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Abstract/Summary:

The aim of this work is to present a dedicated 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 setup of Total Internal Reflection Reflectors made of plastic (Primary Optical System), which concentrate the solar rays up to 5,000 suns, homogenized to 1,000 suns by specially designed Total Internal Reflection Homogenizers (Secondary Optical System). High-efficiency Photovoltaic Cells are used to generate electricity. Furthermore, water -used for cooling down the photovoltaic cells- is heated up to 85-90°C and with the use of an advanced Absorption NH3 Heat Pump, is turned to chilled water for air-conditioning (7-12°C) and subsequently to domestic warm water about 45-55°C. PROTEAS modules are suitably spaced on a low-profile metallic ring which tracks the sun. The engineering of the system has already been initiated and some of the subsystems have been successfully developed. PROTEAS will be installed and evaluated in a building under real operational conditions in order to demonstrate the feasibility of the investment in terms of energy savings and assess its potential as a new market solution, which can be both cost effective and environmentally friendly.

PROTEAS SOLAR POLYGENERATION SYSTEM

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ABSTRACT: The aim of this work is to present a dedicated 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 setup of Total Internal Reflection Reflectors made of plastic (Primary Optical System), which concentrate the solar rays up to 5,000 suns, homogenized to 1,000 suns by specially designed Total Internal Reflection Homogenizers (Secondary Optical System). High-efficiency Photovoltaic Cells are used to generate electricity. Furthermore, water -used for cooling down the photovoltaic cells- is heated up to 85-90°C and with the use of an advanced Absorption NH_3 Heat Pump, is turned to chilled water for air-conditioning (7-12°C) and subsequently to domestic warm water about 45-55°C. PROTEAS modules are suitably spaced on a low-profile metallic ring which tracks the sun. The engineering of the system has already been initiated and some of the subsystems have been successfully developed. PROTEAS will be installed and evaluated in a building under real operational conditions in order to demonstrate the feasibility of the investment in terms of energy savings and assess its potential as a new market solution, which can be both cost effective and environmentally friendly.
Keywords: PV System, Concentrators, R&D and Demonstration Programmes

1 INTRODUCTION

The renewable energy sector has grown steadily in the European and global market despite the successive global economic crises. The most fast-growing renewable energy technology during the past decade has been the photovoltaic (PV) technology. The PV market has experienced vibrant growth for more than a decade with an average annual growth rate of 40%. The global cumulative installed PV power capacity has grown from 1.4 GW in 2000 to 40 GW in 2010 and about 207-342 GW of PV systems likely to be installed in 2016, making the forecasts extremely promising [1].

With a production capacity of 69 GW, PV generates today over 40TWh of electricity. This represents only the 2% of the global electricity demand. PV could supply up to 12% of the electricity demand in Europe by 2020, thus representing 390 GW of installed capacity and 460 TWh of electricity generation [2]. The increase in production capacities has already reduced PV production costs and prices tremendously, making grid parity realistic in some EU Member States, although some markets are still driven by incentives (e.g. Feed-In Tariffs) [3].

The main issues that contribute to today's uncompetitive character of PV systems are:

(a) the need to use large amounts of expensive semiconductor materials;

(b) the use of rare earth elements in some types of PV cells creating a potential environmental impact, and

(c) the relatively low system conversion efficiency.

The first two issues can be resolved by concentration: collecting solar radiation over a large area with a suitable optical system, and concentrating it onto a small target where only a small area of semiconductor material is needed.

Regarding the third issue: conventional silicon-based PV cells convert a limited part (less than 25% of the collected radiation) into electricity. A solution to this is to use the more sophisticated multi-junction cells, capable of reaching efficiencies over 40% under solar concentrating conditions [4]. Furthermore, when PV cells are used under concentrated illumination, they experience a high heat load because the photons not converted to electricity are dissipated in the cells as heat. Thus, a crucial requirement for a successful PV concentrator is a cooling system which can efficiently remove the dissipated heat while keeping the cells at the desired temperature. Higher overall efficiency is achieved by capturing the rejected heat as well, and using it as an additional energy product (e.g. cooling).

PROTEAS Solar Polygeneration System aims to achieve the synergy of the above benefits, providing an innovative solar polygeneration system that would be able to compete with traditional energy systems. The main characteristics and innovations of the PROTEAS System are analyzed in brief in the paragraphs to follow.

2 SYSTEM DESCRIPTION

The core of the PROTEAS System is the innovative setup of Total Internal Reflection Reflectors (TIRRs) made of clear plastic (Primary Optical System), which concentrate the solar rays up to 5,000 suns, homogenized to 1,000 suns by specially designed Total Internal Reflection Homogenizers (TIRHs) (Secondary Optical System). High-efficiency multi-junction PV Cells are used to generate electricity. Furthermore, water -used for cooling down the PV cells- is heated up to 85-90°C and with the use of an advanced Absorption NH_3 Heat Pump, is turned to chilled water for air-conditioning (7-12°C) and subsequently to domestic warm water of 45-55°C. PROTEAS modules are suitably spaced on a low-profile metallic ring which tracks the sun. A simplified representation of PROTEAS System is presented in Fig. 1.

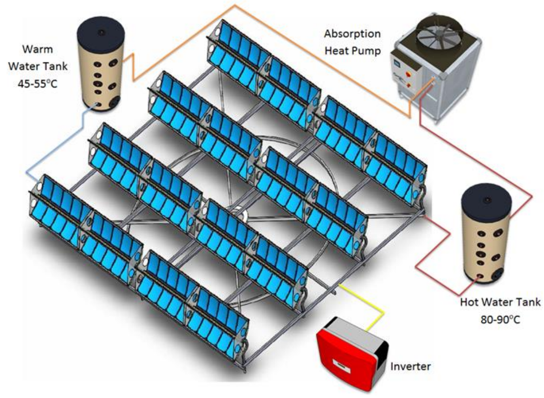

Figure 1: Simplified representation of 2.5 kW_e PROTEAS Solar Polygeneration System

With the PROTEAS System it is estimated that the incoming solar energy can be utilized 6 or 8-fold more efficiently than in the case of the state-of-the-art conventional PV modules. In addition to the direct PV electricity (with efficiencies in the range of 15-30%), the heat generated on the solar cells is collected in the form of hot water 80°-90°C (with collection efficiencies 65-50% respectively), which is fed into an advanced absorption Heat Pump with high conversion efficiency, (COP in the range of 0.9-1.2), to be converted into chilled water of 7°-12°C for air-conditioning, thus increasing the utilization efficiency of the incoming solar energy up to 75%. In addition, the Absorption Heat Pump returns the solar hot water supplied at 80°-90°C as domestic warm water at 45°-55°C, increased in thermal content by 30-50%, because it also returns part of the heat absorbed by the air-conditioning from the building. Thus, the total utilization 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 the 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 to 3-fold is due to its ability to provide air-conditioning by using the 80°-90°C hot water from the PV cooling, and an additional 3 to 6-fold is due to its ability to supply domestic hot water of 45°-55°C after air-conditioning production. This additional capacity to shave more than the 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'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).

3 INNOVATIONS

PROTEAS system is based on several new developments and innovations, while for the rest of the components it utilizes off-the-shelf, simple, as well as novel equipment.

3.1 Optical Concentration System

Current state-of-the-art 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 for two basic reasons. First, 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). Second, 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^o. Light striking this wall is deflected out of the focus. Finally, the tips and valleys have nonzero radius. Clearly, the smaller the facets, the more important this loss is. Modern flat-facet, compression-moulded lenses have an optical transmission of typically about 85% [5].

PROTEAS System is going to advance the state-of-the-art by developing a patented concentrating optical system with a concentration ration of 1,000 suns and optical efficiency up to 95%. The solar concentrator is based on an innovative total internal reflection design in which total internal reflection prisms create the parabolic-form concentrator [6]. The precise geometry of the total internal reflection prisms is a crucial factor for the achievement of high concentration and thus the design and production methods are very important. Furthermore, despite the primary optical concentrator, a secondary total internal reflective flux homogenizer is used to create a uniform solar flux over the solar cells and reduce the need for high sun tracking accuracy. The ray-tracing results from the operation of the optical system are presented in Fig. 2.

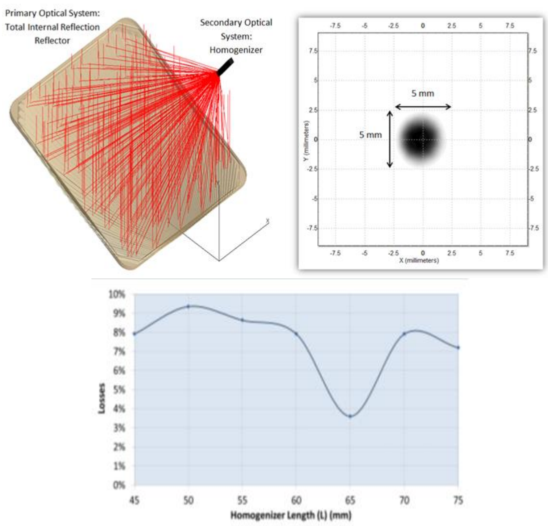

Figure 2: Ray-tracing simulation of the optical concentration system and parametric analysis of homogenizer length.

3.2 Low Profile, Modularity, Heat Exploitation

The described optical system concentrates and homogenizes the sunlight onto 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 rays. Rotation towards the sun is secured by a designed microprocessor and a solar sensor. The short focal length design of the system allows the support platform to be close to the ground. Windstorms have proven to be the pitfall of many competitive system designs, but the PROTEAS design eliminates this problem: standing only 50 cm high, it presents an extremely low profile, not only to windstorms, but hailstorms and sandstorms, as well. By significantly reducing wind loads, the system can be mounted on lighter trackers, thereby reducing 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 application in family houses all the way to large installations in hotels, industries etc. The PV cells are integrated into novel actively-cooled heat sink pipes (Figure 3), ensuring 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. The system achieves high efficiency of transformation of solar radiation to usable energy – the overall efficiency reaches more than 75% (of which about 30% is electricity and 50% heat energy).

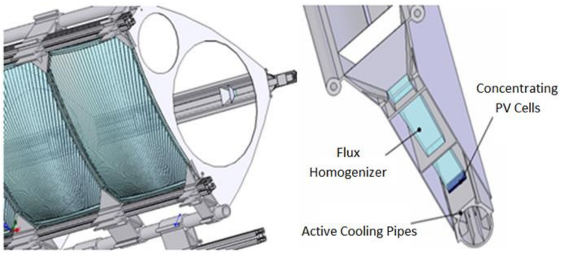

Figure 3: The novel support-connection profiles (left) and the homogenizer/PV cell/ heat sink pipe (right)

3.3 Advanced Absorption Heat Pump

During the last few years many new small-scale sorption chillers have been developed. Many of these absorption and adsorption chillers have now passed from the prototype phase to field tests and into the production. Today absorption chillers with capacities from 4.5 kW to 20 kW and adsorption chillers with capacities from 7.5 kW to 15 kW cooling capacity are available in the market [7]. However, the major drawbacks associated with the developed small-scale thermal-driven cooling systems are their low Coefficient of Performance (COP) for relatively low regenerative temperatures and their high initial cost due to their more complex construction.

PROTEAS System utilizes 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=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 by its new patented cooling cycle [7] (based on bypass principle and steam driven solution-pump; Fig. 4), which allows NH_3 absorption cooling under temperature conditions that were impossible until recently (even with heating temperature of 65°C). Furthermore, the cooling machine is based on an advanced heat exchanger design where a block of sheets of different materials like a microchip is used, in contrary to the conventional cooling machines which are made of a number of heat exchangers connected by a rather complicated and heavy network of bent tubes and fittings. This approach results in a heavier and cost-competitive cooling system.

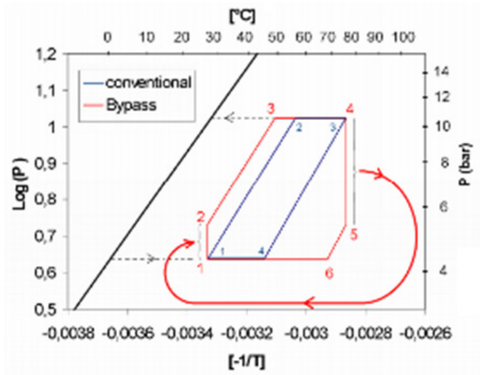

Figure 4: The principle of bypass process on the thermodynamic cooling cycle.

4 CONCLUSION

To largely commercialize a solar energy system, it is necessary to generate energy with high conversion efficiency, low construction, operation and maintenance costs. The innovative PROTEAS Solar Polygeneration System introduced in this work is well matched with these demands. An industrial prototype of 10kWe will be constructed and tested by a Greek consortium under the frame of a National R&D Program SYNERGASIA (2013-2015); after the completion of the demonstration phase is planned commercialization.

5 ACKNOWLEDGEMENTS

PROTEAS Solar Polygeneration System is a project funded by the government of Greece, in the context of the National Action "SYNERGASIA 2011", for the period 2013-2015.

6 ABBREVIATIONS

COP: Coefficient of Performance
O&M: Operation & Maintenance
PV: Photovoltaic
TIRH; Total Internal Reflection Homogenizer
TIRR: Total Internal Reflection Reflector

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Aim of this Work

To present the efforts for the development of a dedicated Solar Polygeneration System (PROTEAS System) for the simultaneous production of electricity, hot water and air-conditioning. The analysis and engineering of the system has already been initiated and some of the subsystems have been successfully developed. An industrial demonstration of 10 kW will be implemented by a Greek consortium under the frame of a National R&D Program.

PROTEAS System Characteristics

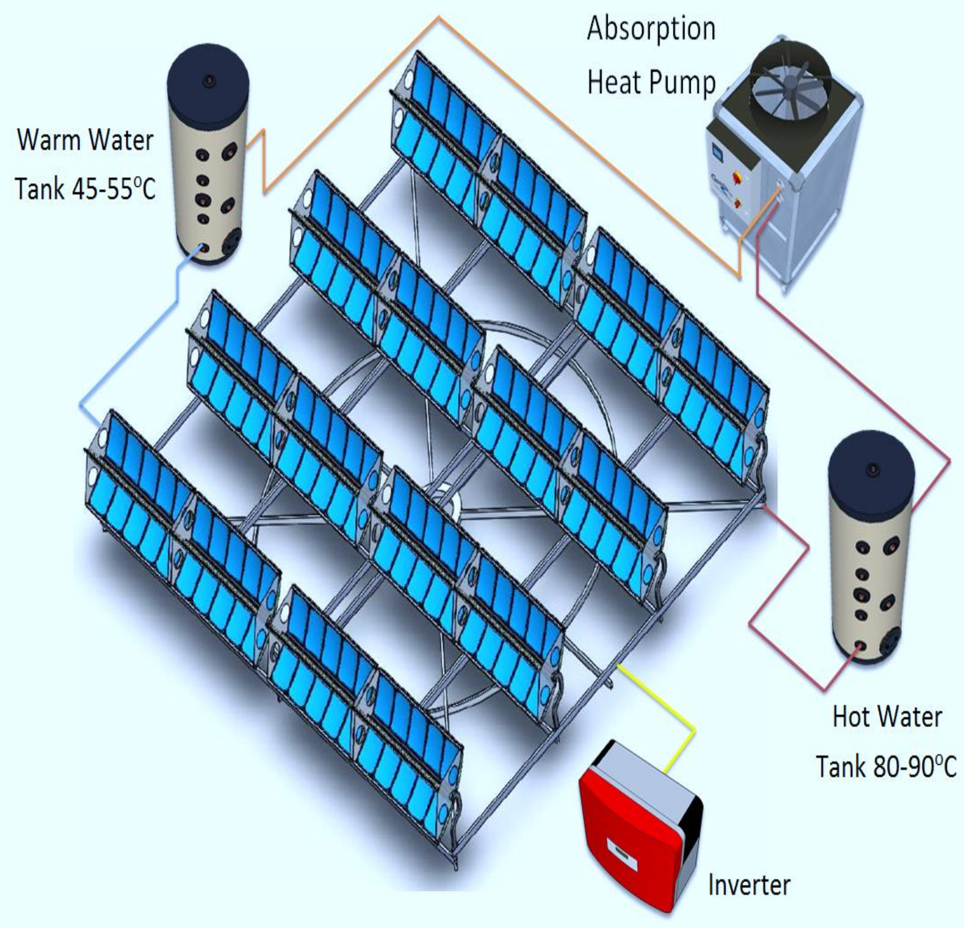
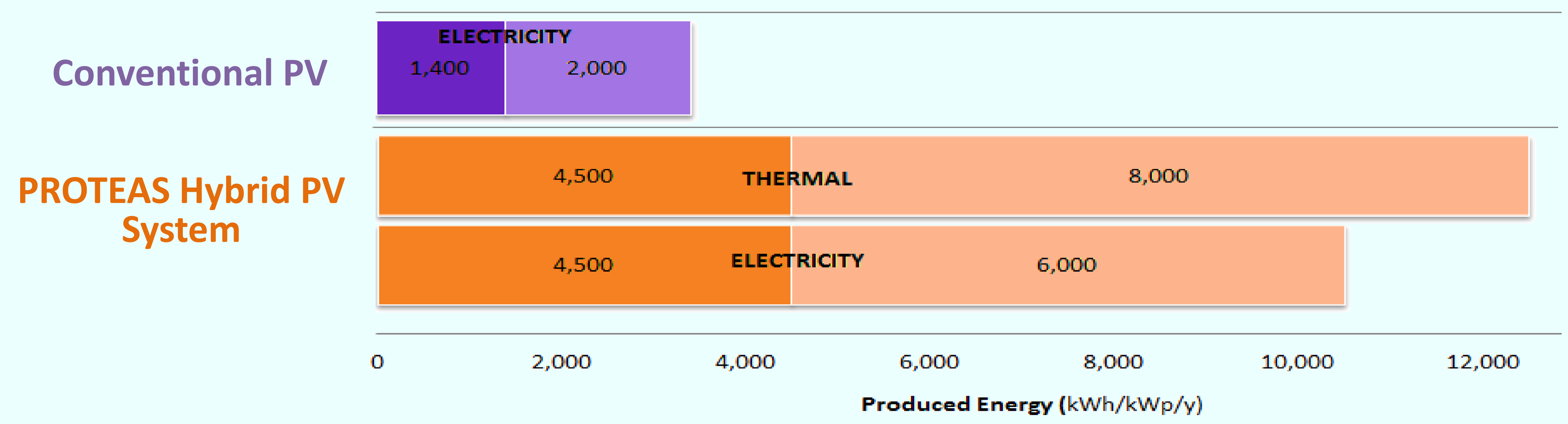


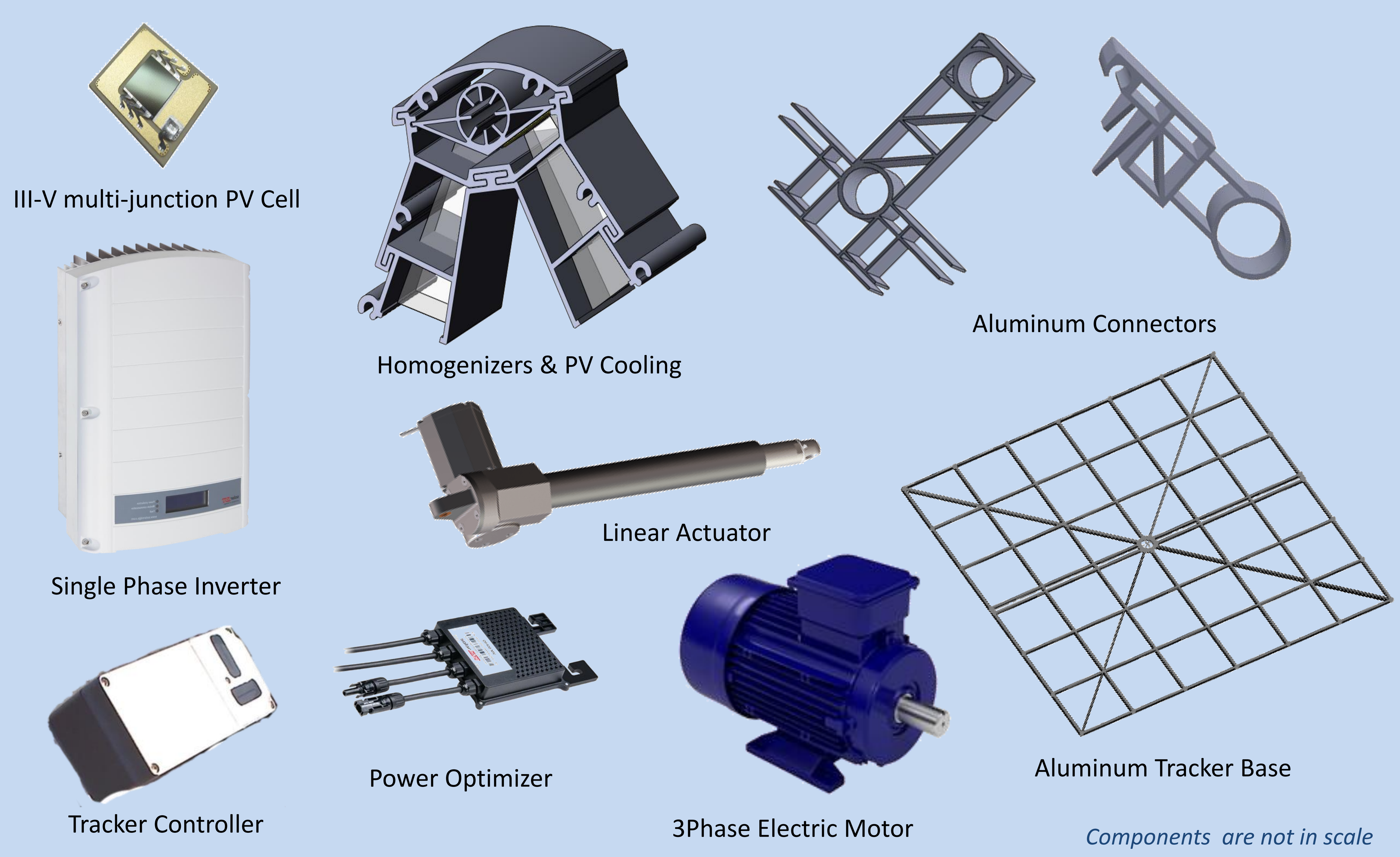
Fig: 2 Simplified Representation of a 2.5 kWe PROTEAS System

Main Characteristics:

- Novel High concentration optical system based only on total internal reflection.
- III-V multi-junction photovoltaic cells.
- Extremely low profile and modular structure
- Active cooling system for thermal energy exploitation .
- Advanced Ammonia Heat Pump working with relatively low regeneration temperatures.
- Further exploitation of rejected heat from heat pump.



Some Components of PROTEAS System



Components are not in scale

State of Development

Analysis and Engineering	Subsystems Development & Supply	Sub-systems Trials	System Integration/ Testing	System Demonstration/ Certification
	Today	12/2014	04/2015	08/2015

Motivation

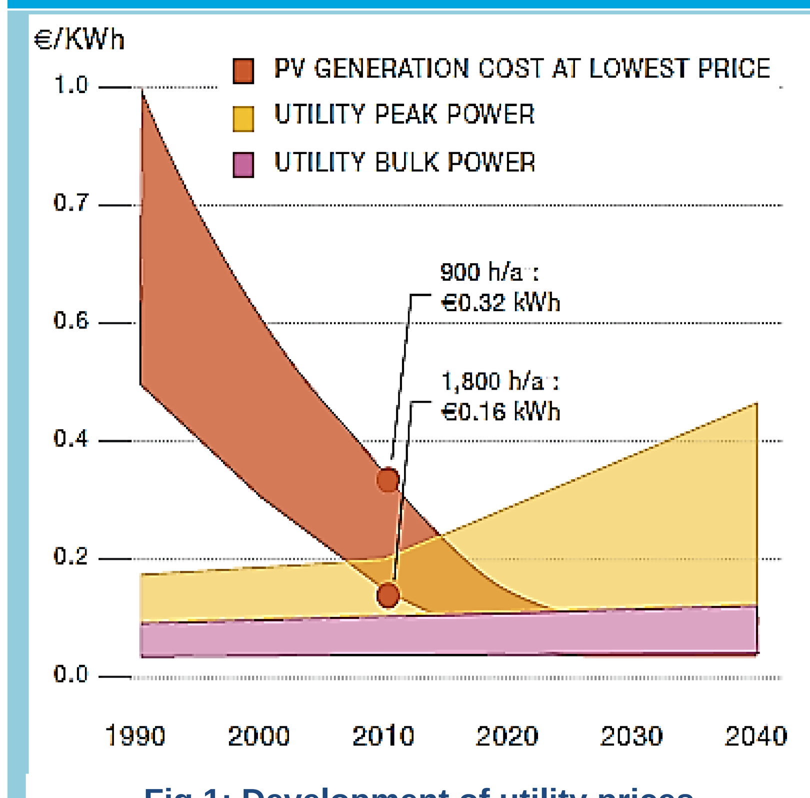


Fig 1: Development of utility prices and PV generation costs

PV systems uncompetitiveness :

- Use large amounts of expensive semiconductor materials.
- Low energy conversion efficiency.
- PV market is still driven by incentives (Feed-In Tariffs).
- Price reduction by a factor 3 to 5 is needed for photovoltaic systems to become subsidy-free and competitive with the conventional production of energy.

Novel High Concentration Optical System

The core of the PROTEAS System is patented* Total Internal Reflection Reflectors (TIRRs) made by clear plastic (Primary Optical System), which will concentrate the solar rays up to 5,000 suns, homogenized to 1,000 suns by Total Internal Reflection Homogenizers (TIRHs) (Secondary Optical System).

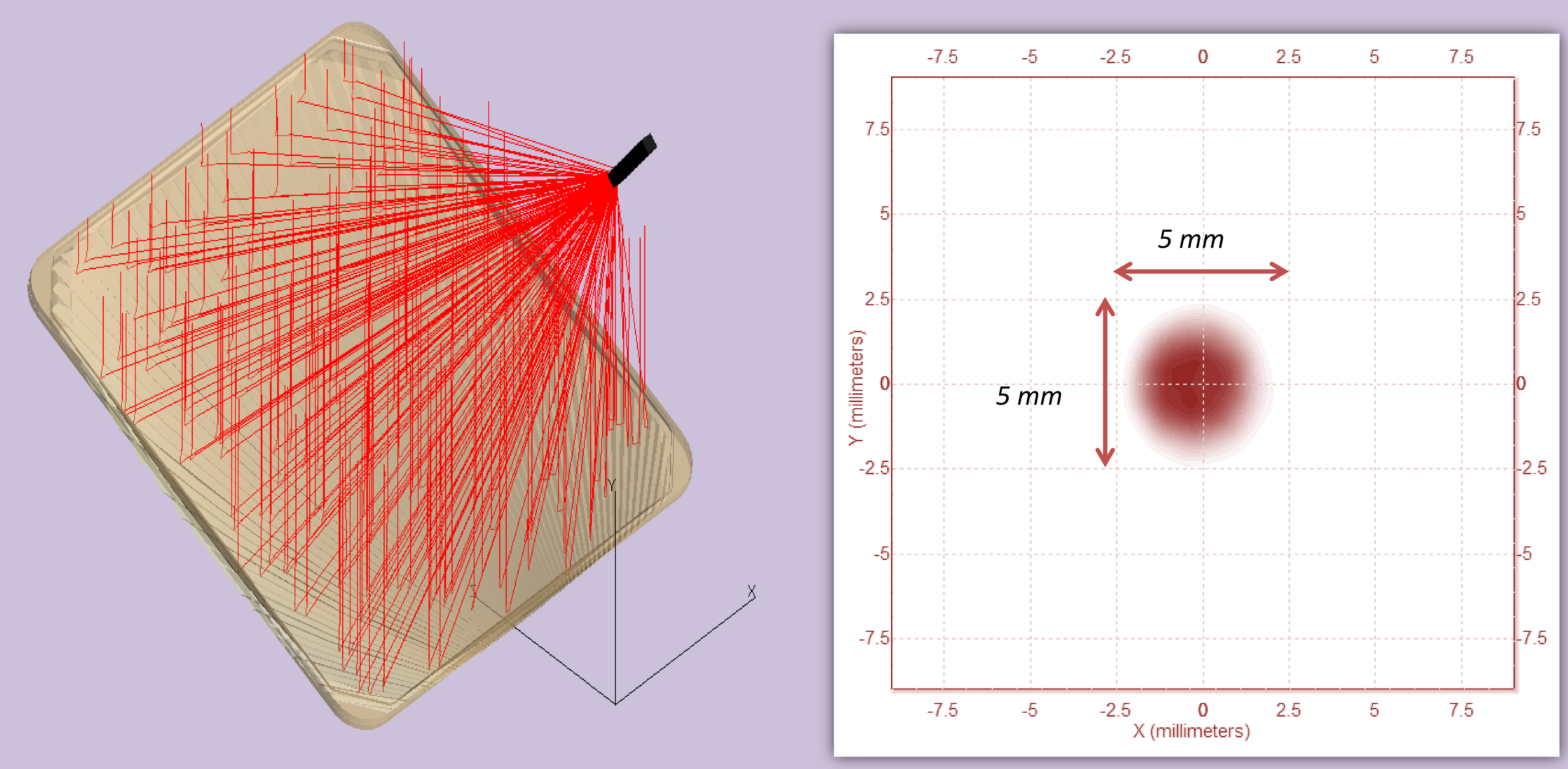


Fig.3: Monte Carlo Ray-tracing simulation for the Total Internal Reflection Reflector

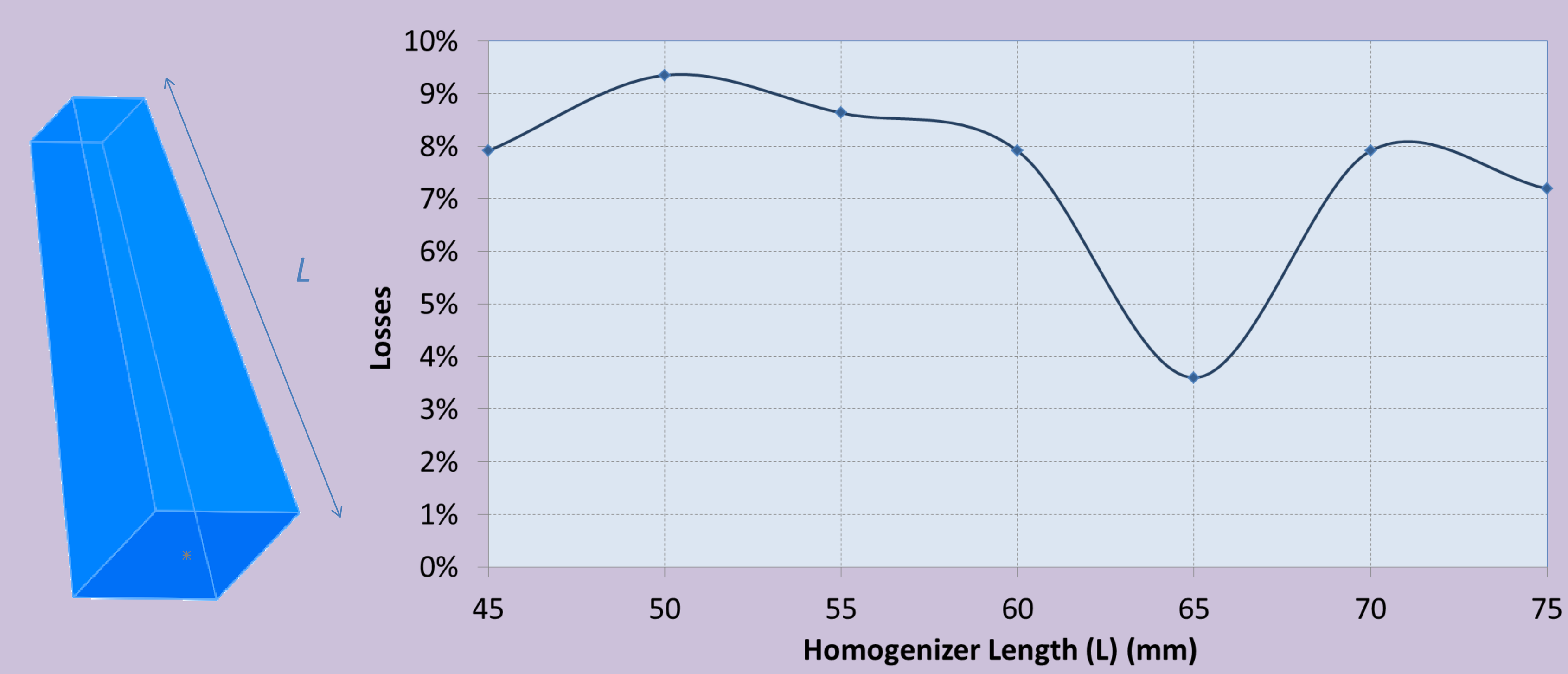


Fig 4: Parametric Analysis for Homogenizer Prism Length

** PAPADOPOULOS Alexandros, Hybrid photovoltaic concentrating system with corrected total reflection reflectors, International Publication Number WO2004/088759 A2, 14 October 2004.*

Business Model for PROTEAS PV System

- The main clients for PROTEAS Technology are not the owners of the buildings (which is also possible as a second scenario), but the local Electricity Utilities, which will install PROTEAS PV System on the roofs of their clients as a Utility's asset.
- Under this Business model, Utilities are credited the cost of PROTEAS PV System the same day of its commissioning, in most countries 50-300% over its cost and most surprisingly 2-3 years before the day of PROTEAS commissioning, due to PROTEAS ability to displace up to 5-fold utility reserve capacity for peak-load, due to supply of air-conditioning from the rejected heat of the concentrating PV cells.

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