

# COMPARATIVE ANALYSIS OF THE SOLAR DISH ELECTRICITY PRODUCTION

by

**Mihajlo FIRAK**

Original scientific paper

UDC: 620.92:662.997

BIBLID: 0354-9836, 9 (2005), 3, 69-83

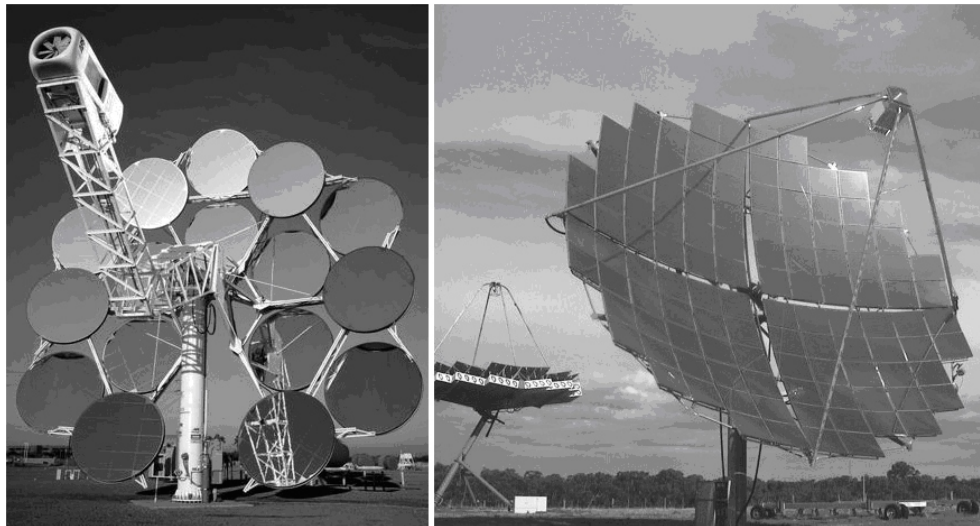
*Round parabolic solar mirror is often called the solar or sun dish. Even when the dish is faceted into several smaller dishes (facets) which are all focusing the sunlight in the single point (focus), it is called a solar dish. When solar radiation to electricity converter is mounted into the dish focus and the sun-tracking system is provided, it could be named solar dish/converter system. Depending on the sort of the converter, two promising systems which are approaching the commercialisation could be mentioned. These are solar dish/Stirling system and solar dish/photovoltaic system. In this paper, majority of the technical and economical aspects of the two systems are examined and compared. Two systems are chosen to represent this: SAIC/STM SunDish<sup>TM</sup>, solar dish with Stirling heat engine/generator, and Solar Systems SS20<sup>TM</sup> representing solar dish with concentrating photovoltaic converter. It is concluded that solar dish with concentrated photovoltaic converter can have much better cost/performance ratio. It is also concluded that recently introduced thermoacoustical converter and photovoltaic cavity converter, probably designates future development of the solar dish systems. World's potential of installing solar dish systems according to geographic and climate conditions was estimated. Also, the number of solar dishes which could, installed in Croatia, cover yearly state's electricity consumption was calculated.*

Key words: solar, dish, concentrating, Stirling, photovoltaic, electricity, converter, comparison

## Introduction

Round parabolic solar mirror is often called solar or sun dish. Even when the dish is faceted into smaller, usually of square shaped parts, that are all focusing the sunlight in a single point (focus), it is called a solar dish. When radiation to electricity converter is mounted into the dish focus and the sun-tracking system is provided, it could be named solar dish converter system. During the long-term development of those systems, four major groups of problems that have to be solved came out. The first group is system supporting structure design including a mechanical part of solar tracking system, the second one is the reflective surfaces (mirrors) design problems, the third are concepts and development of ideal solar radiation to electricity converter, and the fourth one is power

conditioning, electronic control and remote supervision. Recent advancements in each of the mentioned areas brought us the dish systems, which are not only technically matured, but could also, under certain circumstances, be economically acceptable. For example, there are five 22 kW<sub>e</sub> SunDish™ systems [1, 2], (fig.1a), currently in operation in USA. Similar systems, made by SES (25 kW<sub>e</sub>) and by WG Associates (10 kW<sub>e</sub>) are also in precommercial stage [3, 4]. At the time, solar dish thermal system is most efficient in conversion from solar to electric power (30%). In Australia, Solar Systems Pty Ltd. developed SS20, concentrator photovoltaic (PV) power generator that comprises a Sun-tracking parabolic dish and a high power solar cell bank (fig.1b). Only 0.23 m<sup>2</sup> of PV cells generate (after inverter at 1 kW/m<sup>2</sup> solar radiation) about 20 kW<sub>e</sub> [5]. Australian government is now helping in building 42 solar dish concentrating PV units at Broken Hill [6]. All of them are modular units small in size and completely self-contained power systems, approximately 15 m in diameter, requiring no external cooling. It can be linked according to user's needs from tens of kW<sub>e</sub> to multi-megawatt scale. The purpose of this paper is to show where are the dish systems today and where could they be tomorrow.



**Figure 1. (a) Solar Dish/Stirling hybrid system (SAIC/STM SunDish); (b) Solar Dish concentrating PV system (Solar Systems Pty Ltd SS20)**

### **Solar dish systems description**

The following descriptions are oriented to the common features of the solar dish systems with the accent to the solar radiation to electricity converters. For convenience some technical data for SunDish and SS20 systems are given in tab. 1.

**Table 1. Technical data of presented Dish/Stirling and Dish/PV systems**

Technical data	SAIC/STM dish/Stirling system	Solar systems Pty Ltd. SS20
Electrical output	22 kW <sub>e</sub> Net at 1 kW/m <sup>2</sup>	20 kVA
	480 V, 3-phase, 50/60 Hz	415 V AC, 3-phase, 50 Hz
Mirror projected area	113 m <sup>2</sup>	129.7 m <sup>2</sup>
Mirror facets	16 round facets, diameter 3 m	112 facets, 1.1m × 1.1 m
Mirror type	Stretched-membrane, glass	Glass, polymer, steel laminate
Concentration ratio		480
PV receiver aperture		48 cm × 48 cm
Ground cover	405 m <sup>2</sup>	519 m <sup>2</sup>
System height	15 m	14.5 m
Wind stow velocity		14 m/s (50 km/h)
Total weight	10 tons	10 tons

### ***Supporting structure***

Solar dish system construction can be abridged as follows: in concrete fundament, strong metal pedestal is fixed, carrying rotating truss structure of mirrors support and converter supporting arm, which stretches out to the focus of the mirrors system. At the end of the arm (in the focus) thermoelectrical converter is located. Sun tracking part of the system should be supported in its center of gravity. That way solar tracking system, including electric servomotors, spends less energy. The aim is to achieve necessary strength and stiffness of the construction using material as less as possible. The mirrors carrying structure can in the same time be used as a part of the cooling system. The instrumentation, inverter, *etc.* is located nearby or on the pedestal.

### ***Concentrators (focusing mirrors)***

The aim of concentrators is to collect and direct solar radiation of the low density to the small area, which increases several hundred times the density of the radiation. Increased solar radiation density is a prerequisite to its more efficient conversion into the electricity. Round parabolic front surface mirrors are used from the beginning of the solar technology development. The most important parameters that increase the quantity and density of the concentrated energy in the focus of the mirror are concentrator projected area, specular reflection and accuracy of the mirror making. One might say that the ideal

mirror should be as large as necessary, hundred percent reflective at every wavelengths, and therefore it concentrates the whole energy with constant density at the given area. In practice, its own area, weight, and strength of the material and stiffness of the construction limit its size. The greater the area of the mirror is, the greater the weight will be, so the strain in material will become greater than allowed in case of the strong wind. Modern construction of the parabolic mirrors lessens wind problem using faceted mirrors. Squared or round faceted mirrors are used considering that their mutual position and interspaces attenuate the influence of wind. Faceting makes possible for the great mirror to be made out of the number of smaller ones that can be tested and prefabricated into the smaller units. Prefabricated units are more suitable for transport and faster assembling in the field.

Making the reflective mirror surface is the technical challenge yet unsolved. Reflectivity, durability and soiling of the mirror surface are the main problems. To achieve the durability of the mirror, its surface should be hardened so that small particles blown by wind cannot act abrasive and lower the mirror reflection. The most suitable for this is thin glass layer (1 mm). Reflective coating is most often silver or aluminium, since these materials show the greatest reflection (90%) in a broad wave-range of the solar radiation (300 to 1200 nm). Basic carrying material of the reflective surface is thin carbon-steel or stainless steel sheet (1 mm). That kind of laminate could be used in sandwich mirror construction [7] or as stretched across a rim or hoop when it is called stretched-membrane mirror [8]. In the last case, *vis-à-vis* of reflective laminate, the second thin metal membrane is welded across the same rim. By evacuating air out of cylindrical space between both membranes it is possible to obtain the necessary stiffness and curvature of the reflective mirror surface, which could be changed during the work of the device and thus influence the temperature in the mirror focus. For example, SAIC's dish system consists of 16 round facets of the diameter 3 m, air from the facets is evacuated by central ventilator, each mirror has its own valve which controls vacuum and in the same time mirror curvature. Instead of glass mirror, aluminised or silvered reflective follies are often glued to the thin metal sheet (for instance, 3M's ECP 305+). Durability of these reflective surfaces is shorter than of those protected by glass.

A new generation of multi-layer polymer film developed by 3M Corporation demonstrates reflectivity greater than 99% [9]. With a total thickness approximately the same as that of a sheet of paper, these films are comprised of many hundreds to thousands of polymeric layers whose individual thickness is on the order of a wavelength of light. These follies do not contain layer of reflective metal so they are moisture resistant, scratch resistant and virtually unbreakable. These materials will possibly keep their high reflectivity for a longer period because they don't contain metal layer subjected to corrosion.

The amount of the dust on the mirror can be lowered by putting mirror in the stowed position during the night and bad weather. Traditional method for mirrors cleaning is by spraying high pressure demineralised water with hand-held nozzles [10]. According to [11], the problem of dry deposition can be solved by means of electric field, which protects surfaces from airborne dust and clean them. There are some researches making into the problem of keeping wet surfaces free of dust. In spite of maintenance, mirror reflectivity lessens with time.

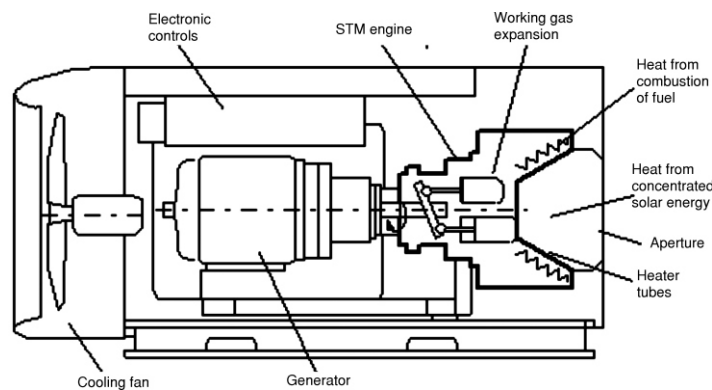
### ***Solar radiation to electricity converters***

Solar radiation to electricity converter is placed at the dish concentrator focus. Historically, a lot of different concepts had been tried. Despite of a great similarity of overall dish systems concepts (a pedestal supported faceted dish mirror with converter at the dish focus), there is a fundamental differences among the converters. Converters could be classified as indirect (heat engines coupled with electrical generator) and direct (thermoelectric, thermoionic and photovoltaic). At the moment Stirling engine with rotating generator manufactured by STM Corporation, USA [12], and concentrating PV converter made by Solar Systems Pty, Australia [5], are pre-commercially available solutions chosen to represent state of the art of the indirect and direct concept respectively. Travelling wave engine developed by S. Backhaus and G. Swift [13] and Photovoltaic Cavity Converter (PVCC) developed by United Innovations, Inc. [14] are briefly described because they probably show directions development in the near future of direct and indirect converters.

#### ***STM Sun/Dish converter based on STM 4-120 Stirling engine***

Although Bryton and organic-Rankine cycle engines had been used with dishes, Stirling engines (kinematic and free-piston) had been used for most of the precommercial systems under development to date. Stirling engines are preferred for these systems because of their high potential thermal-to-mechanical efficiencies, for up to 40%, high power densities (50 kW/litter) and potential for long-term, low maintenance operation. The engine-generator block can be seen in fig. 1a, and cross section in the fig. 2.

STM 4-120 Stirling engine has four cylinders (120 cm<sup>3</sup> swept volume per cylinder) inside of kinematic Stirling engine that uses hydrogen as the working fluid, and is variable-stroke. The variable stroke is gained by using the variable-angle swash plate. The engine



**Figure 2. Schematic of the SunDish Power Unit**

operates a standard off-the-shelf generator and provides up to 25 kW of electricity (480 V, 3-phase, 60 Hz). The Power Unit mass amounts 158 kg. The direct irradiated engine's receiver can be heated either with concentrated solar energy or combustion of hydrocarbon fuel (butane, landfill gas, *etc.*). That is why the whole systems is called hybrid.

### *Concentrating PV converter*

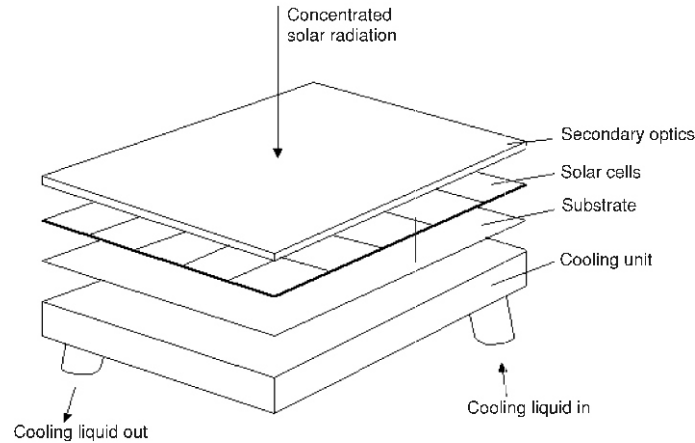
Today's most common PV devices use a single junction, or interface to create an electric field within a semiconductor such as a PV cell. In a single-junction PV cell, only photons whose energy is equal to, or greater than the band gap of the cell material can free an electron for an electric circuit. In other words, the photovoltaic response of single-junction cells is limited to the portion of the sun's spectrum whose energy is above the band gap of the absorbing material, and lower-energy photons are not used.

One way to go round this limitation is to use two (or more) different cells, with more than one band gap and more than one junction to generate a voltage. These are called "multi-junction" cells (also called "cascade" or "tandem" cells). A multi-junction device is a stack of individual single-junction cells in descending order of band gap. The top cell captures the high-energy photons and passes the rest of the photons on to be absorbed by lower-band-gap cells. Multi-junction devices can achieve higher total conversion efficiency because they can convert more of the energy spectrum of light to electricity.

It is known that a solar cell will double the output of electricity if it is lighted by double amount of solar radiation. This is promising method for reducing the cost of PV electricity. The cost of a given area of a reflecting or focusing collector intercepting sunlight is considerably less than the same area of PV-cells. The difficulty in using focused radiation of high intensity is that the increased radiation per unit area of the cell causes a considerable rise in temperature, and the efficiency of the cell decreases with increasing of temperature. But today, using passive or active air or water cooling together with new PV-cell materials and technology can function properly even at concentration ratios of up to 1000 suns.

Flat plate PV arrays and concentrators based on single junction cells use a fraction of the solar spectrum wasting the remainder of the sun's energy. Their module performance is limited to 20% or less. Multi-junction, III-V concentrator cells use a larger fraction of the solar spectrum, but their development is hampered by many problems. Their ultimate cell performance is predicted to be less than 40%.

There are several concentration systems in use having the different solar radiation concentration and cooling concepts. Among them, AMONIX Inc. [15], ENTECH Inc. [16], EUCLIDES™ –THERMIE project [17], and Solar Systems Pty Ltd. [5] have promising pre-commercial projects. All of them use flat plate PV-module design. SS 20 is presented here because of its overall solar dish concept and rated peak power (24 kW DC) comparable to SAIC's Stirling. SS20 system has concentration ratio 480 suns. PV receiver aperture is 48×48 cm; efficiency of 18 to 20% can be calculated from data published on [5]. Schematic of PV receiver is presented in fig. 3.



**Figure 3. Schematic of concentrated PV receiver**

### ***Electronics***

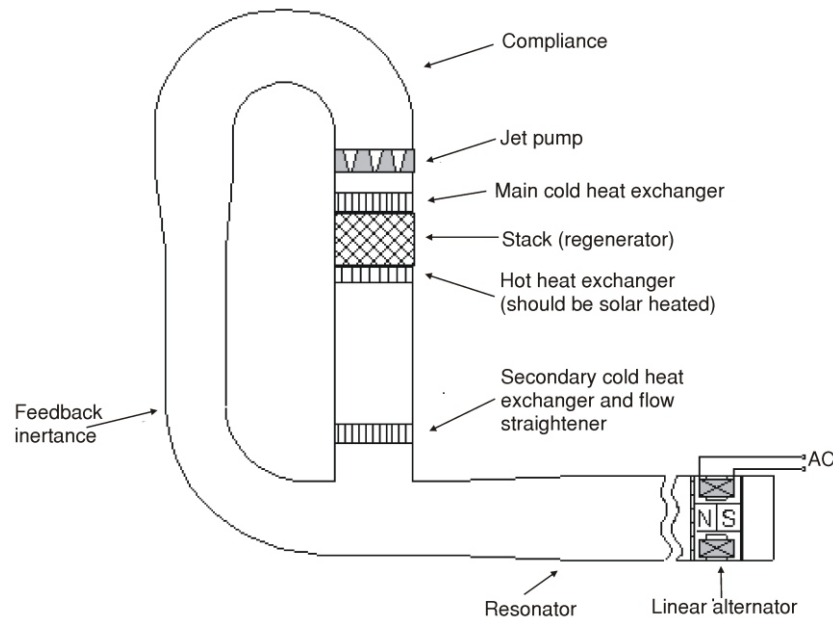
Both representative systems have exhaustive electronic systems. The control system for the SunDish systems includes a micro-processor-based dish controller, a network interface that allows an operator to remote control multiple systems, and a micro-processor controller that controls the engine. SS20 is linked to the operation centre, reporting its performance and condition. The in-built telemetry also allows remote monitoring, diagnostics and control. The dish is programmed for auto shutdown in the event of a fault condition. The system is fully controlled by dynamic auto-educating software, which continually optimises performance.

### **Promissing future**

#### ***Thermoacoustic engine***

This type of engine can convert thermal energy conducted from outside to mechanical energy in a form of resonant standing or travelling acoustical waves. This cyclic changing of temperature and pressure of working gas resembles Stirling process. Part of acoustical energy can then be converted to electricity by using reciprocating linear alternator [18]. Permanent magnetic cores of that alternator and round spiral springs attached to them are the only moving parts. The standing wave engine was being explored about twenty years now. It has a modest thermal to mechanical efficiency, usually less than 20%. This efficiency rose to 30% when in 1999 the first successful travelling wave engine (fig. 4) was demonstrated [13]. The absence of moving parts, lubrication oil, simplicity of design, without tight tolerances of manufacturing process, ensures cheap and





**Figure 4. Schematic of thermoacoustical travelling wave engine (adapted from [13])**

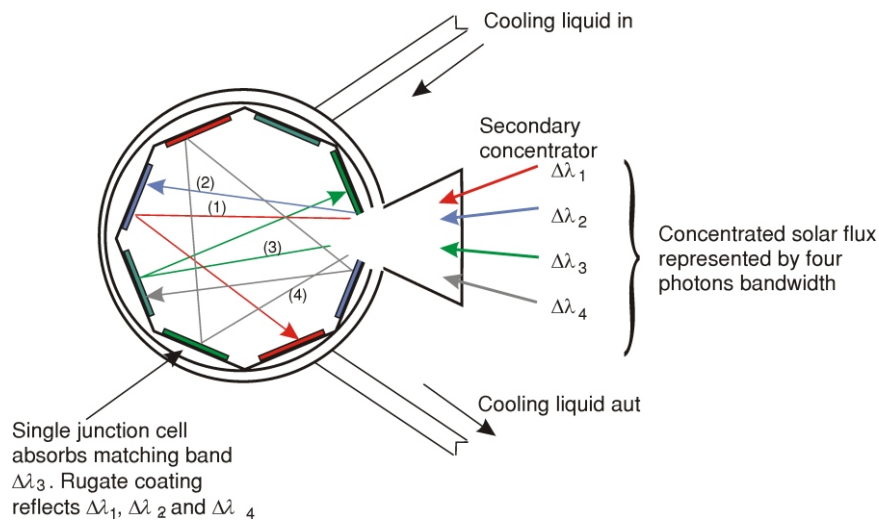
reliable engine. Consequently, these highlights could attract the industries of undeveloped countries. Thermoacoustic effect that converts thermal to mechanical energy of sound can be reverted. That means that mechanical energy (acoustic waves) in properly designed engine can cause heat pumping, i.e. remove heat from lower to higher temperature confined compartments. If two processes are combined in one single engine unit, it is possible to use the outside heat (for example solar heat) to demonstrate refrigeration effect [19]. There are no moving parts (except working gas) in such an engine. At the time only CFIC inc. develops small ( $2 \text{ kW}_e$ ) standing wave solar to electricity converter named TARGET<sup>TM</sup> [20]. The main source of the valuable scientific and technical information about thermoacoustic engine may be found in [21].

### ***Photovoltaic cavity converter***

Photovoltaic Cavity Converter (PVCC) being developed by United Innovations, Inc. [14] is presented in fig. 5. It is placed in focus of Dish/PVCC concentrator system consisting of a first stage parabolic concentrator (not showed), a secondary concentrator, and spherical cavity collecting the highly focused light. Inside the cavity there is multi-band gap cell system that can reach collective efficiencies of 45 to 50%. The underlying principle behind PVCC's high performance is the optimal utilization of the solar



spectrum based on a novel spectral splitting process induced by the Rugate filters, and the use of single-junction cells with different but congruent energy band-gaps. PVCC replaces the vertical, 3D architecture of multi-junction cells consisting of stacked sub-cells with lateral, 2D array of single junction cells. This allows an increased degree of freedom in the choice of semiconductor materials and the elimination of electronic, structural, thermal and optical difficulties that multi-junction technology faces when the number of sub-cells is four or more and the flux concentration exceeds 500 suns.



**Figure 5. Illustration of spectral splitting by selective reflection and transmission inside the PVCC**

### ***Producing hydrogen***

The recent advancements of hydrogen technology, especially of fuel cells development, should not be forgotten. In a fuel cell, hydrogen and oxygen can be combined to produce electric power, heat power and pure water. There are no harmful emissions, and water can be reused in a closed cycle because it can again be split to hydrogen and oxygen using opposite process called electrolyse. This is the only commercial way of producing clean hydrogen and oxygen. Because it uses electricity, this process is as clean as a process to produce this electricity. So, electrical power produced by described solar dish systems can be used to produce clean hydrogen. It could be concluded that intermittent nature of solar produced electricity needs hydrogen as an energy storage, and hydrogen needs solar electricity to be produced in a clean way (there is no free hydrogen on Earth, major part is chemically bonded with oxygen in water or with a carbon in hydrocarbons). Recently there has been an interesting project connecting SAIC/ASTM dish system with

Proton Energy Systems, Inc. hydrogen technology (water electrolyser and hydrogen storage) [22]. Excess in produced electrical energy is used for production of hydrogen by water electrolysis. Hydrogen is feed in the storage tank for later use in Stirling engine for production of electricity, *e. g.*, during night *etc.* Alternatively, hydrogen can be used as a fuel for transportation purposes.

### Comparative analyse

By analysing and comparing two representative systems, SAIC/STM SunDish as the representative sun dish Stirling system, and Solar Systems Pty Ltd. SS-20 as the representative of the most sophisticated concentrated PV system today, the following conclusions could be drawn. Supporting structure of both systems are of an advanced design, yet they have some possibility for further development. Both systems have different storm stow positions. Dish/Stirling mirrors are looking down, with power unit lying on the ground. This is better solution than of SS-20, which mirrors incline towards zenith with PV converter as high as 15 m. It can be expected that SS-20 will have more problems with mirrors soiling and thunderous storms, which could damage the PV-module. At the same time, because PV-module is much lighter then thermal engine, the converter-supporting arm needs less material and consequently is of a simpler design.

The mirrors structure and reflective surfaces still need further development, especially those for PV converters which should be, in contrary of Stirling which is relatively point focus designed, designed to produce uniform radiation flux across squared area of the PV-module. The mirror reflective surface durability and suppression of soiling should be further investigated.

Solar to electricity converters of both systems are completely different. From twenty years ago to nowadays, efforts have been focused to the development of dish/Stirling systems because of the Stirling cycles potential for very high thermal-to-electricity efficiencies, greater then 40% for engines operating at temperatures higher then 700 °C. Peak net solar-electric efficiencies, which include concentrator, receiver, and parasitic power losses, have been measured as high as 29.4% for these systems [23]. In spite of such high record during direct normal insolation between 700 and 970 W/m<sup>2</sup> system net efficiency is between 12 and 17.5% [24]. Although dish/Stirling systems have demonstrated very high overall conversion efficiency, they continue to suffer of reliability problems (that is, leakage of working fluid through dynamic and static seals or control-systems hardware failure [24], it is possible that simpler and more reliable, even less efficient thermoacoustic Stirling engine will perform better.

In the year 2001 we saw strong demand of Solar Energy Industries Association (SEIA) of US (which consists of more than 500 companies) for government support of deploying 5000 MW by the year 2006 [25]. Concentrating Solar Power (CSP) industry as a division of SEIA had a goal to deliver over 1000 MW of new capacity by 2006 [26]. Located at US southwest, CSP facility would cover 15 km<sup>2</sup>, produce 2000 GWh<sub>e</sub> per year, and avoid 0.4 million tons of CO<sub>2</sub> emission per year. In June 2004, the Governors of seven South-Western US States (New Mexico, Arizona, Nevada, California, Utah, Texas,

and Colorado) voted a resolution calling for the development of 30 GW of clean energy in the West by 2015, of which 1 GW would be of solar concentrating power technologies. In November 2004 the US Department of Energy decided to back this plan and to contribute to its financing [27].

Concerning solar dish systems as a whole, today we have the beginning of Nevada 1 MW Solar Dish-Engine Project [28]. As a precursor of the project, two dish/Stirling Systems (one SAIC/STM and one SES system) were installed and are operating on the campus of the University of Nevada, Las Vegas (UNLV). The installation and testing of the systems (40 or more) will be performed in the near future [29]. The project is meant to be a transition of dish engine systems from research and development to a precommercial deployment of the technology. The UNLV will develop a base of highly trained technicians and engineers what is critical for the development of the solar dish industry and the future deployment of dish-engine power plants.

All discussed above can be summarized through the economic considerations. According to [26]: “Stirling Dishes have costs of about \$8000-10000/kW<sub>e</sub> in production volumes under 50, about \$3000/kW<sub>e</sub> for production volumes upwards of a thousand, and \$1000/kW<sub>e</sub> for volumes of tens of thousands.”

On the contrary, concentrating PV converters have greater near future development potential. They could have greater efficiency; need less materials (reduced converter mass), macro simplicity, virtually no moving parts, greater reliability and have lower maintenance cost. It should not be forgotten that semiconductor industry has necessary production capacities. The cost of 10 pc’s SS20 systems which will be located on the South Australian-Northern Territory border is “more than \$AU 200000 each” [30]. Another cost considerations also predict that the PV concentrating system offers “clearly superior” conversion technology [31]. Recently, US DOE, CSP program looks toward alternative converter technologies for use with concentrating dish systems and found “concentrating PV receivers as an obvious candidate due to their potential for high reliability, high efficiency, and low cost at moderate production levels” [32].

## **Installation potential**

### ***World installation potential according to geography and climate conditions***

Concentrating solar power technology relies on beam component of solar radiation *i. e.* on clear sky without clouds and short path length of radiation through the atmosphere (air mass). Both conditions are fulfilled in dry and desert climate region of the Earth (usually located around north or south tropics  $\pm 10^\circ$ ). In terms of irradiated solar energy (kW/hm<sup>2</sup> per year) premium regions should receive more than 2550 kWh/m<sup>2</sup> per year. Excellent regions receive 2370 to 2550, and good between 2200 and 2370 kWh/m<sup>2</sup>. For example, systems like SAIC/STM SunDish begin to work at solar flux above 400 W/m<sup>2</sup> what is difficult to expect on a cloudy day. According to this, the best geography region are South-West part of North America, west costal part of South America,

north and south parts of Africa, Arabia peninsula, Central Asia, and Australia. A short calculation which would rely on assumptions that only 1% of that dry and desert land could be utilised for solar power generation, and that it receives  $2200 \text{ kWh/m}^2$ , we can produce  $8.8 \cdot 10^{13} \text{ kWh/year}$  of electricity. This is  $7.3 \cdot 10^9$  tones of equivalent oil (toe) or 780 times more than global world primary energy consumption was in the year 2002 ( $9.4 \cdot 10^6$  toe [33]). Assuming that one SAIC/STM SunDish system produces 35,000 kWh/year, it should be produced about 3.2 million systems to cover all world's primary energy needs. Assuming the cost of 20000 USD per system the whole price would be 64 billions USD. Today Australia already installed 10 SS-20 systems at Erabella community (Ananga Pitjantjara, South Australia) and three similar solar farms are on the way [34].

### ***Possibilities in Croatia***

The idea of installing solar dish with Stirling engines along Adriatic coast (approximately  $1700 \text{ kWh/m}^2$  per year) had been proposed by Kolin [35]. He compared solar tower concept, non-concentrating solar cells and 50 kW German solar Stirling engine V-160 and found that Stirling system has the highest specific electricity generation per surface area of one square kilometre. Finally, he concluded that using this system, a square area with a side of 8 km is sufficient to cover total electricity needs in Republic of Croatia. Assuming Croatian electricity consumption (2003) of  $3.9 \cdot 10^9 \text{ kWh}$  and that one SAIC/STM SunDish system occupies  $519 \text{ m}^2$  (ground cover, tab. 1), 112,000 systems should be produced and 2.24 billions USD should be spent (assuming 20,000 USD per system). That number of systems would occupy  $58 \text{ km}^2$  *i. e.* square having a side 7.6 km. Another calculation based on average global yearly solar irradiation of Adriatic coast in Croatia to the inclined surface ( $45^\circ$ ) which amounts  $1,750 \text{ kWh}$  and SS20 system with efficiency of 20%, would give 85,500 systems and square of land of  $44.4 \text{ km}^2$  (6.6 6.6 km). If solar tracking would be included into account, about 30% more energy would be available, but one should remember that systems discussed here can use only beam solar irradiation. Nevertheless, this huge numbers suggest that such systems should be grouped to form solar farms consisting from ten to thousands systems, according to local electricity demand, aesthetical, ecological, and other local conditions. Also, this is great opportunity for industry in Croatia, especially for aluminium and electro industry. Knowing that world will be faced with maximum oil production before 2010 [36], it is logical to expect much higher oil prices in the next decade. This will make solar electricity generating systems like this more competitive choice.

### **Conclusion**

Concept of solar dish/converter system's design according to four main design problems has been analysed. They are: system supporting structure design, reflective surface design, solar radiation to electricity converter design and electronics (power condi-

tioning, electronic control and remote supervision). The two representation systems, SAIC/STM SunDish, and Solar Systems Pty Ltd's SS20 have been described with more details. Comparative analysis of two systems showed that main difference arise when solar radiation to electricity converters were compared. These converters are of mechanical type (thermal to electric power conversion using Stirling engine and electromechanical generator on the same shaft – SAIC/STM SunDish) and of direct heat to electricity conversion type without moving parts (photovoltaic cells – Solar System Pty Ltd. SS-20). The expected development in the future of both converter types was showed. Up to date, the solar dish/Stirling solar to electricity converter showed the best solar to electricity conversion efficiency of 29.4%, more than other solar to electricity converters (its apart theoretical maximum approach 40%). Forthcoming thermoacoustic Stirling engines can be more reliable, cost less but have modest efficiency. But because of its high potential efficiency (50%), design simplicity that suggests high reliability and low maintenance, potential for low cost, the new PVCC concept has the promising future. Even though serious projection of further development of dish Stirling systems promises increasing number of units to be manufactured and consequently, installation investment and electricity production cost reduction, it seems that recent Australian investments in PV-concentrating units marks the future trends of solar dish electricity production. Direct solar power to electricity conversion using PV cells is generally compatible with hydrogen production using process of water electrolyse. Because of hydrogen economy knocking on the door it is reasonable to expect that it will generate additional support to the further development in favour of dish/concentrated PV converter systems.

World installation potential for SAIC/STM SunDish system according to geography and climate conditions was calculated giving the number of 3.2 million systems to cover all world primary energy needs. Assuming the cost of 20000 USD per system the whole price would be 64 billions USD. Similarly, the number of solar dishes which could, installed in Croatia along Adriatic coast, produce solar electricity is calculated, and the amount of produced electricity should be equal to state's consumption in the year 2003.

## References

- [1] \*\*\*, SAIC/STM Utility-Scale Joint Venture Project, SAND99-1379, March 1999
- [2] \*\*\*, Ocean Power Corporation Site, <http://www.powerco.com/Power/Solar/Brochures.pdf>
- [3] \*\*\*, The Boeing/SES DECC Project, SAND2001-2530P, August 2001
- [4] \*\*\*, 10-kW Solar Dish/Stirling Remote Power System for Native American Applications, SAND2000-0306, February 2000
- [5] \*\*\*, Solar systems Pty Ltd Site, <http://www.solarsystems.com.au/>
- [6] \*\*\*, Renewable Energy Commercialisation Program, The Australian Greenhouse Office Site, Project offered under RECP 4, January, 2002, <http://www.greenhouse.gov.au/renewable/recp/fundedprojects/four.html>
- [7] Diver, R. B., Grossman, J. W., Sandwich Construction Solar Structural Facets, *Proceedings, Renewable and Advanced Energy Systems for the 21<sup>st</sup> Century*, a joint ASME/JSME/JSES/KSME International Conference, April 11-14, 1999, Maui, HI, USA

- [8] Beninga, J. K., Solar Power Technologies, *SAIC Science and technology trends*, May 1, 2001, <http://publications.saic.com/satt.nsf/externalbycat2>
- [9] Gaughan, R., High-Reflection Mirror Is All-Polymer Film, *Photonics Technology*, July 2000, <http://www.photonics.com/spectra/tech/XQ/ASP/techid.877/QX/read.htm>
- [10] Cohen, C. E., Kearney, D. W., Kolb, G. J., Final Report on the Operation and Maintenance Improvement Program for Concentrating Solar Power Plants, SAND99-1290, June 1999
- [11] Biryukov, S., Method and Apparatus for Dust Removal from Surfaces, Israeli patent application N 116489
- [12] \*\*\*, STM Power Site, <http://www.stmpower.com/Markets/STM%20Solar%20Glossy.pdf>
- [13] Backhaus, S., Swift, G. W., A Thermoacoustic-Stirling Heat Engine: Detailed study, *Journal of the Acoustical Society of America*, 107 (2000), 6, pp. 3148-3166
- [14] Ortabasi, U., Broad Band Rugate Filters for High Performance Solar Electric Concentrators, presented at NCPV Program Review Meeting, Lakewood, Col., USA, October 14-17, 2001
- [15] Garboushian, V., Hoft, D., Roubideaux, D., Innovative High-Performance Concentrator PV System for Grid-Connected Applications, *Proceedings*, 7<sup>th</sup> Arab Conference on Solar Energy & The Regional World Renewable Energy Congress, Sharjah, UAE, February 19-22, 2001, [http://www.amonix.com/Tech\\_Papers/Arab\\_Conf.htm](http://www.amonix.com/Tech_Papers/Arab_Conf.htm)
- [16] O'Neill, M. J. *et al*, Development of Terrestrial Concentrator Modules Incorporating High-Efficiency Multi-Junction Cells, *Proceedings*, 28<sup>th</sup> IEEE Photovoltaic Specialists Conference, Anchorage, USA, September 15-22, 2000, pp. 1161-1164
- [17] Sala, G., *et al*, 480 kW<sub>peak</sub> Concentrator Power Plant Using the EUCLIDES<sup>TM</sup> Parabolic Trough Technology, *Proceedings*, 2<sup>nd</sup> WCPVSEC, Vienna, July 6-10, 1998, pp. 1963-1968
- [18] Corey, J., Yarr, G., HOTS to WATTS, the FPSE Linear Alternator System Revisited, *Proceedings*, 27<sup>th</sup> Intersociety Energy Conversion Engineering Conference, August 3-7, 1992, Vol. 5, pp. 289-303
- [19] Adeff, J. A., Hofler, T. J., Design and Construction of a Solar-Powdered, Thermoacoustically Driven, Thermoacoustic Refrigerator, *Journal of the Acoustical Society of America*, 107, (2000), 6, pp. L37-42
- [20] \*\*\*, CFIC, Inc., Resonant Power: Technology & Market Summary, 1999
- [21] Swift, G., Thermoacoustics: A Unifying Perspective for Some Engines and Refrigerators, Los Alamos National Laboratory, LA-UR 99-895, Fourth draft, 1999
- [22] Friedland, R. J., Speranza, J. A., Integrated Renewable Hydrogen Utility System, *Proceedings*, 1999 U. S. DOE Hydrogen Program Review, NREL/CP-570-26938
- [23] Mancini, R. T., Solar-Electric Dish Stirling System Development, SAND97-2924C, December 1, 1997
- [24] Mayette, J., Devenport, R. L., Forristall, R., The Salt River Project SunDish Dish-Stirling System, *Proceedings*, ASME Solar Forum 2001 Solar Energy: The Power to Choose, Washington, DC, April 21-25, 2001, <http://members.asme.org/catalog/ItemView.cfm?ItemNumber=G01164>
- [25] Butler, B. L., Testimony to US House of Representatives, Committee on Resources, Potential Alternative Energy Sources Available on National Public Lands, Wednesday, October 3, 2001, <http://www.house.gov/resources/107cong/fullcom/2001oct03/butler.pdf>
- [26] Luce, B., Report on the Western Governor's Association Solar Energy Meeting, Desert Research Institute, Las Vegas, NV, USA, January 18, 2002
- [27] Cedric Philibert, International Energy Technology Collaboration and Climate Change Mitigation, Case Study 1: Concentrating Solar Power Technologies, COM/ENV/EPOC/IEA/SLT (2004), 8, [http://www.iea.org/dbtw-wpd/textbase/papers/2004/solar power.pdf](http://www.iea.org/dbtw-wpd/textbase/papers/2004/solar%20power.pdf)
- [28] \*\*\*, The Nevada 1-MW Solar Dish-Engine Project, SAND2001-2533P, 2001
- [29] Kress, A., Stirling, Schuff Partner on Solar Power Dishes, *The Business Journal of Phoenix*, April 30, 2004 print edition, <http://phoenix.bizjournals.com/phoenix/stories/2004/05/03/story7.html?page=1>
- [30] Wroe, D., Town Reflects on the Benefits of a Solar System, *Rural Reporter*, November 9, 2001



- [31] Ward, J. S., Duda, A., Coutts, T. J., Kurtz, S. R., New Concepts for High-Intensity PV Modules for Use with Dish Concentrator Systems, NREL/CP-520-25552, 15<sup>th</sup> Photovoltaics Program Review Meeting, Lakewood, Col., USA, September 15, 1998
- [32] Mehos, M., Lewandowski, A., Symko-Davies, M., Kurtz, S., Concentrating Photovoltaics: Collaborative Opportunities within DOE's CSP and PV Programs, NREL/CP-520-31143, NCPV Program Review Meeting, Lakewood, Col., USA, October 14-17, 2001
- [33] \*\*\*, BP Statistical Review of World Energy, June 2003, [www.bp.com/centres/energy](http://www.bp.com/centres/energy)
- [34] \*\*\*, [http://www.abc.net.au/dimensions/dimensions future/Transcripts/s703853.htm](http://www.abc.net.au/dimensions/dimensions%20future/Transcripts/s703853.htm)
- [35] Kolin, I., Solar Stirling Engines Installed Along the Adriatic Coast, International Congress Energy and the Environment, *Proceedings*, 16<sup>th</sup> Scientific Conference on Energy and the Environment, Opatija, Croatia, October 28-30, 1998, pp. 93-97
- [36] Aleklett, K., From Paris to Berlin – Steps Towards the Final Countdown to Peak Oil & Gas, *Proceedings*, 3<sup>rd</sup> International Workshop on Oil & Gas Depletion, Berlin, Germany, May 25-26, 2004, <http://www.peakoil.net/iwood2004/pptBerlin/Proceeding.html>

Author's address:

*M. Firak*

Faculty of Mechanical Engineering and Naval Architecture  
University of Zagreb, Ivana Lučića 5  
Zagreb, Croatia

E mail: [mfirak@fsb.hr](mailto:mfirak@fsb.hr)

Paper submitted: April 27, 2005  
Paper revised: July 25, 2005  
Paper accepted: August 31, 2005