output of 90% after 10 years and 80 % after a further 15 years, defining the maximum operational life of a system, but if a life beyond this timeframe is needed then care is required when selecting the module, as the rate of output degradation is unknown.

6. ELECTRICAL FACTORS

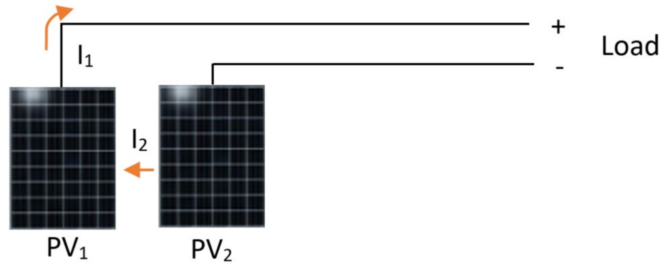
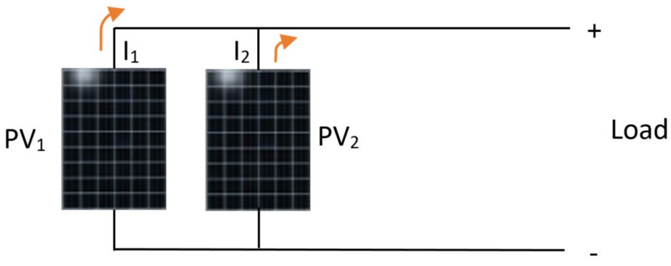
In the application of solar modules to a system, the manner in which they are interconnected, and the adoption of a charge regulator, all contribute to the efficiency and effectiveness of the solution to be implemented. This section considers some these aspects.

6.1. MODULE INTERCONNECTIVITY

Solar modules can be obtained in various nominal voltages, typically 6 V, 12 V, 24 V and 36 V, with the maximum voltages specified by the manufacturers being greater, to allow for a battery charging level. A typical voltage od a solar module used on a larger AtoN, would be a 12 V.

The power that is produced by a single module is based on its physical size and efficiency. However, such units are usually interconnected to achieve a desired performance. That is, additional modules can be wired together in series to increase the voltage generated to match that required by the charge controller. Alternatively, if they are interconnected in parallel, there is a respective increase in current. A combination of series and parallel arrangements are generally adopted to meet the required voltage, current and hence power (voltage x current) needs for the designed system. The table below illustrates the different arrangements,

Table 2 Examples of how module connection arrangements

<table>
<tr><th>Interconnectivity Arrangement</th><th>Performance formula</th></tr>
<tr><td>
</td><td>$I_{total} = I_1 = I_2 = \cdots I_n (Amps)$
$V_{total} = V_1 + V_2 + \cdots V_n (Volts)$
$P_{total} = V_{total} \times I_{total} (Watts)$</td></tr>
<tr><td>
</td><td>$I_{total} = I_1 + I_2 + \cdots I_n (Amps)$
$V_{total} = V_1 = V_2 = \cdots V_n (Volts)$
$P_{total} = V_{total} \times I_{total} (Watts)$</td></tr>
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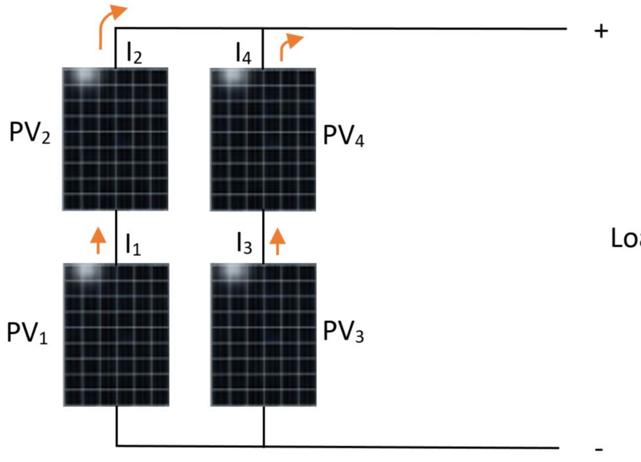
Interconnectivity Arrangement	Performance formula
	$I_{total} = I_1 + I_4\ (Amps)$ $V_{total} = V_1 + V_2\ (Volts)$ $P_{total} = V_{total} \times I_{total} (Watts)$ Note: $I_1 = I_2\ and\ I_3 = I_4$ $V_1 + V_2 = V_3 + V_4$

6.2. SOLAR CHARGE CONTROLLER

The output effectiveness of the solar module is affected by sunlight it receives. Given this, it is easy to charge a battery to its upper voltage limit, during the intense and long sunshine in summer. If the solar module then continues to charge the battery after the battery is fully charged, most of the electrical energy delivered by the solar module will be converted into thermal energy. This can then cause the battery to lose electrolyte resulting in a reduction in capacity. In winter or continuous cloudy weather, where there is limited and inefficient sunlight, and with greater energy consumed from the battery at night, the solar module cannot replenish the energy in the daylight hour to make up for the demands. As this continues, the battery capacity will decrease rapidly. The application of a solar charge controller can effectively prevent the battery from overcharging in the summer, with some charge controllers providing protection to the battery from deep discharging when the solar energy is insufficient. However, it should be noted that the regulator itself does not provide energy and cannot solve the problem of insufficient battery capacity. This problem can only be solved by other methods, such as increasing the number of the solar module or the capacity of the battery.

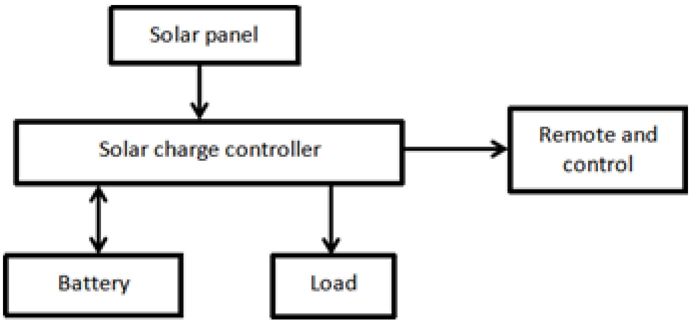


Figure 12 Solar charging system with a controller

Figure 13 A solar charge controller

A solar charge controller is an adaptable device for regulating the solar charge into the battery and control the power output according to the demand of load, protecting the battery and related loads. At the same time, some charge controller can also be connected to a telemetry remote control terminal to monitor the working status of the AtoN energy system. On small AtoN systems, some integrated lanterns contain this charging and discharging protection elements with the lantern, which means there is no need to use a solar charge controller in this situation.

7. ENVIRONMENTAL FACTORS

When considering the use of solar as a power source, the first obvious thought is green energy with no further harmful emission, but the very production of solar modules is not wholly environmentally friendly and still has an impact on the environment.

7.1. PRODUCTION

There is a significant difference when considering solar power as a source of energy to that of other traditional forms, in that it is one of the few that does not produce harmful emissions or toxic waste during its normal operation life, but this is not the case for their production. The following section outlines the step needed for the production of monocrystalline cells.

From an environmental perspective the production of solar cells uses several raw materials, such as silicon (Si), cadmium (Cd), tellurium (Te), copper (Cu), selenium (Se), and gallium (Ga), all of which are mined, followed by an extraction and purification processes, during which chemicals and significant amounts of energy are needed.

The first step, is to transform quarts into metallurgical-grade silicon, using large amounts of energy in a furnace. This is then transformed into a purer form of silicon, known as polysilicon using a distillation process which is achieved using hydrochloric acid, but unfortunately it also produces a very toxic waste product called silicon tetrachloride, for which about three or four tonnes is produced for each tonne of polysilicon. However, at least 98.5% of silicon tetrachloride can be recycled as part of the production process. The output from this process is a bricklike ingot of polysilicon.

This highly pure polysilicon can then be grown into monocrystalline ingots using the *Czochralski* method. This method takes a seed crystal of silicon which is dipped into molten polysilicon. This is drawn and rotated to create a single crystal ingot. It is also during this process that the boron doping is added creating P-type silicon. Again, this process requires high temperatures and significant amounts of energy.

These monocrystalline ingots are then sliced into wafers. Hydrofluoric acid is then used to remove any impurity generated when creating the wafers, this also produces a textured surface, which helps reduce surface reflection. Unfortunately, hydrofluoric acid is a highly corrosive chemical that can destroy tissue and decalcify bones, so needs to be handled with care.

The next step is the creation of the solar cells from the wafers. This is achieved through doping (adding impurity) to the silicon wafer. Boron was added to the wafers as the monocrystalline ingot was created, producing p-type silicon and the n-type silicon is create by add phosphorous to the silicon wafers using thermal diffusion. To achieve this the wafers are sealed back-to-back and placed in a furnace in the presence of a phosphorous gas, at a temperature just below the melting point of silicon. This again uses significant amounts of energy.

The output from this last stage are solar cells ready for inclusion into a monocrystalline solar module. The creation of thin film solar cells eliminates many of the environmental and safety hazards from manufacturing, because there's no need for certain problematic chemicals such as no hydrofluoric acid and no hydrochloric acid. But that does not mean you can automatically consider a thin-film solar cell as green. The doping of thin film cells is achieved using cadmium telluride and cadmium sulphide to create the two doped layers. These chemicals unfortunately contain the heavy metal cadmium, which is both a carcinogen and a genotoxin, meaning that it can cause inheritable mutations.

Although the process of generating solar cells uses significant amounts of power and hazardous chemical, the power generated through their life, offsets that needed in the production process. Typically, this can be achieve within two and a half years.

7.2. OPERATIONAL FACTORS

Although solar modules appear to be an inert object with a glass surface, no moving parts and all held together in a frame, it is influence by its operating environment for both performance and operational longevity. This section outlines the key factor to consider.

There are two major factors that affect solar module performance under normal circumstances, these are irradiance and temperature. There are also other factors that are area dependent, such as shadowing, salt film, dust and bird fouling (Guano) all of which directly impact on the level of irradiance reaching the solar cells.

7.3. TEMPERATURE

One of the factors affecting the life and performance of a solar module, is the temperature that it experiences during operation, which is influenced by the environmental effects within the local area. Depending on the location, those at the more northerly and southerly latitudes, generally have a colder climate, at the expense of the daily available sun hours. This means that the solar modules perform at optimum efficiency, due to the lower operating temperature. However, those modules that are installed nearer to the equator, generally are hotter all year round, which translate to a drop in the module's efficiency.

The output voltage of a module is affected by the cell temperature, which changes in a similar way to the output power. Every type of solar module has its own thermal characteristics determine under STC. This characteristic is known as the "temperature coefficient". The units of this coefficient are expressed in "% per °C", so the lower the coefficient, the more efficient the solar module is. Conversely, the higher the number, the less the solar module will produce in the case of high temperatures in early afternoon. A typical value for monocrystalline is -0.45 %/°C and for polycrystalline a slightly greater value of -0.50 %/°C. A solar module with high temperature coefficient in the region of -0.7 %/°C is generally the sign of a solar module of lower quality. A reasonable number is around -0.5 %/°C, although the best solar modules go down to -0.3 %/°C. Refer to IALA Guideline G1136: *Providing AtoN services in extremely hot and humid climate* for more information (5).

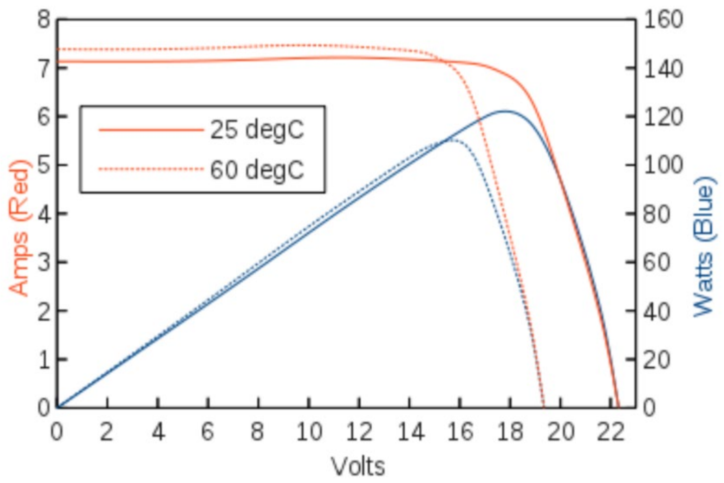


Figure 14 Impact of temperature on solar module performance

7.4. HUMIDITY

Humidity, in a general form, is a measure of the amount of water vapour in the air, where there are three primary measurements, absolute, relative, and specific. This section is not considering the measurement of humidity, but the impact it can have on solar modules. Where the level of humidity is high, its impact on solar modules is very similar to modules which are continuously wave washed. In this situation corrosion and water ingress due to continuous presence is a significant challenge. As such, it is especially important that the edge of the solar module and junction boxes are seal prevent water ingress over time, along with suitable surface protection method to reduce the impact of corrosion.

High humidity can also impact on the performance of a module over and above the effect of temperature, which is usually present in high humidity location. This performance reduction is driven by reflection and refraction of sunlight as it passed through small beads of water vapour, that have collected on the surface of solar module, diverting the sunlight from the solar cells.

7.5. IRRADIANCE

Irradiance is the amount of solar power available per unit area. Symbol = I. Its units are represented by kW/m² or W/m². It is one of the major factors that affects the output of solar modules. How we install each module to face the sun is very important. Due to geometric effects, it is always recommended that each module is facing 90° perpendicular to the sun's altitude angle (when it is at the highest point in the sky) to ensure that the module can capture all the sun's radiation. For different location around the globe, this may mean that the highest point that the modules face is not arranged to be perpendicular to the sun's highest altitude but is aligned with the winter solstice to maximize the winter performance rather than summer performance.

7.6. ATMOSPHERIC EFFECTS

Atmospheric Effects consists of two categories, Direct and Diffuse Radiation. Figure 15 illustrates the two concepts.

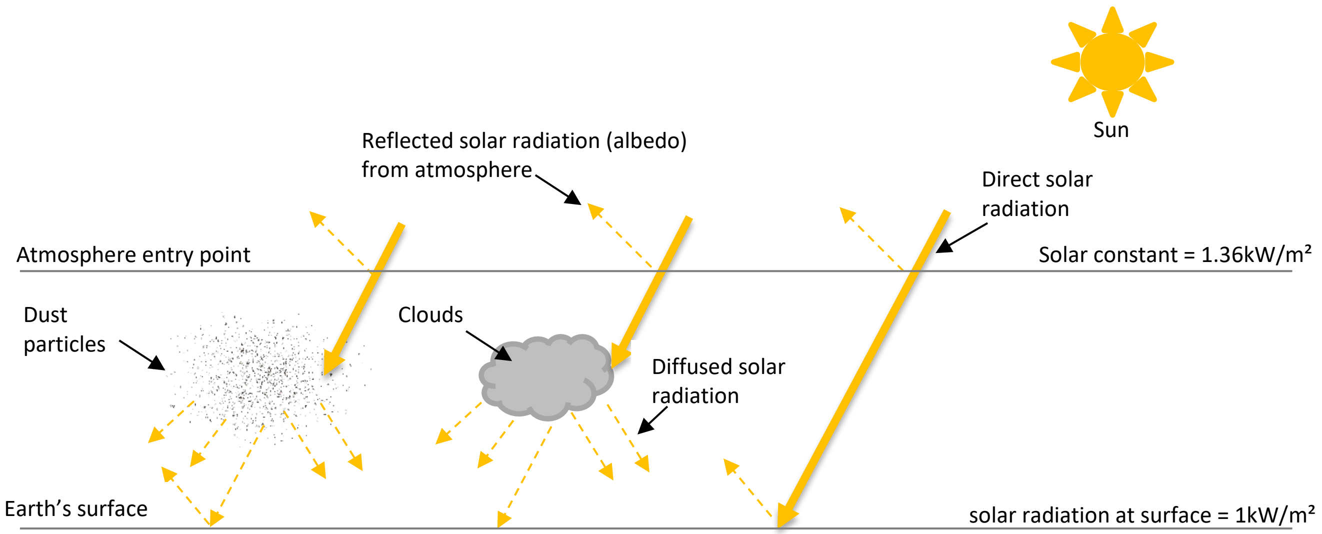


Figure 15 Diagram of atmospheric effects (from maritime and port authority of Singapore)

7.7. POOR LEVELS OF VISIBILITY

This comes in various forms, such as rain, fog, smog, sandstorms, snowstorms, heavy cloud, smoke, and other pollutants. All of these impact on the level of irradiance received by the solar modules and hence the performance of the solar system as a whole. Some of these lead to deposits which can have a more lasting reduction in the performance of the solar modules. Some are naturally occurring and are due to weather events, however some, such as pollutants, are caused by industry, which may have evolved overtime, but could have a significant long-term impact in areas such as inland waterways through built up areas.

7.8. DEPOSITS

These factors impact on the maintenance frequency and sizing of a solar system.

7.8.1. SNOW

The impact that snow can have on a solar system can be catastrophic if it is not allowed for in the design. Even short period of laying snow on solar modules, preventing any energy production, is a challenge even for systems designed for such situation. Naturally, as with all deposits, aligning the module vertically or at a steep angle reduces the likelihood of the snow covering the module. However, blown or drifting snow, piled against a module close to the ground can also limit its performance, in effect through shading a section of the module.

Figure 16 Heavy snow deposits on a solar module in China

7.8.2. POLLUTION DEPOSITS

AtoN located on waterways that pass-through built-up areas or are close to industrialized zones, can be significantly impacted upon by pollution deposits. These deposits not only reduce the modules performance, but in some cases can attack the surface finish. Although modules can be orientated vertically to reduce the impact of deposit, such deposits can be very fine and can continue to build up on surfaces over time. In these situations, unless rainfall is frequent and heavy, such deposits will need to be removed through frequent cleaning by a maintenance team.

7.8.3. BIRD FOULING (GUANO)

While it is possible to prevent birds from landing on the solar modules using bird deterrents i.e., bird spikes, etc., they can still deposit their droppings while in flight. Over time, if not removed, they will become hardened and difficult to remove, resulting is a long-term shading effect that can drastically affect the module's efficiency. For more information of preventing bird fouling, see Guideline G1091 *Bird deterrent and Bird Fouling Solutions [4]*.

Figure 17 An example of a module affected by guano from Chile

7.8.4. SALT

In a marine environment, the build-up of salt will occur over time, to prevent a salt film and dusts build up from forming on the surface of solar modules, it is recommended to install the modules at an angle to induce a natural washing effect when rain occurs. This will help wash away the salt that is gathered on the surface. The optimum angle for a rain-washed surface is 45°, with a minimum angle of 12°. The actual mounting angle of a module is a balance between the angle needed to provide natural cleaning and the angle needed to achieve optimized performance from irradiance.

7.8.5. DUST AND SAND

Dust can be a significant issue in certain extremely hot environments and can cause several issues. The dust can cover the solar modules thereby reducing the ability to charge batteries and its abrasive nature can accelerate deterioration of aluminium and glass surfaces.

Dust can be of different physical properties, both industrial and natural, causing different issues and requiring different control and cleaning methods. Excessive dust also poses health and safety related risks to personnel during the cleaning process.

Figure 18 An example of heavy dust deposit

7.9. EMC IMPACT (LIGHTNING)

Damage can occur to a solar system as a result of either a direct or nearby lightning strike. Consideration should be given to the protection of such systems, given the significant investment and importance. Lightning protection should be prioritized for lighthouse sites located in areas where the risk of lightning strikes is highest. To know the probability of lightning strikes, it is advisable to use a keraunic level map (a map showing the probability of lightning strikes) which will help to define the level of protection needed. For more information, see IALA Guideline G1012 *Protection of Lighthouses and other Aids to Navigation against Damage from Lightning* [3].

8. INSTALLATION

The way an installation is achieved can influence the success, survivability, and maintainability of a solar system in a marine environment. This section looks at some examples, highlighting some of the key differenced.

One of the first steps to consider is to determine what a suitably sized module for the situation. Generally, this is straight forward for a self-contained lantern and to some degree on buoys, but the larger systems on lighthouse provide various options. For example, sometimes having fewer larger modules can be an advantage, with fewer modules to fit, less connectivity and overall, a smaller support frame. However, the very handling of larger modules (weight and size) may present an issue, given the situation.

As a general rule, those adopted on buoys are substantially smaller and more robust, than those fitted to remote and island station, and this is generally driven by the need to maximize solar generation on lighthouses to support the more substantial AtoN mix.

8.1. MOUNTING METHODS

8.1.1. SELF-CONTAINED

Self-contained units are generally compact supporting small efficient light sources. Given this, they are designed with small glass / glass solar module fully integrated into the moulded structure as part of the production process. This ensures they are given the greatest level of physical protection with all the connectivity sealed within the unit. They are usually steeply inclined or vertical to minimize any impact of deposits, with the necessary solar module requirement distributed around the various sides, making the units ambivalent to mounting orientation.

Figure 19 An example of a self-contained lantern

The design of these units is such that any failure results in the replacement of the whole unit, which in turn can make the units price-driven. This may have an influence on the sourcing and quality of price-sensitive parts, such as the solar modules that are fitted. The repair of these units can also be achieved in a more controlled environment, as their removal allows these units to be returned to the base for repair. These units are generally fitted in on buoys that are located in a less stressful environment.

8.1.2. BUOYS

For buoys with more significant and diverse AtoN, a different approach to that of the self-contained lanterns needs to be adopted. This is to ensure sufficient energy is captured to meet the AtoN needs. The fitting of solar modules to these larger buoys is generally achieved through direct fixing arrangement to the superstructure for security purposes, yet there is still a need to be able to simply remove and replace the modules following failure.

Like the self-contained lanterns, the modules are generally inclined and oriented around the superstructure, although in some, they can be aligned to be facing skyward.

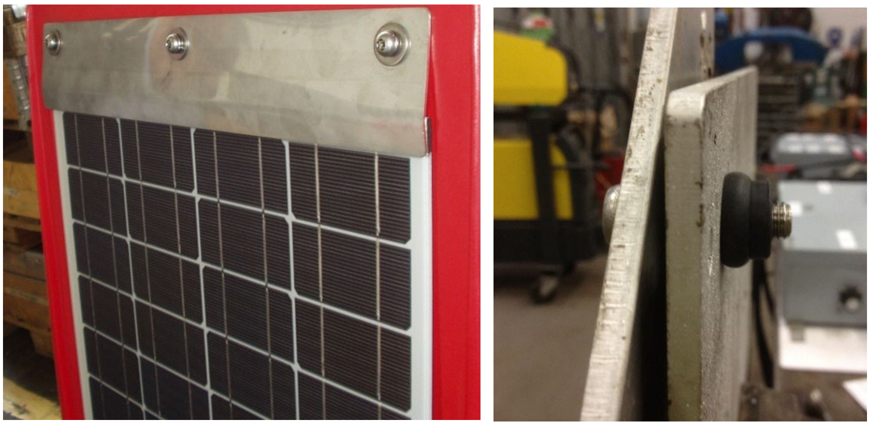


Figure 20   An example of direct fixing.

Where the modules are located closer to the water level, there is a need to ensure there is sufficient module support from direct "green water" impact. This is achieved through integrating the backing support as part of the module, with an additional support structure directly behind the module.

Electrical connectivity of these modules is achieved within the buoy superstructure, where the other electronics are housed. This connectivity is commonly achieved by suitable connectors.

8.1.3. LIGHTHOUSES

The installation of solar modules to a lighthouse usually has a more significant mechanical and civil component, where suitable structures are assembled and fitted directly to the lighthouse or to the adjacent ground. This can be constrained by heritage legislation, and as such, the resulting location may make access difficult. They are usually of a fixed orientation and elevation to maximize the power generated. This elevation usually means that this can provide some form of self-cleaning, but as seen earlier, this can limit its effectiveness.

Solar modules in this situation are generally not as exposed to the weather and sea impact as those on buoys, so they will have less physical rear supporting structure. For simplicity, they are either clamped or directly bolted to the supporting structure to allow unit replacement.

Such systems can have significantly more cabling and connectivity to those on buoys but may either be terminated into junction boxes or employ a connector for connectivity purposes.

Figure 21 Photo of a solar array on La Giraglia lighthouse, Corsica

8.1.4. LIGHTVESSEL

These essentially adopt the same principles as a buoy, with the direct fixing and additional module backing support to prevent module damage from wave action. They also adopt some of the concepts of a lighthouse, with large support frames and limited orientation.

Figure 22 An example of a solar array on a lightvessel

8.2. ORIENTATION – TRACKING

For a major fixed AtoN, where the area and size of the solar array is an issue and where it is likely that the structure is also used to host not only the lantern but other power-consuming AtoN devices, then a better system efficiency may be achieved using a sun tracking arrangement. This can increase the system efficiency up to a figure of 45%. In the most common designs, the solar modules are mounted on a structure which is driven by a computer-controlled engine. This moves the array to the most suitable orientation (horizontally, vertically, or both) to keep the array perpendicular to the sun. When considering the application of a solar tracking system, the following parameters need to be consider:

- Space availability
- Cost (installation and maintenance)
- Overall power consumption of the AtoN

8.3. DOUBLE-FACE MODULES

Where space is constrained on a lighthouse or other fixed AtoN structure and the energy demand from the mix of AtoN is high, then to generate enough power, without using a tracking system, double-faced module arrangements have been tried.

Double-face modules not only take advantage of the direct but also the diffuse and reflected solar radiation. They can be assembled using two single modules by fixing them back-to-back, providing an increment of the generated power up to 30%, using the same space. Attention must be paid to the overall cost, weight, orientation of the array and the distance and efficiency of the reflecting area where light colours would be preferable as they better reflect solar radiation.

8.4. WIND LOADS

Most of the time solar modules operate in what can be considered as benign normal conditions for an area. However, occasionally damaging winds can occur, which when acting on the solar modules of an AtoN can easily result in solar module failure or loss. This loss can lead to a failure of the solar system, which can then result in loss of the energy for the AtoN. As shown in figure 23, the impact of a super typhoon can result in rupturing of the silicon laminate and deformation of the support system.

Figure 23   Example from China of damaged solar modules following a super typhoon

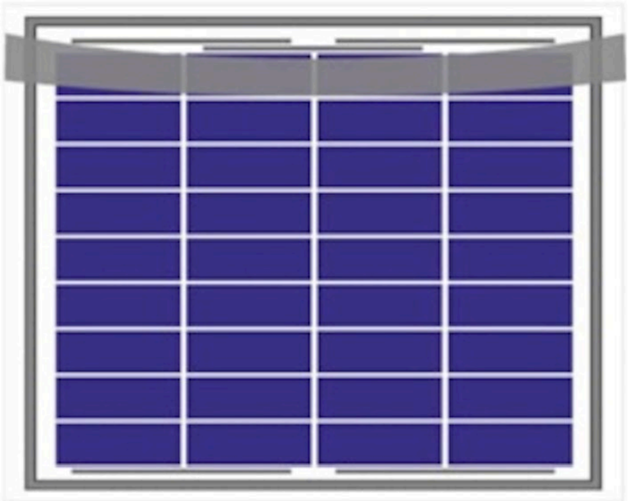
When considering buoys, the manner with which the solar modules are mounted can significantly influence survivability following a significant wind event. It has been seen that it is important to protect the rear side of the solar modules, preventing significant wind pressures from lifting the units away from the mountings. An example of this is shown in figure 24, where the buoy in the left-hand picture has the two 20W modules mounted at the top of the superstructure, where the back of the modules are only partially shielded by the equipment platform. This compares with the right-hand picture, which shows the modules fitted in a manner that has the back of the modules fully shielded by the equipment platform. Adopting this approach has seen a fivefold improvement in survivability of the modules following a super typhoon even.

Figure 24   Wind impact to solar modules on buoys

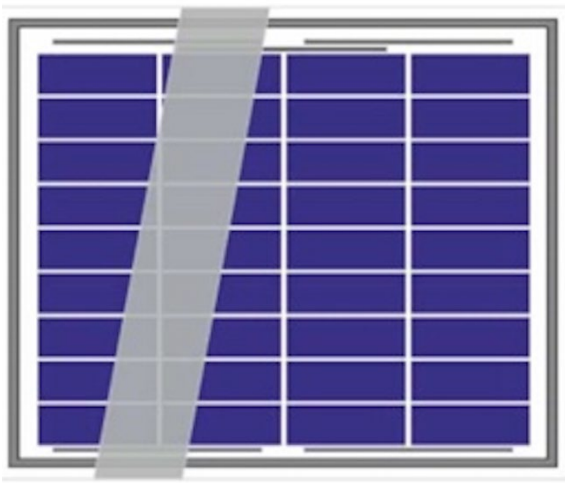
8.5. SHADOWING/SHADING

It is always recommended to install arrays with a clear line of sight to the sun. Any shadowing caused by nearby buildings or trees can result a significant reduction in maximum power point voltage and, therefore a reduction in the maximum power available from the array. Although temporary, meteorological factors like passing clouds during overcast days also affects the modules' efficiency.

It should also be considered that solar modules are sensitive to the presence of small shadows, even a narrow shadow can significantly decrease the output power. For example, shadows generated by vegetation, buildings, daymarks and handrails can cause problems and should be avoided.



The above example of shadowing could result in a 90% reduction in power output.



The above example of shadowing could result in a 75% reduction in power output.

Figure 25 Examples of shadowing on buoys

8.6. THEFT OF MODULES AND WAYS TO PREVENT IT

In recent years there has been a considerable reduction in the theft of solar modules mainly due to the sharp decline in the purchase price. The replacement costs due to logistics for modules located in remote and difficult to access locations, can be high. Therefore, theft can represent a very important consideration in the design of a solar installation. The risk of theft, or unauthorized use of solar modules installed at AtoN sites, warrants consideration of an effective anti-theft solution to protect the solar modules. The most commonly used method for securing solar modules is the use of security fixing screws in the end and mid clamps of the solar mounting system.

Figure 26   An example of a security fixing

The fixings require a special insert bit or key wrench to remove the clamps securing the modules to the mounting frame. Alternatively, the location of the where the modules are installed, such as up high or out of sight, can aid in the reduction in theft and should be a consideration at the design stage.

Adopting a different approach, involving engagement with the local people, outlining the purpose and benefits the solar system will bring, can lead to local support, engagement and eliminate the theft of modules.

8.7. VANDALISM

The effects of vandalism can sometimes be seen as the outcome of attempted theft. Alternatively, this can come in the form of spray painting or target shooting, all of which are very difficult to prevent other than out of reach or out of sight. Regardless of the cause, the inconvenience of this is just as significant as a total loss, resulting in possible AtoN failure and significant cost to repair.

9. PROBLEMS / FAILURES

A solar module that is fitted in the challenging marine environment may experience problems or failures, through various mechanism, throughout its life. Some of these are built in and are because of the production process, whilst others are more environmentally driven, but all impact on the overall life and operational performance of the modules.

9.1. EARLY LIFE PROBLEMS

These are generally associated with the production process or is as a result of the transportation or handling methods, all of which results in either an early failure or reduction in performance. The latter, are usually physical failures such as broken glass, loose or damaged frame which are all quite visual. However, failures such as intercell failure or junction box connection failure tend to only be identified through measurement.

9.1.1. LIGHT INDUCED DEGRADATION

Light induced degradation (LID) is a process that happens to a solar module when it is first exposed to natural sunlight. The result of which is a reduction in the effective output of between 1% and 5% for any given solar module, with respect to the measured output captured during production. This reduction occurs during the first few days of exposure, after which the output reaches a stable state. The reduction is “baked in” to the product and is because of the oxygen being present within the active region of boron doped silicon. This impact is more prevalent with high-efficiency monocrystalline cell but is still present within polycrystalline cells.

9.2. THROUGH LIFE PROBLEMS

Although solar modules have proven to be a very reliable power generation source for remote marine locations, a small number may develop problems through their life. This can either lead to a reduction in performance or at worse total failure. This section outlines some of the issues that can be encountered along with examples experience by various users.

9.2.1. LIGHTNING

The physical impact of lightning can be significant following a direct strike, although the way solar modules are generally mounted limits this impact. The influence lightning has on both the power system and the solar array can be minimized through suitable earth bonding and the application of surge suppression. For more information, see Guideline G1012 *protection of lighthouses and other aids to navigation against damage from lightning* [3].

9.2.2. DIODE FAILURES

The failure of blocking and bypass diodes is significantly influenced by indirect lightning activity generating significant voltage surges, which rupture the diodes. In addition, under sizing resulting in overheating of the diode can be a significant influence on early failure, especially in areas of high ambient temperatures. Failure of the bypass diodes within a module may result in hot spots which in turn can lead to a module failure. Failure of any blocking diode may result in a reduction in the array efficiency as a whole.

9.2.3. POTENTIAL INDUCED DEGRADATION (PID)

This form of module degradation occurs when there is a negative potential with respect to ground. This voltage then causes leakage currents to flow between the encapsulated solar cells and the anti-reflective coating on the front glass surface, frame, or other constituent parts of the module structure. This results in positive ions migrating and accumulating in the semiconductor. Such positive charges near the depletion layer slowly polarizes the junction reducing the junction's EMF and hence the module's generated current.

This problem can occur on ungrounded systems and is accelerated as the system voltages increases, but is also enhanced by high temperatures and humidity. This leakage current then reduces the MPPT operating point and hence the maximum power being generated.

Although this is more of a significant factor for very large arrays, where the operating voltage can be 600 to 1000V, this impact can be seen at the lower voltage end of the spectrum. For these very large arrays the losses can be up to 30%. On smaller systems, it may not be the loss in power that is seen, but the effect of these migratory currents on structures.

This effect can be prevented through the purchase of solar modules which use higher quality materials that minimize the effect of migrating positive ion or through the grounding of the negative supply terminal, thereby providing a shunt path.

This effect is unlikely to be seen on small solar AtoN but may become more likely on system where higher solar voltages are used to maximize the advantages of MPPT regulators.

9.2.4. MICRO CRACKING

Micro cracking in solar cells occurs throughout its life, starting during the production stages where they are both mechanical and thermally stressed. The mechanical stresses are introduced during the laminating stage, whereas the thermal stresses are created as the cell interconnection ribbons are attached during the soldering process. Transportation and handling then allow cracks to develop further because of vibration and physical loading. Then throughout the module's operational life, it will be subjected to repetitive daily thermal stresses, along with other mechanical stresses generated by wind and snow loading. These stresses allow the micro cracks to slowly grow. This is not a problem if any broken section remains electrically connected. Should this not be the case, then a reduction in module performance will be experienced, which slowly gets worse over the life of the module.

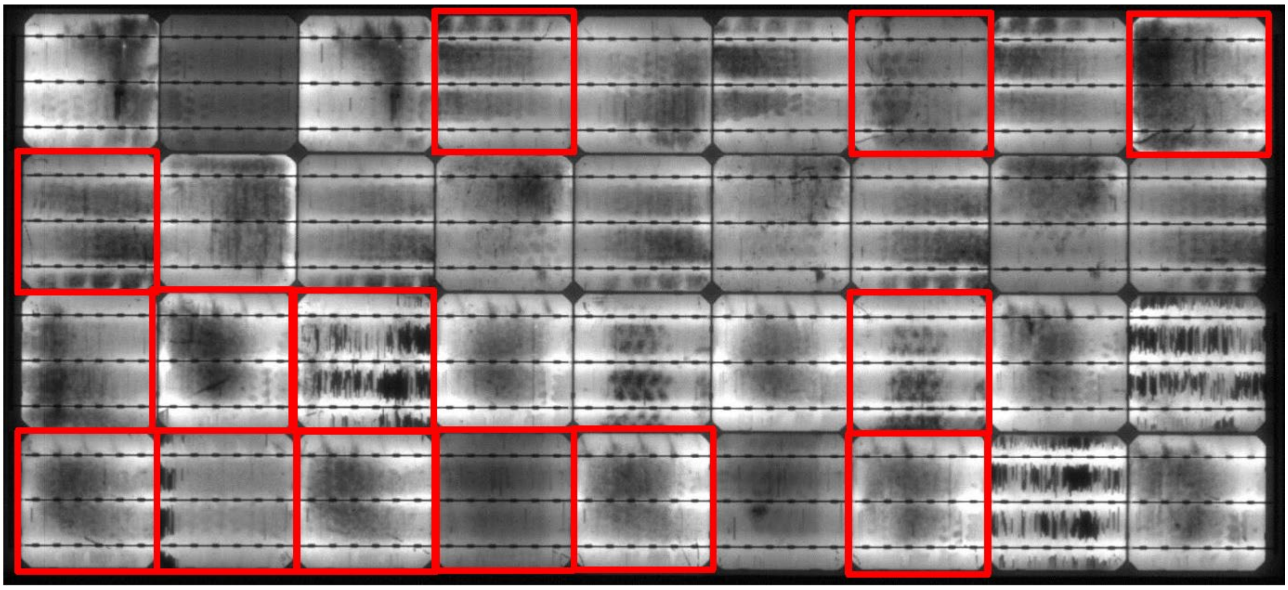


Figure 27 An example of a module with 13 cells which have micro cracking made visible using electro luminescence.

9.2.5. SNAIL TRAILS

As the term suggest, these are a visual discolouration to the surface of a solar cell, which look like a snail's trail. They are part of a chemical process, where silver oxide from the front side of the solar cells migrates into the Ethyl Vinyl Acetate (EVA) and hence result in the discolouration. This often occurs around micro cracks in the cells. This discolouration, however, has no detrimental impact on the cells performance, but can lead to additional leakage current.

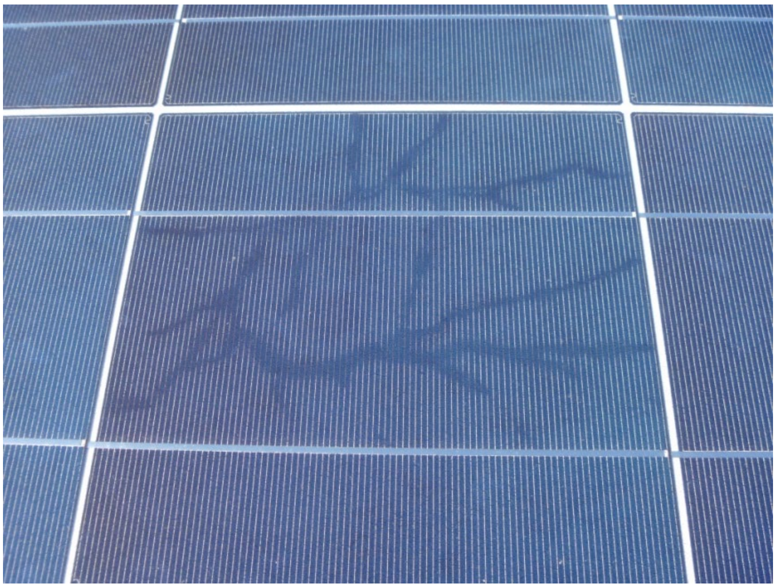


Figure 28 An example of Snails trails on a solar module (from the internet).

9.2.6. HOT SPOTS

Local hot spots in a module can be caused one of three ways; by a poor soldered connection; by an intercell ribbon fracture; or through the application of reverse current flow through a cell or cell string. Hot spots due to solder and ribbon failures are driven by thermal fatigue resulting in a higher resistance location, which leads to spot heating and discolouration. Hot spots generated by reverse current flow can be caused by a cracked cell, shaded section of a module or a failed bypass diode. A hot spot will then occur at a defect or high resistance area possibly leading to thermal runaway.

Figure 29 An example of a hot spot within a module.

Such hot spots don't necessarily mean a reduction in power output, as this is subject to the location where it occurs and how the sections are interconnected, but it would be recommended to replace the module to avoid the possibility of any catastrophic failure.

9.2.7. INTERCELL CONNECTION BREAKAGE

Intercell connection breakage often occurs at the point where the ribbon kinks over the cell edge. These points on the ribbons are prone to fatigue due to thermal stress, however the starting point is often during production, due to too much kink formation pressure, leading to residual mechanical stress. Then, during operation, the daily thermal cycle, and hence expansion and contraction of a weakened bend, results in the fatigue, fracture, and failure. This is not the only cause of intercell connection failure, as poor soldering can also result in the same outcome.

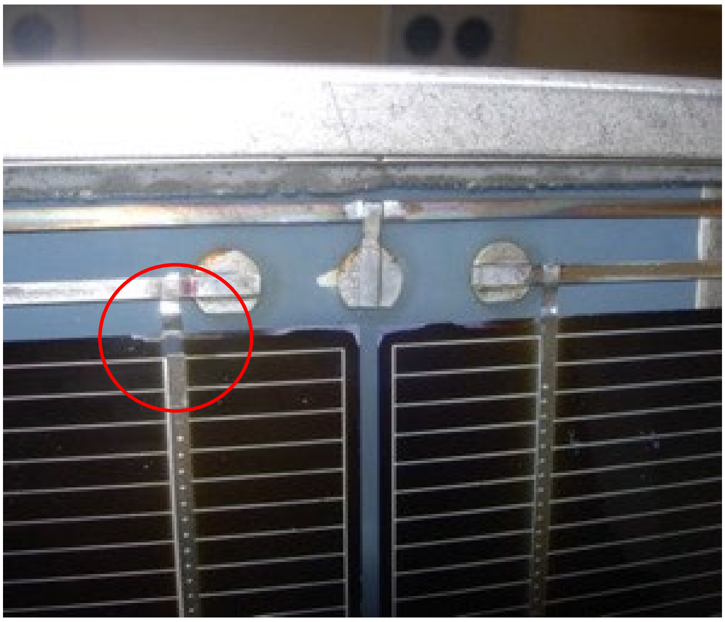


Figure 30 Ribbon fracture.

When such failures occur, it usually leads to a reduction in module performance, through loss of parallel or serial sections, with the only remedy being module replacement.

9.2.8. INTERCELL CONNECTION CORROSION

The initial cause of intercell corrosion is the introduction of moisture into the cell laminate. The persistence of the moisture then allows galvanic corrosion to occur between the lead or tin acting in the solder as the anode, with the copper or silver being the cathode. This leads to the "dissolving" or reduction of the lead or tin and ultimately, loss of the ribbon connection and hence performance. This situation can be quite rapid given the high temperatures and humidity that can be crated within a solar module.

9.2.9. CELL CORROSION

Cell corrosion initially occurs on the edges of the solar cells due to the presence of moisture which reacts with sodium from the glass. This slowly corrodes the glass cover causing it to turn milky, reducing the modules performance. This mode of corrosion has reduced due to the wide use of EVA packaging as part of the laminate.

Figure 31 Cell corrosion.

9.2.10. DELAMINATION

Delamination occurs when the adhesion between any of the layers (glass, encapsulant, cells and backing layers) within the laminate fail. There can be many causes for these failures, such as contamination during production, ingress of moisture during operation or corrosion due to moisture.

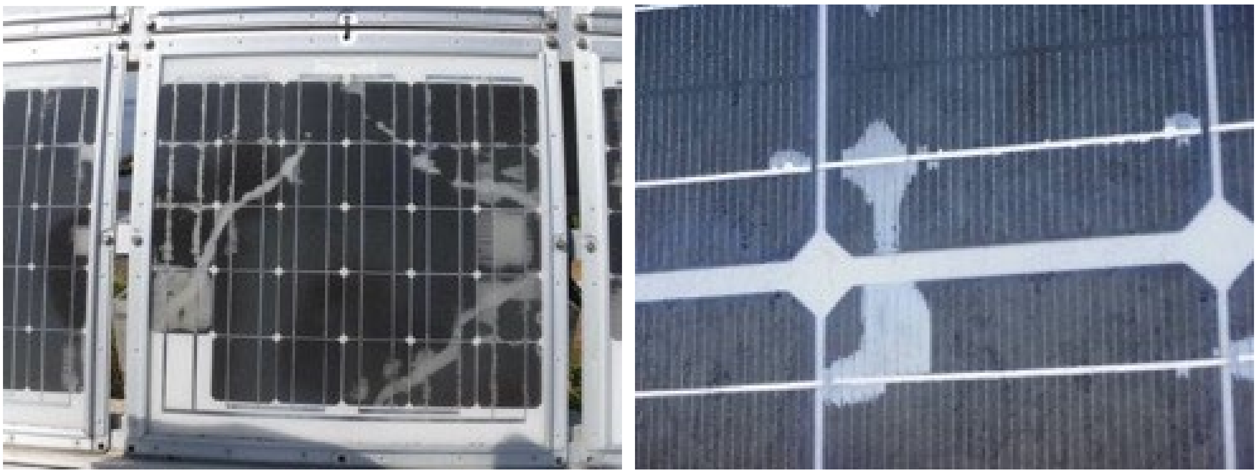


Figure 32 Examples of delamination.

If the delamination impacts on the front side, this can result in a reduction in module performance, but the fact that delamination is occurring, indicates the potential of current if not future moisture ingress.

9.2.11. Sealant failure

Although the solar cells are sealed in a laminate as described earlier, these laminates may then be fitted to a frame or other structural elements, to provide mounting and physical support and protection. These laminates are fitted into these structures with a sealant to enhance the ingress protection. However, the sealant used for this purpose may be poorly selected for the marine operational environment, resulting in premature breakdown and failure. This can be especially critical in areas around the junction box.

Figure 33 Examples of sealant failure.

9.2.12. Metal corrosion

Where the solar module has a metallic element, either as part of the mounting frame or as physical protection in the form of a backing panel, then consideration need to be made about the materials used and how it is to be fixed. This is important in a damp marine environment, where dissimilar material corrosion can occur, or unplanned oxidisation can result in early failure. Sometime, such issues are only cosmetic, but on other occasions it can be significant, such as the combination of stainless steel and aluminium.

Figure 34 Metal corrosion.

As can be seen in Figure 33, the identification of what is good, to what is not acceptable, can be difficult to identify on a new product, but can quickly become apparent when operational, and may be expensive to resolve.

9.2.13. Encapsulant discolouration

The discolouration of the EVA encapsulant within the laminate can be readily seen as the cell first adopts a light-yellow colour, progressing to a brown over time. This discolouration can have an impact on the cell's performance of up to 15% in extreme cases. The cause of the discolouration is due to high levels of UV and heat interact with the diffused oxygen and water in the encapsulant, reacting with chemicals used to treat the glass which forms acetic acid. This can happen during the first few years and is more likely when lower quality EVAs are used. To reduce the likelihood of this happening, a polyvinyl butyral (PVB) encapsulant, or UV blocking glass could be adopted

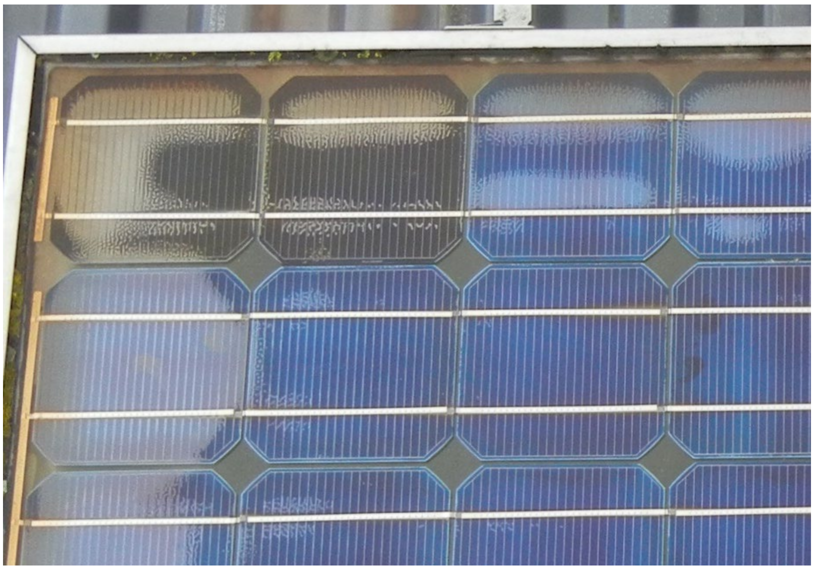


Figure 35 Encapsulant discolouration

9.2.14. POOR INSULATION

Due to the design of solar modules the resistance to the frame it typically high, meaning they have a minimal leakage current flow to the frame, although under certain operating conditions this can increase due to faults, as mentioned earlier. However, the leakage current can be significantly increased due to a production fault. The impact of such faults is a loss in the available energy used to charge batteries.

Where the solar module mounting structures are based on steel, this impact is minimal, but where a more reactive material, such as aluminium is used, then the impact of the leakage current can be more significant on the degradation of the structure. An example of effect of leakage current on an aluminium structure can be seen in figure 35.

Figure 36 Impact of leakage current

Here it can be seen the leakage current has resulted in rapid erosion at key point of dissimilar material to the point where the structure usability is beyond repair. The rate of this erosion is subject to the amount of leakage current, and this example shows the condition after about 2 years.

9.2.15. MECHANICAL IMPACTS AND PHYSICAL STRESS

Mechanical impact is probably one of the most frequent causes of failure, typically caused during handing of AtoN such as buoys. On fixed structures such as lighthouses, such causes can be as a result of loose debris during a storm event.

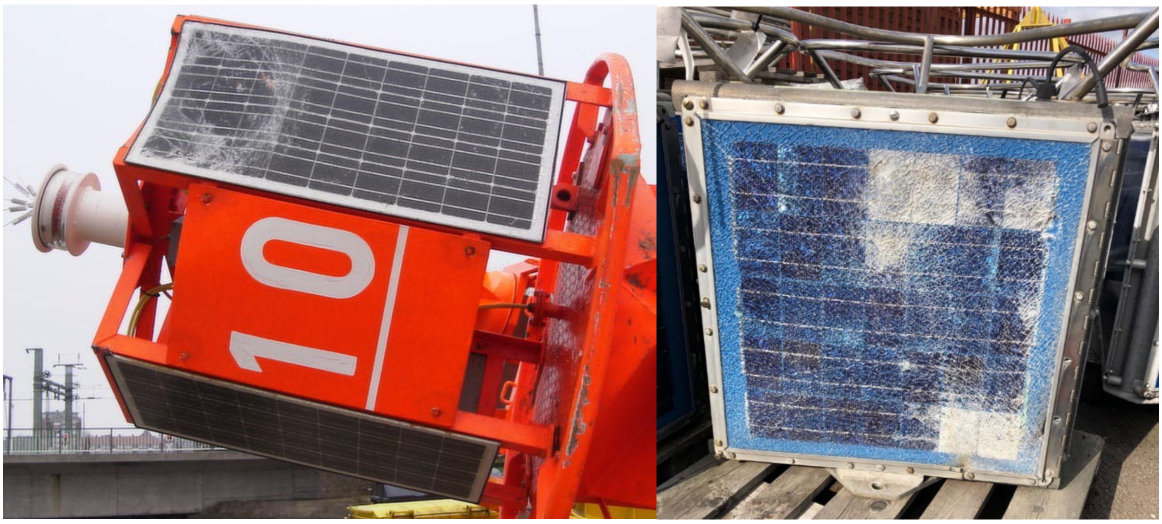


Figure 37 The effects of physical impact

9.2.16. WAVE LOADING

The direct impact of a wave on the delicate solar module structure often ends in deformation and its subsequent failure. See figure 37. This figure shows the effect of wave damage when there is no supporting backing structure.

Figure 38 Wave impact on a solar module

This failure mode is now less frequent due to experiences gained. This has resulted in changes in the mounting and supporting arrangement.

9.2.17. WATER INGRESS

Given the challenging marine environment that marine solar modules operate in, the ingress of water is always a risk. Manufacturers often quote ingress protection (IP) ratings indicating the level that their product has been designed and tested to withstand, yet failures can and do occur. The way this can be seen on a failed solar module is initially through delamination, if the failure is significant, or through cell corrosion if minor or intermittent.

Figure 39 Delamination on a new solar module

9.2.18. CONNECTOR FAILURE

Although the solar module may prove to be an excellent product, its application in a marine environment may prove problematic. An example of this is the use of a standard connector, widely used in an industrial and domestic environment. Although on inspection the connectors have a suitable IP rating and look suitable, over time, failure of the connector can result in the need to replace solar module early.

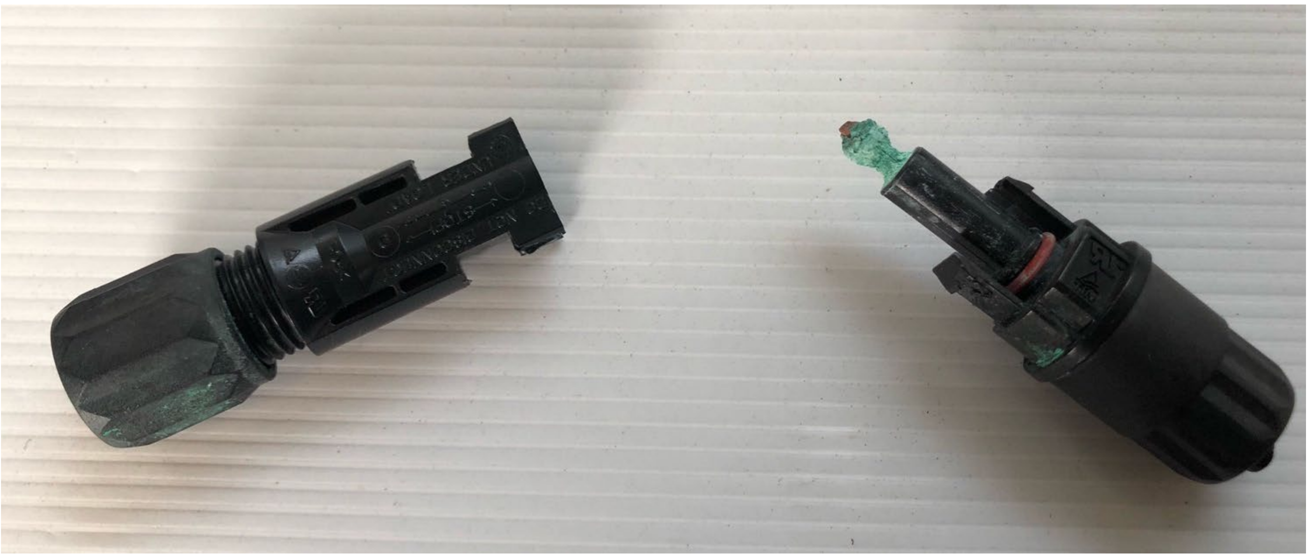


Figure 40 Connector failure

9.3. ICE

Although ice is not the failure mode of solar modules, it can be the cause of the failure, with the result being some form of physical mechanical damage. This may come about through immersion under an ice floe, yet damage can also occur because of ice build-up between surfaces as the water expands and changes into ice.

This is generally very rare, but as four season lit buoys become more extensively adopted, this failure mode may become more prevalent.

Figure 41 An example of ice build-up on a buoy.

9.4. JUNCTION BOX FAILURE

The junction box, where fitted, is a key component to the effective, reliable operation, given that all of the module's power is managed through it. Like the rest of the module, the junction box is subjected to similar environmental attacks. Unlike the rest of the module's structure, the junction box is often manufactured from some form of plastic or glass reinforced plastic (GRP). Some of these materials are more susceptible to failure caused by high temperature and high UV levels, which can result in the boxes becoming brittle and breaking down over time.

Another failure mode of the junction box can be caused through incorrect specification or production, resulting in the junction box coming away from the solar module backing. The main cause of this is the breakdown of the adhesive due to the operating environment or insufficient / poor adhesive application.

Both of these failure modes can lead to water ingress and subsequent modules failure. As such, the junction boxes can be provide fully potted, limiting the impact of any such failure.

10. MAINTENANCE AND TESTING

The general view of solar modules is that they are a very low maintenance solution, with no moving parts, sealed to the environment, providing a long-term energy source. They are, however, not maintenance free and at the very least require periodic cleaning to remove any environmental debris.

10.1. SITE TESTING

Although manufacturers make "best efforts" to eliminate sources of solar module performance loss and failure, it is known that the performance of solar modules degrades over time. Additionally, failures do occur through various means as outlined earlier. To avoid any adverse impact on the AtoN, some form of inspection and testing will need to be employed at some point through the life of a solar array. This section outlines some of the common approaches adopted. Others are available, but become more specialized, both in the equipment used and the knowledge to interpret the results.

10.1.1. PHYSICAL INSPECTION

Probably the most frequently used method to assess the condition of installed solar modules. It can be quick, non-intrusive and achieved during any cleaning process. The level of technical knowledge needed for these checks to be done are low, allowing this to be done by non-technical personnel.

10.1.2. OPERATIONAL CHECKS

There are some quick checks that can be achieved by technically trained personnel to confirm a module's operation. These are usually comparative measurements of the solar module's open circuit voltage. This can be achieved by isolating the modules and measuring and comparing the voltage relative to others in an array. It assumes the level of irradiance remains about the same during the period of the checks. Such checks just confirm module operation and can identify if any sections of a module have failed.

10.1.3. PERFORMANCE MEASUREMENT OF SOLAR MODULES

It is known that the output of solar modules degrades and reduces over time. The rate of this reduction is usually guaranteed by the manufacturer, but as the effective performance of the power system is dependent upon the predicted output level, it is occasionally necessary to confirm the performance. This is especially the case, if the operational life of the modules is extended beyond the original design life.

As the operating point of a solar module typically lies in the range around the maximum power point (mpp), measuring the open circuit voltage and the short circuit current gives a first indication of its performance.

In the following, a simple method is shown with which a measurement of the solar module is possible. The open circuit voltage U_{oc} and the short circuit current I_{sc} can be measured directly with a suitable multimeter during the day. Care is needed when measuring the short-circuit current: When removing the measuring tips, an arc may occur if the voltage is > 50V!

Using a typical solar module current voltage curve (see figure 42), the position of the mpp can be estimated from the open circuit voltage and the short circuit current as described:

$U_{mpp} = (0.75 \dots 0.9) \times U_{oc}$

$I_{mpp} = (0.85 \dots 0.95) \times I_{sc}$

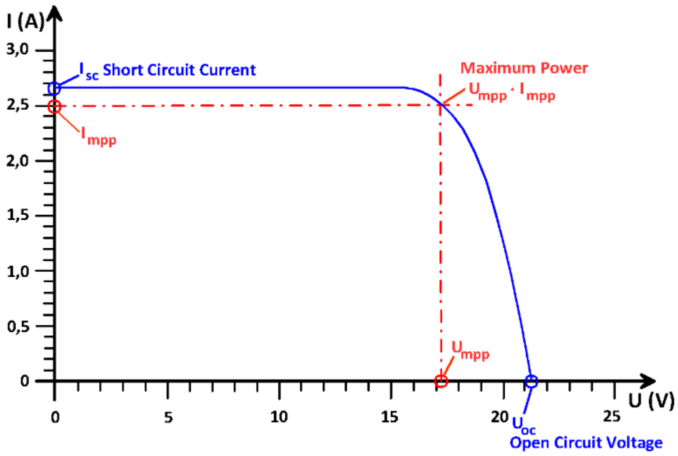


Figure 42 Current / voltage curve

However, defects caused by shading or cell breakage may remain hidden. Therefore, a complete current-voltage characteristic curve has the greatest significance for the proper functioning of a solar module. To record such curves, devices are on the market that allow measurement on site and subsequent evaluation of the data by a computer.

Figure 43 module tester

10.1.4. INFRARED IMAGING

This type of testing is usually done as part of the solar module production process but can be applied in the field. More recently, drones have been used to assess large solar array farms. This method, known as solar thermography, is another non-intrusive method of checking that all is operating correctly. It can be quick to do but does require specialist equipment and knowledge to interpret the results. This method of testing typically identifies the following problems:

- poor or failed connections, both in the module or junction box;
- inactive cells; and
- short circuits.

11. PROCUREMENT

The process adopted for procurement will be different for each organization, but this section provides information that is not process dependant and yet beneficial to obtaining a high quality marine solar module.

11.1. HOW TO SPECIFY

As with all items purchased, it is the communication and translation of the requirements that will determine the satisfaction of the product received. This is usually conveyed in some form of specification, ideally capturing measurable desires, but sometimes these are dimensionless, such as “good build quality”. A sample specification is provided in Annex 1 for guidance on some of the requirements that can be specified.

Even if selecting solar modules from a catalogue, it can be useful to capture a specification beforehand to aid in comparison.

11.2. QUANTITIES

When purchasing solar modules, quantity significantly influences the likelihood of achieving your specification. If the quantities are small, then the only choices may be to select from a catalogue. If the wattage required is high, then these modules may well be of the high-volume industrial units often used on solar farms. These can be high quality modules, because of the mass production processes employed, but may lack some features for a marine environment.

Low volume products may be available but achieving a high quality may come at a premium cost and could be more difficult to achieve due to the batch nature of the assembly process. It will however, likely have all the features specified for a marine environment.

11.3. IDENTIFICATION OF MODULES

To aid in the tracking, identification and performance monitoring of all solar modules, it is recommended that each module is uniquely identified and ideally has the following information visible:

- Date of manufacturing
- Manufacturer
- Model
- Electrical performance (maximum voltage and current)

11.4. DELIVERY

It has been highlighted earlier that micro cracking of solar cells often occurs during handling and transportation phase. It is therefore important to ensuring effective packaging is achieved to minimize vibration and shock loading. In addition, the packaging and handling also need to avoid physical damage of a more catastrophic nature.

12. PRODUCT ASSESSMENT

The initial phase of a product assessment happens during the review of the products specifications against the requirements to see how closely these are achieved and what differences can be tolerated. After this, any assessment involves availability of physical products, either on loan, or after purchase. This can allow for assessment of quality and suitability for the environment, along with confirming things such as physical fit, mounting arrangement and connectivity.

As for longer term performance, such as the ability to resist water ingress and provide the guaranteed output, these are almost impossible to assess, other than through a long-term test. However, such test may well prove pointless as the technology may well have moved on by the time the trials are complete. What these tests do provide is confidence in the supplier's product generally.

13. RECYCLING AND REPURPOSING

Solar modules, at the end of their life, are considered easy to recycle. The frame, whether aluminium or stainless steel can easily be separated. The glass can be broken and collected. The challenge is then around the laminate. This requires heat to burn off the small amount of plastic, leaving the silicon wafers that can be etched away and then smelted into an ingot for reuse. This process does use significant energy and specialist equipment, and is driven by the economics of material costs. Such recycling needs to be done by a specialist approved recycling organization.

An alternative to this, is repurposing. Although a solar module may have reduced in power output, such that it considered unsuitable to provide sufficient energy for AtoN, the module will continue to produce power. This allows the possibility of using old modules for other non-critical purposes or resale for private use. An example of this is volunteer projects, though this is become less appealing as the cost of new modules is so low.

14. STANDARDS

The manufacture of photovoltaic modules is governed by several standards required by the International Electrotechnical Commission (IEC) in order to be sold on the international market. These may also be supported by national standards. Some of these are identified below for information.

- IEC 60068-2-53: 2010 Environmental testing - Part 2-53: Tests and guidance - Combined climatic (temperature/humidity) and dynamic (vibration/shock) tests
- IEC 60068-2-68: 1984 Environmental testing - Part 2-68: Tests - Test L: Dust and sand
- IEC 61215 – 1: 2021 Terrestrial Photovoltaic (PV) modules – Design qualification and type approval - Part 1: Test requirements
- IEC 61215 – 1-1: 2021 Terrestrial photovoltaic (PV) modules – Design qualification and type approval – Part 1-1: Special requirements for testing of crystalline silicon photovoltaic (PV) modules
- IEC 61215 – 2: 2021 Terrestrial Photovoltaic (PV) modules – Design qualifications and type approval – Part 2: Test procedures
- IEC 61701: 2020 Photovoltaic (PV) modules - Salt mist corrosion testing
- IEC 61730 – 1: 2016 Photovoltaic (PV) module safety qualification - Part 1: Requirements for construction
- IEC 61730-1: 2016 Photovoltaic (PV) Module Safety Qualification - Part 2: Requirements for Testing
- IEC 62716: 2013 Photovoltaic (PV) modules - Ammonia corrosion testing
- IEC 62753: 2015 Photovoltaic (PV) modules - Transportation testing - Part 1: Transportation and shipping of module package units
- IEC 62790: 2020 Junction boxes for photovoltaic modules - Safety requirements and tests
- IEC 62941: 2019 Terrestrial photovoltaic (PV) modules - Quality system for PV module manufacturing
- IEC 60529 Ed. 2.1 b:2001 – Degrees of Protection Provided by Enclosures (IP Code)
- UL 1703: Standard for flat-plate PV modules and panels

15. DEFINITIONS

The definitions of terms used in this IALA Guideline can be found in the International Dictionary of Marine Aids to Navigation (IALA Dictionary) and were checked as correct at the time of going to print. Where conflict arises, the IALA Dictionary should be considered as the authoritative source of definitions used in IALA documents.

16. ABBREVIATIONS

AtoN	Aid to navigation or aids to navigation
EVA	Ethylene-vinyl acetate
GRP	Glass reinforced plastic
IEC	Electrotechnical Commission
IP	Ingress protection
IPSL	Integrated power system lantern
LID	Light induced degradation
LV	Lightvessel
PID	Potential induced degradation
PV	Photovoltaic
PVB	Polyvinyl butyral
STC	Standard test conditions
UV	Ultraviolet
WSV	Wasserstrassen- und Schifffahrtsverwaltung des Bundes (German Federal Waterways Administration)

17. REFERENCES

[1] IALA Guideline G1064 Integrated Power System Lanterns

[2] IALA Guideline G1039 Designing Solar Power Systems for Marine Aids to Navigation (Solar Sizing Tool)

[3] IALA Guideline G1012 Protection of Lighthouses and other Aids to Navigation against Damage from Lightning

[4] IALA Guideline G1091 Bird deterrent and Bird Fouling Solutions

[5] IALA Guideline G1136 Providing AtoN services in extremely hot and humid climate

ANNEX A SPECIMEN SOLAR MODULE SPECIFICATION

Below is a list of key parameters that can be considered as part of a solar module specification.

Table 3 Specimen specification

Parameter	Sample value	Comments
A.1. ELECTRICAL CHARACTERISTICS		
Nominal power (@ STC)	100 W	
Nominal voltage	12 V	
Open circuit voltage	<20 V	
Short circuit current	>5 A	
Module efficiency	>15 %	
Temperature coefficients		
Voc	-0.17 ± 0.01 V/°C	
Isc	3 ± 1 mA/°C	
Pmax	-0.4 ± 0.1 %/°C	
Leakage current	<0.1 µA	
A.2. ELECTRICAL FACILITIES		
By-pass diodes	Fitted	
Blocking diodes	Fitted	
Connectivity	Latching MC4 IP65/ IP2x (mated/ unmated) 2 ± 0.1 m cable	
Cable		
Junction box size	100 mm x 100 mm x 50 mm	
Junction box attachment	Adhered to backing panel	
A.3. MECHANICAL CHARACTERISTICS		
Dimensions	1600 mm x 1000 mm x 50 mm	
Mounting arrangement	Frameless	
Weight	< 12 kg	
Material	Aluminium - Marine Grade 5083-0	

Parameter	Sample value	Comments
A.4. ENVIRONMENTAL CHARACTERISTICS		
IP rating	IP65	
Max & min operating temperature	70 °C to -10 °C	
Humidity	100 % condensing	
Shock & vibration	4 G at 600 Hz	
Corrosion class	Offshore	
A.5. ENVIRONMENTAL LOADINGS		
Maximum wind loading	1200 N/m^2	
Maximum snow loading	600 Nm^2	
Maximum structural deflection	<30 mm	
A.6. WARRANTEES		
Service life	20 years	
Material warrantee	10 years	
Warranted output power	90 % of nominal after 10 years 80 % of nominal after 20 years	
A.7. STANDARDS		
See section 14 for details of standards		
A.8. TESTS / DOCUMENTATION		
Typical IV performance curve	Provided	
A.9. OTHER		
Module Identification	Unique serial no.	