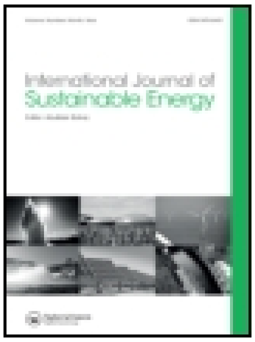

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Innovative optics for concentrating photovoltaic/thermal (CPVT) systems – the case of the PROTEAS Solar Polygeneration System

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ABSTRACT

The aim of this work is to review the current status of photovoltaic (PV) power generation, focusing on concentrating PVs mainly as regards their typology, market and state-of-the-art feature. The incorporation of a heat recovery system can increase the overall efficiency by exploiting the waste heat. The proposed solution is a Solar Polygeneration System (PROTEAS System) for the simultaneous production of electricity, hot water and air-conditioning. The core of the PROTEAS System is the innovative set-up of total internal reflection reflectors made of plastic (primary optical system), with the potential to concentrate solar rays up to 5000 suns, while specially designed total internal reflection homogenisers (secondary optical system) later homogenise the radiation to 1000 suns. The engineering of the system is an ongoing task, while some of the subsystems have been successfully developed.

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Photovoltaics; concentrating photovoltaics; solar electricity

List of abbreviations

COP	coefficient of performance
CPV	concentrating photovoltaics
DNI	direct normal irradiance
EU	European Union
HCPV	high concentration PV
LCOE	levelised cost of electricity
LCPV	low concentration PV
POE	primary optical element
PV	photovoltaic
SOE	secondary optical element
TIRH	total internal reflection homogeniser
TIRR	total internal reflection reflector

1. Introduction

Renewable energy has shown a continuous growth in the global market despite the ongoing economic recession, with the most rapidly growing technology during the last decade being photovoltaic (PV) technology. By the end of 2013, the global cumulative installed PV power capacity exceeded 134 GW, representing at least 0.85% of the global electricity demand (IEA International Energy Agency 2013). In Europe alone, the capacity reached 79 GW, representing 3% of its electricity

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demand and 6% of its peak electricity demand; a total of 80.2 TWh of PV electricity was generated (EurObserv'ER 2014).

PV could supply up to 12% of the electricity demand in Europe by 2020, representing an installed capacity of 390 GW and 460 TWh of electricity generation (EPIA & Greenpeace 2011). The increase in production capacities has already reduced PV production costs and prices tremendously, making grid parity realistic in the Southern EU Member States and also in other countries with high insolation, although some markets are still driven by incentives (e.g. Feed-In Tariffs) (Tsoutsos et al. 2015).

Amongst the main barriers that PV systems should overcome to continue their commercial augmentation in the mid-to-long term are:

(a) the use of large amounts of expensive semiconductor materials;
(b) the use of rare earth elements in certain types of PV cells implying a potential environmental impact and an increase in the price of these elements;
(c) the low system conversion efficiency.

The first two issues can be addressed by concentrating solar radiation, with a suitable optical system, onto a smaller target where much less semiconductor material is needed; this constitutes the main advantage of the concentrating photovoltaics (CPV).

Conventional silicon-based PV cells convert a limited part (less than 25%) of the collected radiation into electricity. The use of multi-junction cells, capable of reaching efficiencies over 40% under solar concentrating conditions, is providing a solution to the third issue (King et al. 2007). PV cells under concentrated illumination can reach high temperatures as solar energy not converted to electricity is dissipated in the cells as heat. Thus, a crucial requirement for CPVs is a cooling system capable of efficiently removing the excess heat, keeping the cells at an ideal temperature. Moreover the dissipated heat can be recovered as an additional energy product, increasing in this way the overall system efficiency.

PROTEAS is an innovative Solar Polygeneration System aiming to achieve the synergy of the above benefits, and becoming competitive with conventional energy systems. The last part of this paper discusses the main characteristics and innovations of the PROTEAS System.

2. The current status of CPVs

2.1. *Typology of CPVs*

CPV systems can be grouped into two major classes, according to their concentration ratio, high concentration PV (HCPV) and low concentration PV (LCPV), as shown in Table 1.

A typical CPV module is composed by the following main parts: the primary optical element (POE), secondary optical element (SOE), PV cells and the cooling system. Table 2 provides a summary description of these components, as well as some references, where extensive descriptions and reviews of each can be found.

2.2. *Market*

Crystalline silicon modules currently dominate the PV market with around a 90% share, while thin films represent only about 10% of the market. CPVs, although growing significantly, still lie below 1% (IEA International Energy Agency 2014), with the market volume being 100 MW in 2013 (Mittelman, Kribus, and Dayan 2007). Figure 1 shows the evolution of yearly installed CPV capacity globally, for both HCPV and LCPV systems.

Table 1. Classes of CPV systems (Philipps et al. 2015).

Class	Typical concentration ratio	Typical characteristics
HCPV	300–1000	Two-axis tracking, high-efficiency III–V multi-junction cells
LCPV	<100	One- or two-axis tracking, c-Si or other cells

Table 2. Main components of CPV systems.

Component	Description/function	Types	References
POE	Allows for the concentration of the incident solar radiation	• Reflective • Refractive • Hybrid • Luminescent	Muhammad-Sukki et al. (2010) and Khamooshi et al. (2014)
SOE	Used as a homogeniser for the irradiance, before it hits the solar cell; creates a uniform irradiance flux over the surface of the cell and increases the acceptance angle. Not used in all CPV systems	• Reflective • Refractive	Leutz et al. (2001) and Victoria et al. (2009)
PV cell	Generates electricity	• III–V • Silicon	Philipps et al. (2015) and Cotal et al. (2009)
Cooling system	Dissipates the heat from the solar cell, to avoid degradation of the cell and efficiency reduction	• Active • Passive	Khamooshi et al. (2014) and Royne, Dey, and Mills (2005)

Some interesting figures about the cumulative CPV capacity in countries with a total capacity of 1 MW or more are presented in Figure 2. China is the global leader (150 MW) followed by USA (80 MW).

Market forecasts (IEA International Energy Agency 2014) expect a growth up to 10 GW with a conservative scenario and up to 50 GW with an optimistic scenario (Figure 3).

Already today, at locations with high direct normal irradiance (DNI), CPVs compete with PVs (IEA International Energy Agency 2014). In 2013, investments for CPV utility scale power plants of 10 MW were ranging from €1400/kW to €2200/kW, while their levelised cost of electricity (LCOE) was between €0.10/kWh and €0.15/kWh for a location with a DNI of 2000 kWh/(m^2a) and €0.08/kWh to €0.12/kWh for DNI of 2500 kWh/(m^2a) (IEA International Energy Agency 2014). Projections for 2030 show that LCOE could reach as low as €0.045/kWh to €0.075/kWh and system prices would lie in the range of €700/kW to €1100/kW (Kost et al. 2013).

2.3. *Technology state-of-the-art*

Today, more than 90% of the capacity installed is HCPV systems with two-axis tracking, employing Fresnel lenses with point-focus (Mittelman, Kribus, and Dayan 2007). These are mainly ground-mounted installations that are modular and can be scaled up. Several other designs have been also deployed while others are being tested or are still at the research level. CPV research mainly focuses on balancing high efficiency with system cost; high efficiency is the main driver of CPV technology to compete with conventional PV and other solar technologies. Particular focus is given to

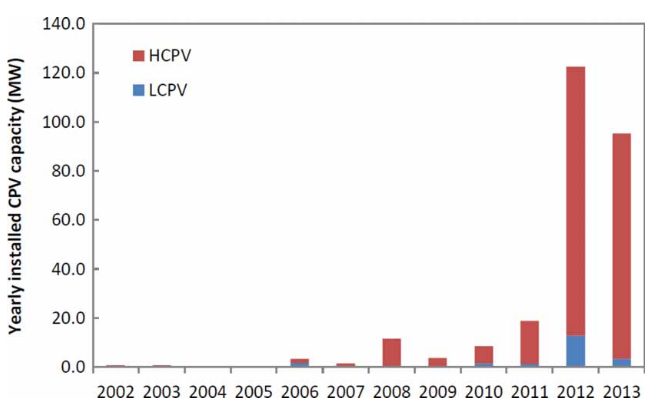

Figure 1. CPV capacity installed each year globally.
Source: Data from Philipps et al. (2015).

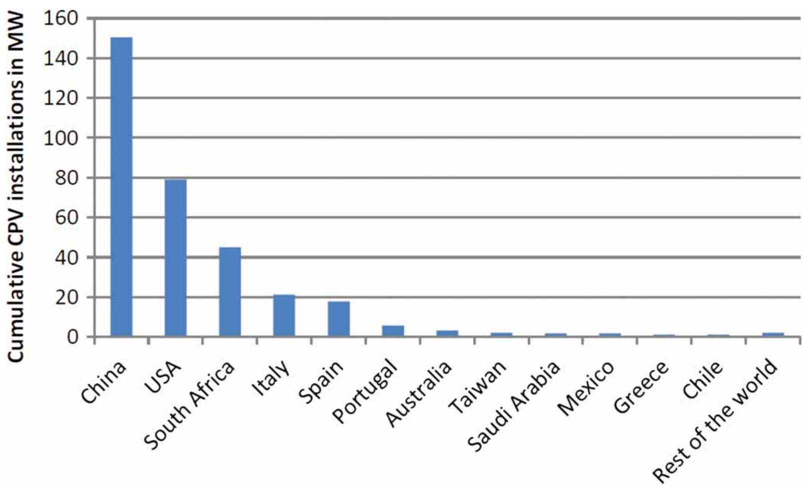

Figure 2. Cumulative CPV capacity per country.
Source: Data from Philipps et al. (2015).

achieving higher concentration ratio through the optical system, reducing the cost of the optical system, using higher efficiency cells and improving the cooling system (Kribus and Mittelman 2007).

Despite the fact that several novel optical systems have been proposed, it seems that not all of them make it to full commercial scale. Factors associated with it are perhaps the lack of an efficiency breakthrough, which would put such a system in an advantageous position when compared to currently available commercial systems. However, optical systems offer the possibility of a low-cost innovation. Systems focusing on novel optical systems often target rooftop applications, besides ground-mounted ones (Arbore, Klein, and Conway 2010; Correia, Braig, and Shulenberg 2013; Electro Therm Solar 2014; Krasnov and Den Boer 2013). Various types of POEs have been extensively described in other works (Khamooshi et al. 2014; Muhammad-Sukki et al. 2010; Sharaf and Ohran, 2015).

PV cells are at the core of a CPV system. In high-concentration systems multi-junction cells are used, whereas in low concentrations, silicon or other cells are used. Most of the commercial systems available are based on high-efficiency PV cells, showing that research advancements in PV cells

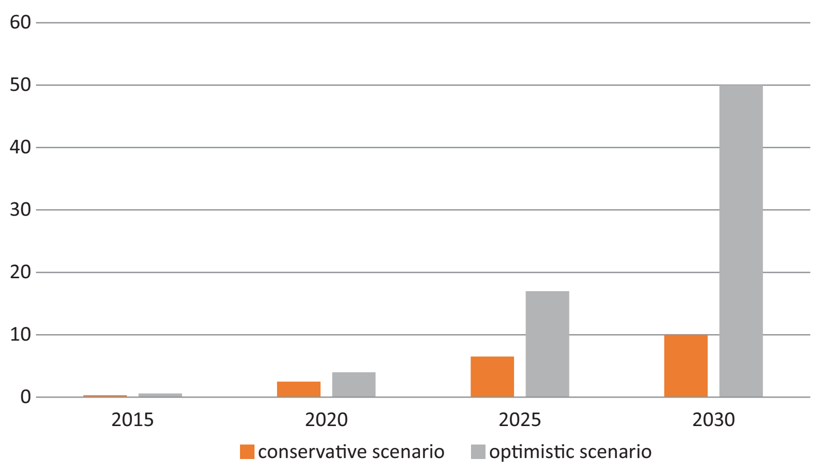

Figure 3. Market forecast of cumulative power plant capacity for CPV in GWp.
Source: Data from Kost et al. (2013).

Table 3. Development of record efficiencies (%) of III–V multi-junction solar cells, CPV modules and CPV systems.[a]

	2000	2010	2020 (projection)	2030 (projection)
III–V Multi-junction PV cells	32	42	50	52
CPV Modules	25	32	40	44
CPV Systems	–	26	36	40

[a]Based on a graph of Philipps et al. (2015).

usually find their way to full commercial scale through CPV systems. Table 3 shows the development of record efficiencies of III–V multi-junction solar cells, CPV modules and CPV systems.

In addition, incorporating a heat recovery system can increase the overall (electrical plus thermal) efficiency of the system, allowing the thermal energy to be further exploited. Applications of recovered thermal energy may include water heating for domestic/commercial or industrial purposes (Correia, Braig, and Shulenberg 2013; Electro Therm Solar 2014), solar cooling (IBM 2015), thermoelectric generation (Lu 2012) and even geothermal storage (Kiesewetter 2011).

3. System description and innovations of PROTEAS

3.1. *Description*

The basic components of the PROTEAS System are the innovative set-up of total internal reflection reflectors (TIRRs) made of clear plastic (primary optical system) and the total internal reflection homogenisers (TIRHs) (secondary optical system), which manage to concentrate the solar rays up to 5000x and later homogenise them, resulting in a concentrating ratio of 1000x (Papadopoulos et al. 2014). High-efficiency multi-junction PV cells are used to generate electricity. The water – used for cooling down the PV cells – rises to a temperature of 85–90°C and subsequently is turned to chilled water for air-conditioning (7–12°C) with the use of an advanced Absorption NH_3 Heat Pump and then to warm water of 45–55°C for domestic use. The PROTEAS modules are arranged on a low-profile metallic ring tracking the sun at two axes. The described configuration of the PROTEAS module that includes the basic components is presented in Figure 4.

The Integrated PROTEAS System consists of six subsystems. The first subsystem involves electricity production and it consists of the PV field and inverter. The second subsystem includes PV heat recovery with the active cooling pipes, pump, piping and heat exchanger between the solar and storage circuits. The storage/hot water circuit is defined as the third subsystem, consisting of the pump, storage tank, three-way valve, piping and generator pump. The fourth subsystem is the absorption chiller itself. The fifth subsystem is the cooling water circuit with the pump. The last subsystem consists of a heat exchanger, piping and a pump in the chilled water circuit, separating the evaporator from the ceiling panel circuit. A schematic representation of the Integrated PROTEAS System is given in Figure 5.

In the frame of detailed engineering, some of the subsystems were analysed using different simulation tools (e.g. TRACEPro for analysis of the optical system and COMSOL Multiphysics for thermal analysis of heat-sink pipes). The efficiency ranges for these subsystems were determined by the results of simulations and have been used in order to provide the overall efficiency of the entire process. It is estimated that the PROTEAS System can utilise the incoming solar energy 6 or 8-fold more efficiently than state-of-the-art conventional PV modules due to the higher conversion rate in electricity production and the further exploitation of dissipated thermal energy. PV electricity is generated with efficiencies in the range of 15–30%, while the excess heat is collected in the form of hot water at 80–90°C with collection efficiencies of 65–50%. The hot water is then fed into an advanced absorption NH_3 Heat Pump with high conversion efficiency (coefficient of performance (COP) in the range of 0.9–1.2), to be converted into chilled water of 7–12°C for air-conditioning, increasing in this way the utilisation of the incoming solar energy up to 75%. The absorption heat pump returns the hot water supplied at 80–90°C as warm water of 45–55°C for domestic use, increased in thermal

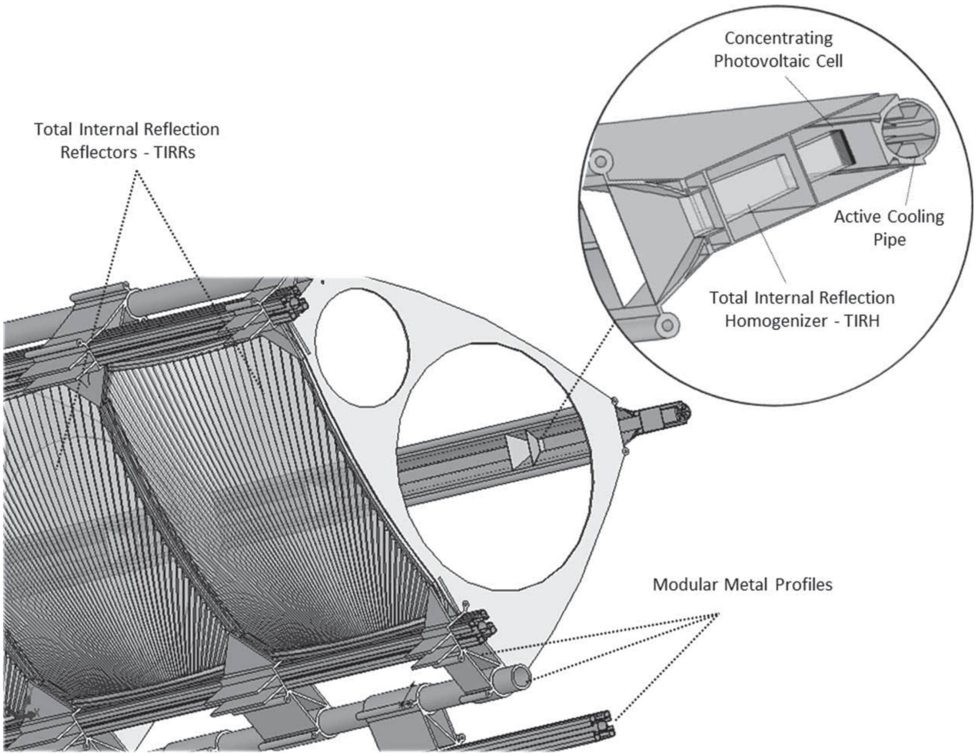

Figure 4. Design of the PROTEAS photovoltaic/thermal module.

content by 30–50%, as it also returns part of the heat absorbed by the air-conditioning from the building. Therefore, the total utilisation of the incoming solar energy is increased by 15–35% in heating energy.

The PROTEAS System has the additional capacity to 'shave' (cut-off) more than 5-fold of its nominal PV power in utility summer peak-loads. Indeed, 1-fold is due to its PV electricity production during the time when air-conditioning is needed, a further 1–3-fold is due to its ability to provide air-conditioning by using the 80–90°C hot water from the PV cooling, while an additional

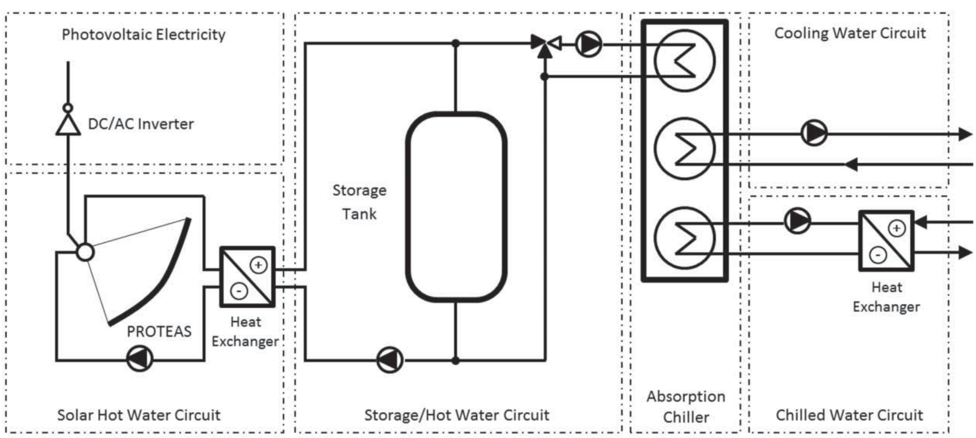

Figure 5. Schematic representation of the Integrated PROTEAS System.

3–6-fold is attributed to its ability to supply domestic hot water of 45–55°C after air-conditioning production. This additional capacity to shave more than 5-fold of its nominal PV power in utility summer peak-loads implies that the utility is saving more than the cost of the installed Solar Polygeneration System's capacity, due to the avoided 5-fold utility summer peak-loads (including the cost of the avoided peak-load facing facilities, the cost of the avoided relative transmission and distribution lines, the avoided cost of transmission and distribution losses and the avoided cost of O&M of the above).

The concept of PROTEAS System is based on several new developments and innovations. For the implementation of the system several off-the-shelf components as well novel pieces of equipment have been used.

Engineering of the PROTEAS System has already been initiated and some of the subsystems such as the support-connection profiles, tracker controller, cooling pipes and homogenisers have been successfully developed. Although the basic research has been performed and the successful implementation of several parts has been achieved, some obstacles need to be overcome for the effective and reliable implementation of the PROTEAS System.

The major barrier is the required precise geometry (2–3 μm) of the total internal reflection prisms, which is a crucial factor for the achievement of high concentration and the biggest challenge is the successful and low-cost manufacturing of these optical elements. For effective mass production of TIRRs, an optimised injection compression moulding method will be used. According to this method a molten resin is injected into a temperature-controlled mould, which is loosely clamped to prevent the escape of material through the mould parting line. Following the injection portion of the cycle, a secondary clamping operation fully closes the mould during the curing portion of the cycle. The results are a higher level of feature replication and tighter part tolerances. Because the cycle times are shorter for this process than in compression moulding, this process is well suited to large and thick components as TIRRs. A first optimised production line of TIRRs is expected in 2015 and the results will determine the successfulness of the PROTEAS System.

3.2. *Optical concentration system*

The current state-of-the-art technology in solar collectors for high concentration is mainly capable of mass producing expensive reflective collectors and Fresnel lenses (0.8–1.0 €/Wp). Fresnel lenses do not transmit all the light they intercept to the focus because (a) Fresnel reflection from the optical interfaces causes about 8% loss (more for a short focal length lens because of the steep angle of the exit ray to the facet surface) and (b) the vertical regions between facets cannot be completely vertical or the lens cannot be removed from the mould. The angle of this portion is called the draft angle, and it is around 2°; light striking this wall is deflected out of the focus. Finally, the tips and valleys have non-zero radius. The smaller the facets, the more important this loss is. Modern flat-facet, compression-moulded lenses have an optical transmission of typically about 85% (Luque and Hegedus 2003).

The PROTEAS System is going to advance the state-of-the-art technology by developing a patented concentrating optical system with a concentration ration of 1000x and optical efficiency up to 96%. The solar concentrator is based on an innovative total internal reflection design in which total internal reflection prisms create the parabolic-form concentrator. More precisely, instead of using a simple prism, an upper perfect parabolic surface and a lower edge was designed as a perfect parabola. The path that the incident -on the parabolic prism- ray follows is shown in Figure 6. All the shown planes Π1, Π2, Π3 and Π4 are perpendicular to the back edge of this prism. The incident ray enters the prism at point A, which is on plane Π1, while a small percentage of the incident energy is reflected towards the focal point. First the ray hits the back surface of the prism at point B, which belongs to plane Π2. At this point the ray is reflected again at the opposite surface of the prism at point Γ, which belongs to plane Π3. Finally, the ray is reflected out of the prism at point Δ, which belongs to plane Π4. It must be noted that the four planes Π1, Π2, Π3 and Π4 are perpendicular to the back parabolic edge on the prism (Papadopoulos 2004).

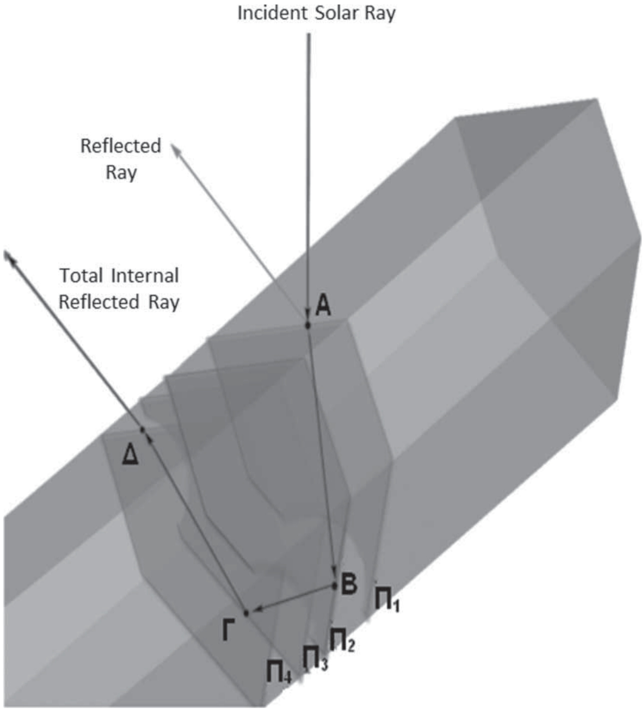

Figure 6. Total internal reflection prism design and associated sunray reflection.

Furthermore, despite the primary optical concentrator, a secondary total internal reflective flux homogeniser is used to create a uniform solar flux over the solar cells and reduce the need for high sun-tracking accuracy. In order to evaluate the efficiency of the optical system, ray-tracing simulations (with TracePro software) were performed, using the actual sun incident light and simulating real conditions. In particular, the incident light was emitted from a blackbody surface at 5840 K and equal to the size of the surface of the sun located at a distance from the reflector equal to the actual sun–earth distance. A Lambertian angular distribution was used, using a large number of emitted rays in order to minimise the statistical error to values of 1% or less. The results of ray-tracing simulation are shown in Figure 7. These results depict the distribution of the incident

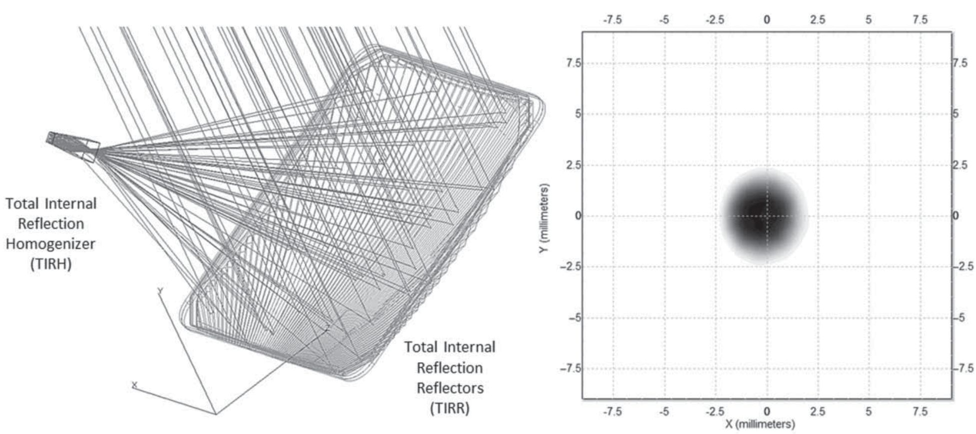

Figure 7. Ray-tracing simulation of the optical concentration system and radiation map on homogeniser input.

rays to the homogeniser and indicate the size of the focus point (5 mm × 5 mm). Based on the simulation results, the optical efficiency of the primary optical system was calculated to be $n = 96\%$.

In order to evaluate the effects of the manufacturing process on the efficiency of the system, various sizes of radii in the formation of the back edges of the TIRR were taken into consideration in calculating the efficiency n and these radii. The efficiency loss of the reflector was calculated in relation to the respective edge radii imposed by the manufacturing process and is presented in Figure 8.

3.3. *Low profile, modularity, heat exploitation*

The described optical system concentrates and homogenises the sunlight on high-efficiency III–V solar PV cells. The concentration panels are mounted on a rail-based 2-axis solar tracker, which provides automatic positioning always perpendicular to the sun's rays. Rotation towards the sun is secured by a specially designed microcontroller system and a suitable solar sensor. The short focal length design of the system allows the support platform to be close to the ground; standing only at 50 cm high, this extremely low profile is resistant to windstorms, hailstorms and sandstorms, managing to avoid this pitfall of many competitive system designs. The reduced wind loads allow the system to be mounted on lighter trackers, reducing in this way the material costs.

The novel design of the support-connection profiles results in a simple assembly and arrangement of the system, which facilitates tracking and makes the overall system more reliable. The system's modularity provides for its wide scope of use – ranging from smaller individual applications in residential buildings all the way to bigger-scale installations in hotels, industrial buildings, etc. The PV cells are attached to novel actively cooled heat-sink pipes, safeguarding the optimal working temperature for achieving the highest possible performance and a long life-cycle, while at the same time enabling the system to produce heat in the form of hot water (Figure 4). The system achieves high conversion efficiency of solar radiation to usable energy, with the overall efficiency reaching above 75% (of which about 30% is electricity and 50% heat energy).

3.4. *Advanced absorption heat pump*

During the last few years many new small-scale sorption chillers have been developed, many of which have now passed from the prototype phase to field tests and into manufacturing. Nowadays, absorption chillers of 4.5–20 kW capacity and adsorption chillers of 7.5–15 kW cooling capacity are available in the market (Wang et al. 2009). However, the major drawbacks associated with these small-scale thermal-driven cooling systems are their low COP for relatively low regenerative temperatures and their high initial cost due to their more complex construction.

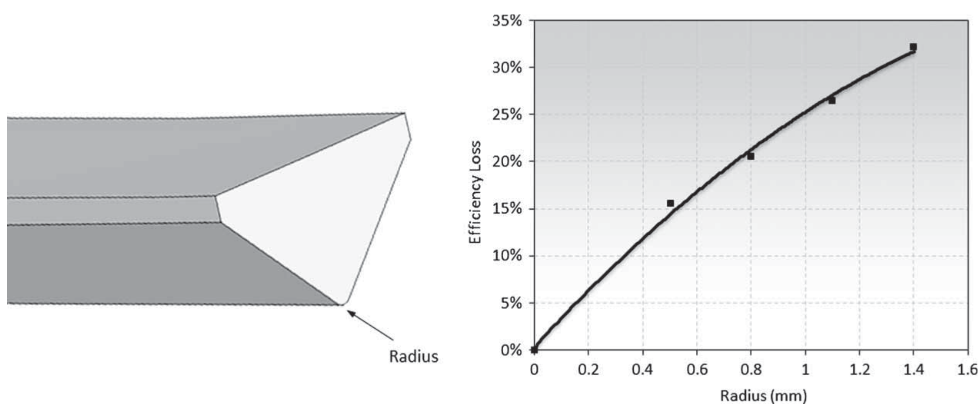

Figure 8. Efficiency loss due to the increase of the prism-edge radii.

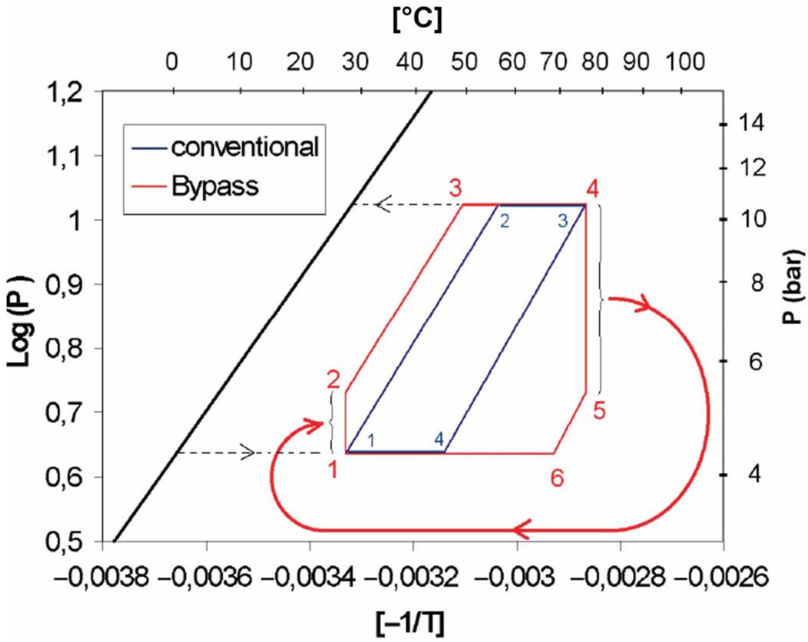

Figure 9. The principle of the bypass process on the thermodynamic cooling cycle (Kunze 2008).

The PROTEAS System utilises a novel absorption heat pump which will be able to turn hot water of 70–90°C into chilled water for air-conditioning (7–12°C) with COP in the range of 0.7–1.2. Hot water will be subsequently turned into warm water of 50–60°C for domestic use. This cooling machine is revolutionary due to its new patented cooling cycle (Kunze 2008) (based on the bypass principle and steam-driven solution pump; Figure 9), which allows NH_3 absorption cooling under temperature conditions that were impossible until recently (even with heating temperature of 65°C). By means of this bypass process the conventional blue cycle parallelogram 1, 2, 3, 4 is changed into the red cycle hexagon 1, 2, 3, 4, 5, 6. Between the red points 4 and 5, ammonia is extracted from the solution and re-added to the solution between the red points 1 and 2. This portion of ammonia does not pass through the processes of condensation, evaporation and absorption. It 'bypasses' them all, going directly to the preheating of the generator process. Of course such a process consumes a certain amount of energy. Nevertheless at the same time the generator and absorption process bars grow considerably. Both temperature intervals show a good overlap which allows a great part of the heating energy to be recycled. The amount of recycled heat in most cases is bigger than the amount consumed by the bypass process. Thus overall balance is positive, combined with the fact that the bypass cycle is possible under all meaningful temperature conditions.

Moreover, the cooling machine is based on an advanced heat exchanger design where a block of sheets of different materials like a microchip is used, contrary to the conventional cooling machines made of a number of heat exchangers connected by a rather complicated and heavy network of bent tubes and fittings. This latter approach results in a heavier and cost-competitive cooling system.

4. Conclusion

CVPs allow the solving of critical bottlenecks in the further sustainable growth of the PV market, collecting solar radiation over a large area with a suitable optical system and concentrating it to a small target where only a small area of semiconductor material is needed.

In addition, incorporating a heat recovery system increases the overall (electrical plus thermal) efficiency of the system, allowing the thermal energy to be further exploited. Applications of recovered thermal energy may include water heating for a wide range of applications.

The PROTEAS Solar Polygeneration System provides an innovative Solar Polygeneration System that would be able to offer a feasible alternative to the traditional energy systems.

The PROTEAS System includes a concentrating optical system with a concentration ratio of 1000 suns and optical efficiency up to 96%. Additionally, the system utilises a novel absorption heat pump capable of utilising hot water of 70–90°C for air-conditioning (7–12°C).

An industrial prototype of 10 kWe is planned to be constructed and tested by a Greek consortium under the frame of a National R&D Programme SYNERGASIA (2013–2015); after the completion of the demonstration phase, commercialisation is planned.

Disclosure statement

No potential conflict of interest was reported by the authors.

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