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**THIN FILM CI(G)S PV MODULES:
RESULTS FROM MONITORED INSTALLATIONS AND COMPARISON TESTS**

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ABSTRACT: The paper explains the main features of the thin film CIS PV modules and tries to highlight the advantages of the technology even in Mediterranean countries. In the real world conditions CIS PV installations have a better performance in terms of specific generated output (kWh/kWp) in comparison with crystalline silicon modules, improving the return on investment for the end user/investor and maximizing the self-consumption. The main factors that contribute to the higher yields of CIS PV installations in comparison with c-Si are: the high temperature stability, the good behaviour with low light and low angle irradiation, high shadow tolerance and the light soaking effect. Several installations in different parts of the world with various weather conditions have been monitored scrupulously throughout the years with the production of a significant number of case studies. The results confirm that PV installation with CIS modules generate an average of 10% more electricity per rated power (kWh/kWp) even in optimal condition (modules facing south with 20-30° tilt). This gap increases as the condition of the weather (ambient temperature, irradiation) and of the roof (tilt, azimuth) varies from the optimal one. Due to their high flexibility in the installation it is possible to maximize the yield for the given area (kWh/sqm).

Keywords: temperature stability, low light behaviour, light soaking , performance ratio, yield per area

1 INTRODUCTION

Today crystalline silicon solar modules still dominate the PV market with a share of 85%. Recent progress has been made by thin-film module technologies that now hold a 10% of market share.

The common feature of all thin-film modules is the use of a single, very thin deposited layer of semiconductor material in order to avoid the high costs of the raw materials and energy needed to produce high-purity silicon wafers.

Different kind of semiconductor materials are utilized to produce thin-film modules. Those in commercial production include: amorphous silicon (a-Si), micromorph silicon (mSi), cadmium telluride (CdTe) and CIS.

Among the technologies of serial production, CIS is to be considered as the most innovative and with the most development potential in relation with power generation, efficiency and environmental impact.

CIS is an acronym that stands for the main constituent elements of the absorber layer: copper (C), indium (I) and selenium (S). Atoms of Indium may be substituted with Gallium (Ga). That's why the technology is sometimes called CI(G)S. It has a crystal structure, tetrahedrally bonded like the one of the chalcopyrite (Fig.1).

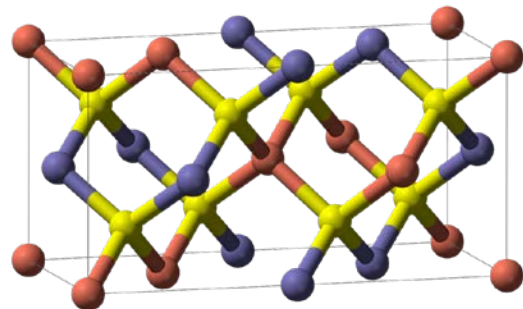


Figure 1: CI(G)S structure: Red = Cu, Yellow = Se, Blue = In/Ga

2 THE CIS-BASED SOLAR CELL

The most common device structure for CI(G)S solar cells is shown in the below diagram (Fig.2).

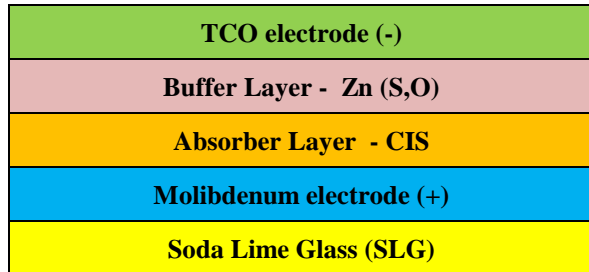


Figure 2: not to scale diagram of the CIS-based solar cell

- 1) Substrate: soda-lime glass (SLG - the normal window glass) is the most common used material. The substrate is necessary since the layers are so thin that cannot be supported by themselves.
- 2) Positive electrode: a molybdenum metal layer with a thickness of $500 \div 1000$ nm, deposited by sputtering is used as back-contact and reflects most of unabsorbed light back into the absorber.
- 3) Absorbing material: a CI(G)S film, which is the p-type layer, with a thickness between 1500 and 2000 nm is deposited by means of various unique methods, which include sputtering, vapor co-deposition, selenization, electrochemical deposition, nanoparticle printing and ion-beam deposition.
- 4) Buffer layer: a very thin film, $50 \div 100$ nm thick. It forms the so-called window layer. This is the n part of the p-n junction; the constituent material are transparent in order to allow the light to reach the p side of the junction that is the CIS absorber. For environmental reasons some manufacturers have substituted the conventional cadmium sulfide (CdS) with Zn by using zinc oxysulfide Zn(O,S)
- 5) Negative electrode: a Transparent Conducting Oxide (TCO) made by a pure bi-layer of ZnO and an Al-doped ZnO is used as a transparent electrical contact (front-contact), which together with the Mo back-contact allows the transport of the photocurrent to an external load. To improve the transparency the thickness of this bi-layer is never over 1000 nm.

3 ECOLOGY, ENVIRONMENT

CIS technology is very environmental friendly since its simpler manufacturing process consumes much less raw materials and less energy in comparison with crystalline silicon based technologies.

The starting materials are used in the form of very thin layers (a few grams of each substance per m^2 are required, while Si technology needs 120 times higher amount of raw materials).

CIS has one of the lowest Energy Payback Time (EPT) between the photovoltaic technologies. The energy used to produce the PV module returns in less than a year (7-8 months).

Another advantage, not only in comparison with crystalline silicon modules but also with other-thin film technologies, such as cadmium telluride, is the low environmental impact of CIS technology.

CIS modules are free from lead and cadmium, the used components do not represent any particular risk for human health and the environment, therefore not requiring any special recycling procedure at their end of life.

4 EFFICIENCY

Modern thin-film modules, particularly those with CIS technology, have achieved in the last years significantly higher module efficiency levels, comparable to crystalline silicon modules, reaching a good rate of nominal power (kWp) / given area (sqm) in installations integrated in the roofs or building walls.

The recent results on CIS prototypes show that there is still a big potential for enhancing efficiency.

For example the leading CIS Japanese manufacturer Solar Frontier, in its Research Center, has recently achieved 22.3% efficiency (World Record) on a 0.5 sqm cell [1].

5 PERFORMANCE IN THE REAL WORLD CONDITIONS

It is common belief that a module with higher conversion efficiency, as it is indicated in the data-sheet, will perform better when installed on the roof or in a field. But that's not always true.

Conversion efficiencies are measured in laboratory under a very controlled set of conditions, the so called Standard Test Conditions (STC). These conditions are: irradiation of 1000 watt/sqm, module temperature of 25° , Air Mass of 1.5 AM. But in the real world this set of conditions are very rare and technologies that have high conversion efficiency in laboratory conditions might not perform so good when facing hot, humid or cloudy conditions.

CIS modules have technological features that are suited to dealing with real-world conditions. As a result they can generate more electricity per rated power unit (kWh/kWp) than crystalline silicon panels in real-world conditions, despite their lower conversion efficiency.

The main factors are :

- ✓ High temperature stability;
- ✓ Good behavior with low irradiation angles and low light;
- ✓ High shadow tolerance;
- ✓ Light Soaking Effect.

In the following paragraphs, it is explained each of the above technological advantages that contribute to the higher yield of CIS in comparison with conventional technology (c-Si).

5.1 High Temperature Stability

As all the other semiconductor devices, also PV cells are very sensitive to temperature. As the temperature rises there is an output decrease of the module that produces yield losses. The amount of the output decrease in percentage is indicated in the data-sheets of the various modules by the parameter “Temperature Coefficient on the Power” (- %/°C).

The output loss can be easily calculated multiplying the Temperature Coefficient by the temperature increase of the module above 25°C (standard test condition).

CIS modules have a lower temperature coefficient, which means that the temperature has less effect. The advantage of greater temperature stability becomes more important in PV installations in hot regions.

In the below chart there is an example with calculation of the power losses of the different technologies at the module temperature of 75° C, that can be reached in case of an ambient temperature of 35°C. (see Fig. 3).

Technology	Power Temp. Coeff. (%/°C)	Power Losses (%)
Poly c-Si	-0.45	- 22.5%
Mono c-Si	-0.40	- 20.0 %
CIS	-0.31	- 15.5%

Figure 3: Power losses at module temperature of 75°C

5.2 Low Light Behaviour

The spectral response (SR) of a PV cell is governed by the ability of the photons to be absorbed in the depletion region of the detector and generate the photovoltaic effect.

The sunlight spectrum absorbed by standard crystalline silicon cells ranges from 400 to 700 nm, while the absorption range for CIS cells is between 350 and 1200 nm. This means that the effective time for generating electricity is much longer each day for CIS than other technologies, allowing more energy (kWh) to be produced per rated kWp installed and increasing the self-consumption

percentage of the end customer since the energy is more distributed along the day.

5.3 Good Behavior with Low Angle Irradiation

In the visible part of the solar spectrum (400 ÷ 800 nm), silicon cells reflect more than 30% (between 30% and 50%) of the incident light (see Fig. 5). On the contrary CIS exhibits a reflectance less than 15% over the entire solar spectrum (10% in average). (see Fig. 6)

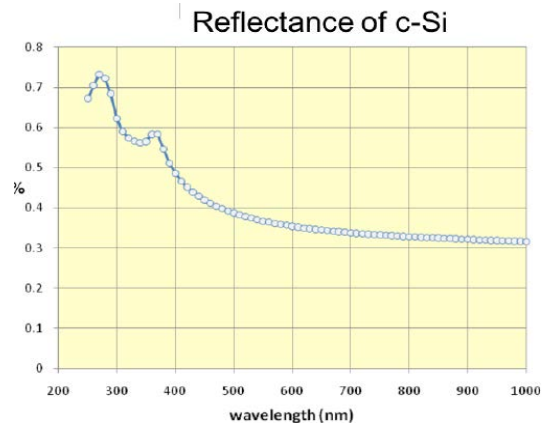


Figure 5: Reflectance of c-Si

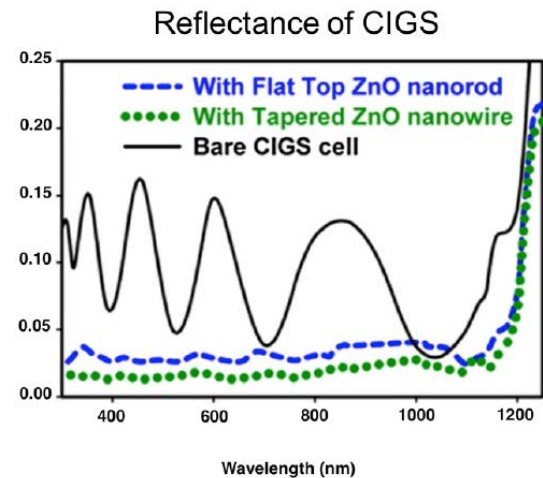


Figure 6: Reflectance of CI(G)S

For this reason, the crystalline silicon modules manufacturers use an anti-reflecting (AR) coating in order to minimize the light losses due to the high reflectivity of the c-Si surface. The AR coating is normally applied on the front-contact layer during the production process of the Si cell.

The thickness of the AR layer is designed to work efficiently with a “normal” incidence of the solar light over the Si surface. When the incident light angle is low or grazing, the AR coating is not able to minimize the reflection. In this condition (low angle irradiation- diffused light) the Si-based solar cells loose at least 30% of their photovoltaic

conversion efficiency. CIS based solar cells doesn't need any AR layer on top of the transparent electrode because the reflectance value is low enough to save the high costs of the coating.

With crystalline technology there are significant production losses when the modules are installed with a tilt and an orientation different from the optimal condition (flat, vertical, east, west, north). On the other hand, high output can be achieved with CIS modules on installations with tilt and orientation that result in low angle irradiations.

CIS modules are suited for building integrated application (vertical), achieving even in these cases very good yields. The real outputs of different installations in non-optimal conditions confirm this (see case studies 2 , 3, 4).

In case of building with flat roofs typical of the Mediterranean countries, the energy yield on the given area can be optimized with CIS technology, by lowering significantly the tilt of installation and reducing the spacing between rows with the added benefit of minimizing the visual impact [2].

5.4 Shadow Tolerance

Unlike traditional crystalline panels, CIS cells design allows them to perform even if part of the panel is shaded. Due to their circuit layout CIS is very shadow tolerant. The square silicon cells in the module are connected in substrings, while the long, narrow thin-film cells are connected in series.

In case the modules are installed perpendicular (portrait) to the cast of the shadows the reduction of output is proportional to the shaded area. This brings the advantage that the distance between module rows can be reduced on flat rooftops or on ground installations and therefore more power (kWp) can be installed in a given area.

5.5 Light Soaking Effect

Most of the PV technologies change their performance under extended continuous illumination (metastable behavior or light induced degradation)[3].

While c-Si (crystalline silicon), a-Si (amorphous silicon) and CdTe (cadmium telluride) show degradation with light absorption, CIS shows improvement in efficiency and module rated power during the beginning hours of light absorption. The increase in power is caused by the phenomenon of the so called light soaking effect. Because of this effect there is an increase in the output of the module (5 – 10 %) after being exposed to sunlight.

For instance a module with a nominal power of 170 Wp (at the standard test conditions) may produce 180 Wp when subjected to illumination.

The Light Soaking Effect starts after the module's exposure to sunlight and stabilizes after about 50 hours of sunshine.

6 RESULTS FROM MONITORED INSTALLATIONS

Many installations with CIS have been monitored in different parts of the world with different conditions of roofs and weather, confirming the higher performance of CIS in comparison with other PV technologies.


In all the monitored installations the yearly specific output (kWh/kWp) of CIS installation was always 8-10% more than the one with c-Si installations in the same area and same characteristics of tilt and orientation. This gap increases in non-optimal conditions of roofs or bad weather condition.

In order to measure and compare correctly the performances of the different PV technologies a reliable indicator that was used is the Performance Ratio. It refers to the ratio between the actual yield and the energy yield that would theoretically be possible under standard test conditions. With c-Si technology we have normally performance ratio between 70% and 85% depending on the quality of the PV system. With CIS the PR is always well above 90%.

PR Formula:

$$\frac{\text{Actual output (AC) from installed capacity (kWh)}}{\text{Installed capacity (kW) } \times \frac{\text{Actual Radiation (kWh/m}^2\text{)}}{1 \text{ sun (1 kW/ m}^2\text{)}}}$$

Data and comparisons with c-Si:

CASE STUDY 1 – COMPARISON			
Location: North Italy (Mantova) – Industrial Roof			
INSTALLATION TECHNICAL INFO			
Size: 39.9 kWp	Module type: SF-150-L		
Azimuth: 20° W	Tilt: 20°		
Modules integrated in the roof			
			
OUTPUT DATA			
Year	Yield (kWh/kWp)	c-Si yield (kWh/kWp)*	Delta
2013	1,320	1,184	+ 12%
2014#	1,259	1,152	+ 9%
2015	1,366	1,206	+ 13%

*Average specific production (kWh/kWp) of c-Si based installations facing south in nearby geographical area (within 10 kilometers from the CIS installation) – (data from Solarlog free Webportal- <http://home.solarlog-web.it/1.html>)

year with frequent days of raining in summer time

CASE STUDY 2 (TEST FIELD) –ITALY

Location: North Italy (Ceresara) – Industrial Roof

INSTALLATION TECHNICAL INFO

CIS INSTALLATION

Size: 163.80 kWp Module type: SF-150-L

Azimuth: 120 ° N / -30° Tilt: 6°



C-SI INSTALLATION

Location: North Italy (Ceresara) – Industrial Roof

Size: 19.78 kWp Module type: poly 215

Azimuth: 120 ° N / -30° Tilt: 6°



SPECIFIC OUTPUT DATA – COMPARISON

Year	CIS (kWh/kWp)	C_Si poly (kWh/kWp)	Delta
2012	1,272	1,109	+15%
2013	1,185	1,037	+14%
2014	1,177	1,056	+11%
2015	1,210	1,098	+10%

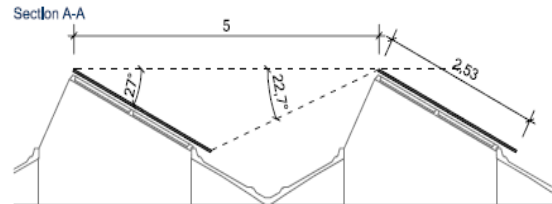
CASE STUDY 3 – (SHADING)

Location: Italy – Reggio Emilia – Industrial Roof

INSTALLATION TECHNICAL INFO

Size: 221.34 kWp Module type: SF-170-S

Azimuth: -90 (EAST) Tilt (shed): 27°



(for part of the day the lower row is shadowed)

OUTPUT DATA

Period	Yield (kWh/kWp)	Irradiation (kWh/sqm)	Performance Ratio (PR)
08/15 - 07/15	1.089	1.157	94,11 %

CASE STUDY 4 (COMPARISON) - MALTA

INSTALLATIONS TECHNICAL INFO

CIS (NEARLY FLAT)

Location: **SIGGIEWI**

Size: 3.06 kWp

Module type: SF-170-S

Azimuth: 180°

Tilt: 5°



The modules are shadowed by surrounding trees

C-SI TOP BRAND MONOCRYSTALLINE

Location: **TARXIEN**

Size: 3.00 kWp

Module: Mono c-Si

Azimuth: 180°

Tilt: 20° *



DAILY AVERAGE SPECIFIC PRODUCTION

Month (2016)	CIS (kWh/kWp)	Mono c-Si (kWh/kWp)	Delta
August	5.87	5.25	10,65%
September	4.96	4.41	11,02%

Note: monocrystalline is installed with a better inclination in comparison with the one of CIS.

7. CONCLUSIONS

The results of the monitoring of real installations and comparisons in field tests show that:

- CIS modules can generate more energy (kWh/kWp) than crystalline silicon panels in real-world conditions (average of 10% of more specific output) maximizing the return of investment;

- due to their high temperature stability CIS technology is particularly suited for installation in hot climates;

- the good behavior with low angle irradiation allows a better use of the roof or field maximizing the electricity yield in a given area (kWp/sqm). This is particularly interesting for countries with space limitations as the Mediterranean islands;

- CIS modules start to produce earlier in the morning and stop later in the evening due to their high sensitivity to infrared light-waves, increasing in this way the self-consumption of the PV end-user;

- CIS modules are very efficient even when shadows are cast over the modules or their surfaces are partly covered therefore are suited for installation on domestic roofs;

- CIS modules increase their efficiency of more than 5% after 50 hours of sunshine-exposure, due to the light-soaking effect.

- CIS technology is ecologic and has a low impact on the environment in its production and end-life.

As a criticality in the installation is to be highlighted the high open circuit voltage of the CIS module that brings to a slight increase of the installation costs (€/kWp) due to the more string parallels to be realized.

8. ACKNOWLEDGEMENTS

I acknowledge the support of the Institute for Sustainable Energy for providing us with data for solar radiation and temperature in Malta.

9. REFERENCES

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