AtaMo: PV meets the high potential of the Atacama Desert

Modules for harsh environments | Chile's Atacama Desert has some of the best irradiance resources on the planet but also some of the harshest operation conditions. Scientists are working on a new type of bifacial glass-glass PV module , AtaMo, designed to make the best of the region's resources while withstanding its rigours. Here they outline some promising preliminary results from the project

Since 2014 the most important goal of the Chilean Centre for Innovation and Promotion of Sustainable Energy (CIFES) has been the elaboration, development and implementation of a national solar strategic programme. In terms of numbers, Chile's cumulative PV capacity was 741MW at the end of October 2015, with PV projects under construction and environmentally approved adding up to 12.4GW. The main reasons for PV implementation in Chile are high electricity prices, cost-effective PV modules and high radiation levels in the Atacama Desert.

> "Certification and testing standards defined by IEC and UL have not been developed for PV applications in such climates as in the Atacama Desert"

It is important to point out, however, that certification and testing standards defined by IEC and UL have not been developed for PV applications in such climates as in the Atacama Desert. This desert experiences extremely high irradiation levels (mostly in the ultraviolet range), large temperature gradients, a corrosive environment, partial high humidity and fine dust; therefore performance and longevity of PV systems may be seriously affected. In addition, the above-mentioned standards can only be applied in part when determining module stability in the face of climatic impacts.

With the objective of carefully considering and profiting from Chilean natural resources and their peculiarities, the International Solar Energy Research Center (ISC) Konstanz (Germany) and the University of Antofagasta (within the Solar Energy Research Center – SERC Chile) have been working together on the development of a bifacial glass–glass PV module adapted to the local conditions. This module, aptly named the *Atacama Module (AtaMo)*, has been implemented at the solar platform in the Atacama Desert (PSDA). Preliminary outdoor measurements carried out at the PSDA and in Konstanz reveal that glass with an anti-reflection coating (ARC) helps to improve the performance ratio (PR) by up to 1%. Full-size cell modules show a high PR for irradiances higher than 800Wm^{-2}. Half-size cell modules with an ARC exhibit a specific yield of up to 2.3% higher, compared with standard glass, and up to 4.3% higher than full-size cell modules for illuminations above 900Wm^{-2}. It is expected that these modules will be incorporated in large PV systems in the Atacama Desert, and, at later stage, manufactured in Chile.

Solar strategy in Chile

At the beginning of 2014 the Chilean Ministry of Economy, Promotion and Tourism launched its Productivity, Innovation and Development Agenda [1]. In this document, one of the strategic targets took into consideration a recommendation from the Organisation for Economic Co-operation and Development (OECD), which states that developing countries should select and boost specific economic sectors with a strong and big growth potential, depending on the global market opportunities and natural conditions of the country [2]. In such a context, the solar industry represents one of the most valuable sectors for the Chilean economy, given the local irradiation, which is one of the highest in the world [3]; moreover, solar energy can help improve the competitiveness of all economic sectors in Chile, thereby lowering energy prices.

At the same time, in May 2014, the Chilean Ministry of Energy published its Energy Agenda [4], which looked at the transformation of the old CORFO Committee Renewable Energy Center into a new and more relevant institution, namely the Centre for Innovation and Promotion of Sustainable Energy (CIFES). (CORFO is the Chilean Economic Development Agency.)

Under these two Agendas, one of the main targets of CIFES is to elaborate and develop the Solar Strategic Program (PES), implementing the public policies established by the ministries above. In order to accomplish this work, the IfM Cambridge road-mapping methodology has been adopted [5], not only as a technological development approach but also as a broader one. This methodology has been combined with the Quattro and Quintuple helix innovation system approaches [6], recognising the extreme relevance and importance of the stakeholders, who create and support the development of the roadmap. The social, academic, private and public sectors have been working together on the process of identifying the vision of the programme, the baseline, the opportunities and gaps, and the main projects that will support the reduction of the existing gaps in order to achieve the following:

- an efficient use of the solar resource;
- a national solar technology and service industry at low levelised costs of electricity for PV (LCOE);
- a higher quality of life for the Chilean people, who are the main pillars of PES' vision.

Figure 1. Aerial view of the Amanecer Solar CAP PV power plant [8].

Status quo of PV in Chile

The last renewable energy report of October 2015 prepared by the Chilean Ministry of Energy through CIFES points out that the renewable energy contribution in Chile has reached 11.4% and that solar produced 21.1% (131GWh) of electricity during September 2015. The installed PV capacity in operation reached 741MW and more than 2.1GW are under construction in the country [7]. Examples of large PV installations in Chile are given next.

Amanecer Solar CAP

In June 2014 a 100MW PV power plant located near Copiapó in the Atacama Desert was inaugurated: Amanecer Solar CAP (Fig. 1), developed by the company with the same name, and the largest PV plant in Latin America at this time. Comprising more than 340,000 mc-Si solar panels mounted on single-axis trackers, the installation is expected to generate 270GWh of electricity per year [8].

Salvador Solar Park

The 70MW PV Salvador Solar Park plant became operational in November 2014 and is expected to produce 200GWh of electricity per year. Located in the Atacama region, approximately 5km south of El Salvador, it is one of the first installations in the world to supply competitively priced solar energy to the open market without government subsidies [9].

Lalackama I and II

The 60MW PV Lalackama I plant (Fig. 2), located close to Taltal in the Antofagasta region, became operational in 2014 and is expected to produce 160GWh of electricity per year. Located nearby is the 18MW Lalackama II plant, which is capable of generating approximately 50GWh per year [10].

Luz Del Norte

Construction on the 141MW PV Luz Del Norte plant, located in the Atacama region and 58km north-east of the city of Copiapó, began in October 2014. Its scheduled date of completion is December 2015 [12].

Bifacial power plants

MegaEngineering together with Imelsa have started to install bifacial power plants in Chile using glass–glass bifacial BiSoN modules [13]. Predicted high bifacial gains in these systems of up to 40% untracked and 60% tracked have been demonstrated.

The Atacama Desert

The Atacama Desert is located in South America along the Pacific coast, extending slightly more than 1,000km between latitudes 20°S and 30°S and covering an area of approximately 105,000km^2. This desert is hyperarid, with annual precipitation below 50mm per year [14]. During the cold months, mean temperatures between 10 and 20°C are recorded, whereas during the warm months, 20 to 30°C are usual, with the air temperature remaining below 38°C [15].

With regard to composition, no other place in the world generates as many nitrates as the Atacama Desert, and for 10–15 million years, the nitrate has virtually covered this land. Nitrates account for 28% of the soil, forming a specific rock called *caliche*; individual layers of caliche can even reach a thickness of 5m in some places. Apart from nitrates, other water-soluble salts can be found – for example perchlorates and iodides, which are often not present anywhere else. Most salts were transported here from the ocean by wind and from local evaporated lakes whose sediments were also carried by the wind [16].

The Atacama Desert is one of the places on earth with the highest surface irradiation. The desert boasts a high mean altitude, a large number of days with clear skies, and low absorption columns of ozone and/or water vapour; as a consequence, values of global horizontal irradiation (GHI) above 8kWh/m^2 per day (or more than 2,500kWh/m^2 per year) have been measured [17]. The conditions of extreme aridity and clear skies result in values of direct normal

Figure 2. Aerial view of the Lalackama I PV power plant [11].

irradiation (DNI) above 9kWh/m^2 per day. Based on Solar GIS data, and the model of Collares-Pereira and Rabl [18], the DNI for the site of the PSDA (24° 05′ 14″ S, 69° 54′ 47″ W and 963 m.a.s.l.), shown in Fig. 3, was estimated to be 3,420kWh/m^2 per year (compare with SolarGIS [19]). The conditions described create an excellent opportunity for PV technology to compete with traditional energy sources in the Chilean electricity market.

As a first approximation, SMARTS v. 2.9.2 code [21,22] is used to calculate the global tilted spectral irradiance (GTI_λ) at the PSDA. The goal of this method of estimation is to compare and study the differences with the ASTM G173-03 reference spectra also derived from SMARTS v. 2.9.2 [21–25].

The current standard G173-03 was created by the North American PV industry in conjunction with the American Society for Testing and Materials (ASTM) [26] and the research and development laboratories of the US government. The standard spectral distribution of solar irradiance at ground level is calculated in relation to the North American atmospheric and geographic conditions: an air mass (AM) equal to 1.5, a receiving surface inclined at 37°, and mean values of US atmospheric conditions [27].

There is not enough information about atmospheric parameters at the PSDA to calculate the solar spectrum using an atmospheric transmittance code. The most important parameter affecting the shape of the solar spectrum during a given period (day and year), however, is the AM, which can be calculated from equations relating to the sun's position. The AM is associated with the length of the path of light as it passes through the atmosphere and, therefore, with the possible interactions between photons and atmospheric components, such as aerosols or gas molecules. The shorter the path, the smaller the attenuation of the radiation.

The mean value of AM over the year at noon for the PSDA was calculated to be 1.17. A surface tilt of 20° was considered, which corresponds to the inclination of PV modules at this location. The other atmospheric parameters required for the calculation of the solar spectrum were set equal to the values in the ASTM G173-03. The results are presented in Fig. 4.

As the results show, there are significant differences between the two spectra, mainly in the short wavelengths, for both ultraviolet (UV) ranges and visible (VIS) spectral ranges; there is no noticeable variance in the remaining spectral ranges. In terms of the spectral range, compared with the G173-03 GTI_λ, the PSDA GTI_λ is 200% higher for UVB (290–315nm), 127% higher for UVA (315–400nm) and 109% higher for VIS (400–780nm).

On the one hand, this result highlights the importance that the AM plays in the estimation of the solar global irradiance at ground level. It can be expected that the Atacama Desert solar spectrum will show significant differences from the ASTM G173-03 reference spectrum, mainly at latitudes that are not similar to those used for the ASTM G173-03 calculation, despite the other unknown atmospheric parameters. However, it is necessary to await the results of future series of measurements of the solar spectrum and/or atmospheric parameters in order to obtain a more realistic characteristic spectrum for this desert location.

On the other hand, it is known that the UVB component of the solar spectrum is the most affected by ozone. According to a short measurement campaign carried out at the beginning of 2015 by CIFES [28], the UVB levels in Chile are much higher than in other places on the planet: annual UVB radiation values can be between 35 and 65% higher in northern Chile than in Europe.

> "Although commercial PV modules do not usually absorb low-wavelength radiation, their lifetime may be affected by the extreme doses of UVB in the Atacama Desert"

UV stability and soiling

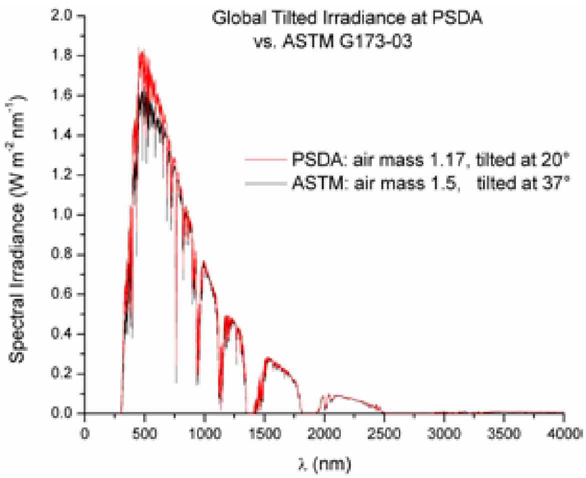
Although commercial PV modules do not usually absorb low-wavelength radiation, their lifetime may be affected by the extreme doses of UVB in the Atacama Desert. Whether or not the desert conditions of the Atacama Desert reduce the lifetime, and whether or not specific testing standards regarding UVB are required, must be investigated.

Figure 3. Terrain at the location of the PSDA in the Atacama Desert [20].

The degradation of the transmittance per kWh/m^2 received by a variety of PV modules with several types of glass, encapsulant and backsheet and different solar cells must be determined in order quantify the pertinence of specific norms and standards to the extreme conditions of UVB radiation in the Atacama Desert. Such measurements will allow an identification of the technologies that are capable of withstanding high UV exposure and lead to recommendations for the design and necessary modifications of norms for this location in Chile.

Two main issues should be addressed by the technology development: 1) independently of the particular characteristics of the solar spectrum in the Atacama Desert, a wider range of the available solar spectrum (UV and IR) is absorbed; 2) because of the high albedo in the Atacama Desert, more light is captured. Along with these factors, it is known that the spectrum from the albedo differs, depending on the reflective surface; furthermore, the infrared (IR) wavelengths make an important contribution to the albedo spectrum, especially in the case of sandstone, which is the most common surface found in desert regions [29].

Figure 4. Global tilted spectral irradiance comparison between the PSDA (red) and the ASTM G173-03 North American standard (black), both provided by SMARTS [21,22].



(a)

(b)

(c)

◄ ►Figure 5. Outdoor testing of modules at the PSDA: (a) setting up the structure; (b) albedometer; (c) taking AtaMo module measurements [20].

For PV technologies, no long-term scientific data exist that help to gain a deep understanding of the 'real lifetime' of PV power plants in the Atacama Desert, thus creating considerable uncertainty for large investments. In the coming years, it is expected that several GW of utility-scale PV plants will be installed in the Atacama Desert and in Chile; the estimation and quantification of the effects of soiling on planned and operating PV plants is therefore crucial. A brief summary of an initial quantification of soiling in the Atacama Desert concluded that soiling losses can vary significantly depending on the site and the seasons. On a positive note, dew can contribute to self-cleaning in some cases.

It has been observed that the soiling patterns of large PV plants can be inhomogeneous, but the monitoring of further parameters – such as the maximum power (P_{max}) and current-voltage (*I–V*) curves – can provide valuable information. The knowledge of the effect of soiling for PV technologies operating in specific locations is relevant for designing plants with frameless or framed modules, as well as for determining cleaning frequency and cleaning methods on the basis of information about accumulated dust [30].

Some investigations involving small PV plants in the kWp range, installed in the coastal region of the Atacama Desert, concluded that the performance ratio can degrade at a rate of 4.5% per month for multicrystalline and monocrystalline silicon and for amorphous silicon/microcrystalline silicon thin films [31,32]. Another investigation [33] based on preliminary simulations showed that, in spite of the higher irradiance in San Pedro de Atacama (Chile) than in Stuttgart (Germany) and El Gouna (Egypt), it is not possible to obtain higher yields in San Pedro de Atacama because of the decrease in PV module efficiency at irradiances higher than those used under standard test conditions (STC).

AtaMo: the SolarChilD project

In the PV Tech blog article "Atacama Module (AtaMo): A long lasting, powerful, highly efficient module for desert applications" [34], Kopecek highlights the importance of tests under 'unknown real environmental conditions' and remarks that the SolarChilD project acts as an important key in breaking the initial disinclination to do something.

SolarChilD, derived from **Solar**e Kollaboration zwischen **Chil**e und **D**eutschland (solar collaboration between Chile and Germany), is a project publicly funded by the German Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung, or BMBF) and coordinated by ISC Konstanz e.V. There are two main goals of the project:

- To intensify the collaboration and to promote joint R&D projects between the Solar Energy Research Center (SERC) Chile, the Antofagasta Center for Energy Development (CDEA) and ISC Konstanz. This is envisaged to be achieved through an exchange of technologies and ideas for testing innovative PV concepts, through young researchers publishing results in high-impact journals and proceedings, and through the organisation of workshops and training sessions.

- To develop the so-called **Ata**cama **Mo**dule, or AtaMo, adapted to the Atacama Desert. The project encompasses the investigation of different solar materials (such as a variety of glass thicknesses, cell configurations, encapsulants, backsheets and glass–glass configurations) to evaluate their longevity and choose the best solar components. In the process, a better understanding will be gained of the physics involved in the degradation mechanism of solar module performance under Atacama Desert environmental conditions.

Preliminary results and experience

The current IEC and UL certification and testing standards were not developed for PV applications operating in climatic conditions such as those found in the Atacama Desert, which is well known for the extremely high irradiation levels (including UV), large temperature gradients, corrosive environment, high humidity ('camanchaca') in certain parts, and extremely fine dust ('chusca'). In extreme environmental conditions, PV system performance and longevity may be seriously affected, and the standards are only partly applicable for determining climatic impact on module stability.

So far, the performance of different set-ups of half-size and full-size cell modules under accelerated indoor test conditions have been investigated. These modules were built at ISC Konstanz, Germany, and later installed at the PSDA in Yungay, Chile (Fig. 5). Modules were fabricated employing a variety of glass thicknesses and cell configurations (p- and n-type technologies), three types of encapsulant (EVA, low UV light cut-off EVA and thermoplastic material), three different backsheets (white standard, transparent and desert type) and several glass–glass configurations.

After 6,000 hours of damp heat (DH) exposure, the groups performed differently because of the encapsulated materials used, with the best results being observed for the thermoplastic material, regardless of the backsheet used. The humidity freeze (HF) 41 test revealed a negligible degradation for all module configurations. Thermal cycling (TC) 200 testing showed less relative P_{mpp} loss when glass was used on the rear side, while half-size cell modules were more sensitive to thermal stress than full-size cell modules, demonstrating more defects, such as cracks and metallisation damage [35].

A study of the fill factor (FF) losses for solar cell interconnection using soldered ribbons, and of how high-irradiance operation affects the losses, was also performed. For PV to compete with other electricity sources, the cost per watt needs to be reduced; this directly implies that the conversion efficiency (η) must be increased, by decreasing the electrical and optical losses in the cell-to-module (CTM) process. In respect of the electrical losses, the FF decays throughout the module process in relation to cell FF. These losses increase at irradiances greater than 1,000Wm^{-2} (STC), which are certainly found in the Atacama Desert.

If, for most of the time, PV modules are exposed to a solar irradiance greater than 1,000Wm^{-2} (e.g. in Egypt and Northern Chile), the current at the maximum power point (MPP), or I_{MPP}, is significantly higher than that measured at STC. Higher values of I_{MPP} have been observed to increase electrical losses, especially for longer periods of exposure, and have a measurable effect on the normal operating cell temperature (NOCT) of the module. In order to reduce these losses, a conductive cell interconnection scheme, or a material with lower electrical resistance, is required; this would mean using ribbons with larger cross sections, half-size solar cells, or solar cells with more than three busbars (BBs). It has been proved by experimental data (taking into consideration the operating temperature at several irradiance levels) that the electrical losses of PV modules decrease by increasing the ribbon cross section, by implementing multiple busbars or by cutting the cells by half. In desert conditions the lower CTM loss for a three-BB (1.5mm width), half-size solar cell module results in an increase in module efficiency of up to 0.36% abs. compared with a four-BB (1.0mm width) full-size solar cell module.

Figure 6. First stage of development at the PSDA [20].

A measurement campaign was carried out at the PSDA by a research group formed by the University of Antofagasta and ISC Konstanz. The goal of this experiment was to obtain data regarding the performance of one-cell modules fabricated within the SolarChilD project. For this purpose, a current–voltage (*I–V*) curve tracer, an albedometer and a photocell for solar resource quantification were used.

From measurements taken in the wintertime, preliminary results have revealed that the full-size cell modules have a strong PR decay above 800Wm^{-2}, in contrast to half-size cell modules, which perform better because of the lower electrical power loss. Moreover, ARC glass helps to improve the PR, but the impact on the PR for irradiances above 800Wm^{-2} is more noteworthy. For irradiances above 900Wm^{-2}, when the specific yields are compared for full- and half-size cell modules, both with ARC on the front glass, the difference is up to 4.3% to the advantage of half-size cell modules. Future measurement campaigns are planned for 2016, along with the installation of new instrumentation, at the PSDA (Fig. 6).

Figure 7. Future plans for the PSDA [20].

"Future measurement campaigns will improve on the current manual measurement approach by employing an automatised methodology"

Before measurements could be taken in the field in the Atacama Desert, the platform needed to be set up: this entailed the construction of offices; the installation of basic amenities, such as drinking water, toilet facilities, and electricity from PV panels with batteries; and the design and mounting of the structure for the one-cell modules. The experience was successful in the sense that the required data about the solar resource and the performance of several types of c-Si solar cell with different glass and encapsulant configurations were collected. Future measurement campaigns will of necessity improve on the current manual measurement approach by employing an automatised methodology, especially when an entire day in full sun in one of the driest deserts on earth is planned for quantifying solar resource and module performance.

Future of the PSDA

The PSDA will be an applied research solar platform, in which new technologies and materials will be developed and tested, bearing in mind the high-radiation conditions of the Atacama Desert. Furthermore, it will support the productive chain of the local solar energy industry, and technical certificates for PV and concentrated solar power (CSP) facilities, as well as the certification of products for high radiation environments, and complementary technologies to supply heat and mineral processes to mining companies in the Atacama Desert. The PSDA will host research activities and will be linked to satellite laboratories located in other regions of Chile, thus creating a collaborative network formed of universities, government, national and international centres, and companies.

Fig. 7 shows a possible PSDA scenario in which PV, CSP and storage systems are present. AtaMo and bifacial systems, as well as concentrated photovoltaics (CPV), will be a reality for PV in the coming years. A central receiver solar power plant, parabolic trough collectors and thermal flat collectors are also planned for CSP in the future. In addition, different configurations of thermal storage prototypes – such as sensible heat storage (using nitrate and carbonate molten salts), latent heat storage (using phase change materials produced in northern Chile) and thermochemical heat storage (involving copper oxide as the storage material) – will be part of the PSDA.

Acknowledgements

The authors acknowledge the generous financial support provided by:

1. Education Ministry of Chile Grant PMI ANT 1201.
2. CONICYT/ FONDAP/15110019 Solar Energy Research Center (SERC) Chile.
3. BMBF Solar Collaboration between Chile and Germany (Solar Child) project number 01DN14005. ■

References

[1] Ministry of Economy, Promotion and Tourism of Chile [http://www.agendaproductividad.cl/wp-content/uploads/sites/22/2014/10/Agenda-de-Productividad-Innovacion-y-Crecimiento.pdf].

[2] OECD/OCDE 2013, "Innovation-driven growth in regions: The role of smart specialisation", Report [www.oecd.org/innovation/inno/smart-specialisation.pdf].

[3] SolarGIS 2015, "Solar radiation maps: GHI" [http://solargis.info/doc/free-solar-radiation-maps-GHI].

[4] Chilean Ministry of Energy 2014, "Energy agenda: A country challenge, progress for all" [http://www.minenergia.cl/documentos/estudios/2014/agenda-de-energia-un-desafio-pais.html].

[5] Phaal, R., Farrukh, C. & Probert, D. 2010, *Roadmapping for Strategy and Innovation: Aligning Technology and Markets in a Dynamic World*. University of Cambridge, IfM.

[6] Carayannis, E.G., Barth, T.D. & Campbell, D.F.J. 2012, "The Quintuple Helix innovation model: Global warming as a challenge and driver for innovation", *J. Innov. Entrepren.*, Vol. 1, No. 2, pp. 1–12.

[7] CIFES 2015, "Renewable energy in the Chilean electricity market", Report (Oct.) [http://cifes.gob.cl/wp-content/uploads/2014/06/Reporte_CIFES_Octubre_EN.pdf].

[8] CNW 2014, News Release (June) [http://www.pv-tech.org/news/sunedison_inaugurates_100mw_chile_solar_plant].

[9] Etrion 2014, "Etrion announces completion of 70 MW solar park in Chile", Press Release (4 Nov.) [https://www.etrion.com/dm/Press/pr_chile_04-11-14.pdf].

[10] ENEL Green Power 2015, Press Release (5 May) [https://www.enelgreenpower.com/eWCM/salastampa/comunicati_eng/1663736-1_PDF-1.pdf].

[11] Soltec 2015, "Projects: Our best reference" [http://www.soltec.com/proyectos/].

[12] Evwind 2014, News Report (17 Oct.) [http://www.evwind.es/2014/10/17/first-solar-panel-for-the-141-megawatt-mwac-luz-del-norte-solar-power-plant-in-chile].

[13] Kenning, T. 2015, News Report (10 Jul.) [http://www.pv-tech.org/news/worlds_largest_bifacial_pv_plant_nears_completion_in_chile].

[14] Larraín, T. & Escobar, R. 2012, "Net energy analysis for concentrated solar power plants in northern Chile", *Renewable Energy*, Vol. 41, 123–133.

[15] McKay, C.P. et al. 2003, "Temperature and moisture conditions for life in the extreme arid region of the Atacama Desert: four years of observations including the El Niño of 1997–1998", *Astrobiology*, Vol. 3, pp. 393–406.

[16] Navarro-González, R. et al. 2003, "Mars-like soils in the Atacama Desert, Chile, and the dry limit of microbial life", *Science*, Vol. 302, No. 5647, pp. 1018–1021.

[17] Escobar, R. et al. 2014, "Solar energy resource assessment in Chile: Satellite estimation and ground station measurements", *Renewable Energy*, Vol. 71, pp. 324–332.

[18] Collares-Pereira, M. & Ralb, A. 1979, "The average distribution of solar radiation-correlations between diffuse and hemispherical and between daily and hourly insolation values", *Solar Energy*, Vol. 22, pp. 155–164.

[19] SolarGIS 2015, "Solar radiation maps: DNI" [http://solargis.info/doc/free-solar-radiation-maps-DNI].

[20] Antofagasta Center for Energy Development (CDEA) [http://www.uantof.cl/cdea].

[21] Gueymard, C.A. 2001, "Parameterized transmittance model for direct beam and circumsolar spectral irradiance", *Sol. Energy*, Vol. 71, pp. 325–46.

[22] Gueymard, C.A. 1995, "SMARTS2, A simple model of the atmospheric radiative transfer of sunshine: Algorithms and performance assessment", Technical Report FSEC-PF-270-95, Florida Solar Energy Center [http://rredc.nrel.gov/solar/models/smarts/relatedrefs/smarts2_report.pdf].

[23] ASTM G173-03 (2012), "Standard tables for reference solar spectral irradiances: Direct normal and hemispherical", ASTM International.

[24] Gueymard, C.A., Myers, D. & Emery, K. 2002, "Proposed reference irradiance spectra for solar energy systems testing", *Sol. Energy*, Vol. 73, pp. 443–467.

[25] Gueymard, C.A. 2004, "The sun's total and spectral irradiance for solar energy applications and solar radiation models", *Sol. Energy*, Vol. 76, 423–453.

[26] ASTM [http://www.astm.org/].

[27] National Renewable Energy Laboratory (NREL), "Reference solar spectral irradiance: Air mass 1.5" [http://rredc.nrel.gov/solar/spectra/am1.5/].

[28] CIFES 2015, Internal Report.

[29] Brennan, M.P. et al. 2014, "Effects of spectral albedo on solar photovoltaic devices", *Sol. Energy Mater. Sol. Cells*, Vol. 124, pp. 111–116.

[30] Darez, P. & Darr, C. 2015, "Quantifying PV soiling losses in the Atacama Desert", *Proc. 31st EU PVSEC*, Hamburg, Germany.

[31] Ferrada, P. et al. 2015, "Performance analysis of photovoltaic systems of two different technologies in a coastal desert climate zone of Chile", *Sol. Energy*, Vol. 114, pp. 356–363.

[32] Fuentealba, E. et al. 2015, Photovoltaic performance and LCoE comparison at the coastal zone of the Atacama Desert, Chile", *Energy Conv. Man.*, Vol. 114, pp. 356–363.

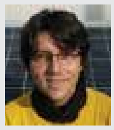
[33] Rabanal-Arabach, J., Schneider, A. & Cabrera, E. 2015, "Minimization of electrical losses of PV modules located in places with high solar irradiance", *Energy Procedia*, Vol. 77, pp. 402–406.

[34] Kopecek, R. 2015, PV-Tech Guest Blog Article [http://www.pv-tech.org/guest_blog/atacama_module_atamo_a_long_lasting_powerful_highly_efficient_module_for_de].

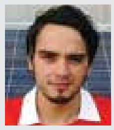
[35] Cabrera, E. et al. 2015, "Advancements in the development of 'AtaMo': A solar module adapted for the climate conditions of the Atacama Desert in Chile", *Proc. 31st EU PVSEC*, Hamburg, Germany.

Authors

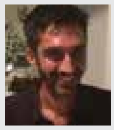
Dr. Pablo Ferrada works at the Centro de Desarrollo Energético Antofagasta (University of Antofagasta) and as a guest researcher at the Solar Energy Research Center, Chile. He focuses on PV module performance evaluation under the conditions of the Atacama Desert, material characterisation, and supporting development projects in collaboration with external centres.



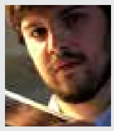
Jorge Rabanal Arabach has a Dipl.-Ing. degree and is a researcher academician at the University of Antofagasta. He is currently a Ph.D. student working on the SolarChilD project in the module development department at ISC Konstanz.



Dr. Enrique Cabrera received his Dipl.-Ing. degree (honours) in electrical engineering from the University of Santiago, Chile, and his Ph.D. in physics in the field of metallisation of silicon solar cells at ISC Konstanz in conjunction with the University of Konstanz. He leads the BMBF SolarChilD project and supports cooperative R&D projects in Chile.



Dr. Aitor Marzo works as researcher at the Centro de Desarrollo Energético Antofagasta (University of Antofagasta) and as a guest researcher at the Solar Energy Research Center (SERC) Chile. His research focuses on radiometry and providing support to the different research areas in solar technologies, both for PV and for CSP.



Pablo Tello has a Dipl.-Ing. degree and has been working at the Centre for Innovation and Promotion of Sustainable Energy since 2010. He is now in charge of the stakeholders' engagement process for the Chilean Strategic Solar Program and is part of the technical team responsible for the related roadmap elaboration.

Dr. Andreas Schneider has been with ISC Konstanz since 2011 and in charge of the module development department since 2013. He is mainly responsible for the scientific supervision of ISC's module test laboratories and outdoor facilities.

Dr. Radovan Kopecek is one of the founders of ISC Konstanz. He has been working at the institute as a full-time manager and researcher since January 2007, and is currently the head of the advanced solar cells department.