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MODULAR SOLAR SYSTEMS FOR 24/7 SCALABLE, FLEXIBLE, AFFORDABLE ELECTRICITY

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ABSTRACT

A successful transition to a low carbon future requires that power be generated all of the time, 24/7, not just when the sun is shining. But few clean emissions power technologies can operate 24/7. Concentrated solar power (CSP) can because it can store thermal energy at 10-20% of the cost of batteries[1] and can then burn fuel when its solar resource is exhausted. However, many see first generation CSP as too costly, complex, risky, and economical only at utility scale.

Alternatively, by mimicking the all-factory, standardized, modular approach of wind and PV, next-generation CSP, with low-cost dry thermal storage (e.g., firebrick, not molten salts), and no requirement for water/steam (just hot air), offers the potential to achieve baseload affordability.

This technical paper summarizes an Engineering and Cost Feasibility Study[2] funded by the US Department of Energy and presents a new breakthrough power generation product based on the Brayton power tower system called 247Solar Plants™. Design, construction, and operation are all simplified with greatly reduced costs and increased deployment speeds.

Such modular CSP systems can be installed as single units or 100s of modules at utility scale. The microturbines used by the system stabilize grids by responding nearly instantly, similar to battery response time, to changing power demands and voltage fluctuations, while offering dispatchable, reliable electricity. The redundancy of multiple modules in a single project increases capacity factor, operational flexibility, and project reliability.

The DOE Study shows that such a system may be able to achieve the two key DOE targets including: 1) a capacity factor of at least 75%, of which >85% would be solar with <15% from fuels; and LCOE[3]s <9¢/kWh. Indeed, LCOEs under 6¢/kWh may be possible with further development and widespread deployment.

Keywords: 24/7 solar; CSP; solar; Brayton CSP; solar receiver; modular solar; thermal storage; TES; grid stabilization; distributed power; micro-grids

1. INTRODUCTION: A NEW LOW-COST APPROACH TO CONCENTRATING SOLAR POWER - MODULAR BASELOAD BRAYTON POWER TOWERS

In August 2011, Wilson Solarpower Corporation and an international team of experts[4] completed its Engineering and Cost Feasibility Study funded by the US Department of Energy (DOE). The purpose of the study was to identify and assess a baseload CSP system that can compete against conventional baseload power plants. In other words, such a system needed to be firmly dispatchable any time of the day or night 24/7 365 days per year and do so at a competitive cost of power.

Wilson chose to assess the potential for Brayton solar power towers. The reason was that the intrinsic design of the only Brayton system on the market, from Aora[5], was based on using high-pressure air throughout. However, it was not gaining market acceptance because it was expensive and offered no thermal storage for off-sun power generation. No studies of low-pressure Brayton power tower systems had

[1] See Commercializing Standalone Thermal Energy Storage, January 8, 2016 http://www.renewableenergyworld.com/articles/print/volume-18/issue-110/features/thermal-renewable-energy/commercializing-standalone-thermal-energy-storage.html and The threat of Electrical Storage to CSP, November 2014 http://www.csptoday.com/csp/pdf/TESvsBatteriesENG.pdf

[2] Wilson Solarpower Corporation "Brayton-Cycle Baseload Power Tower CSP System" Final Report, Phase 1, Award EE003587, US Department of Energy, 2011

[3] LCOE is Levelized Cost of Electricity, a measure of cost to compare the value of different methods of electricity generation on a comparable basis.

[4] The team included DLR (the German Aerospace Center), WorleyParsons, Oak Ridge National Laboratories, Brayton Energy, SolaFlect, EZKlein, the NorPro division of Saint-Gobain

[5] See http://aora-solar.com/about-aora-solar/

been conducted before, because assumptions were that low-pressure was not possible due to the temperature limitations, <850ºC, of materials used in heat exchangers. Low-pressure systems require a heat exchanger that can operate >970ºC. Wilson Solarpower had been developing such a heat exchanger when it discovered its application to Brayton power towers. It then conceived the low-pressure system and won DOE funding to assess and develop it.

The conclusion of the Study was to propose a low-pressure system configuration with a near-ambient-pressure receiver and thirteen (13) hours[6] of dry thermal energy storage, e.g., small ceramic pieces or cheap firebrick. Analyses showed that such a system had the potential to meet or exceed DOE's various performance targets for a 100 MW or greater CSP power plant. The two key DOE targets included: 1) a capacity factor of at least 75%, of which >85% would be solar with <15% from fuels; and LCOEs <9¢/kWh. Indeed, LCOEs under 6¢/kWh may be possible with further development and widespread deployment. The Study determined that the best module size to develop initially is 300-400 kWe.

The Feasibility Study outlined a very plausible path by which, based on the team's modeling of its performance and assessment of its costs, the concept could become among the world's lowest cost ways to produce power. In addition, it showed that this concept could also be among the most reliable and flexible approaches to power generation – it could actually make the grid more stable, rather than less, as most other approaches do, including PV, wind, first generation Rankine cycle CSP, and conventional power generation.

DOE then funded the development of key breakthrough components, including an innovative air-heating, near-ambient pressure solar receiver and a simple, low-cost, ambient pressure thermal energy storage system. Today, Wilson Solarpower has sold its inventions to 247Solar Inc., which in turn is commercializing the technology in various locations around the world.

2. WHAT IS A MODULAR BASELOAD BRAYTON[7] POWER TOWER?

A typical Brayton power tower system has four key elements, see Figure 1.

1. A conventional tower ~30-40 m tall
2. A field of heliostats that track the sun, reflecting sunlight onto an air-heating solar receiver on the tower;
3. An air-heating solar receiver that converts that sunlight to heat and transfers it to compressed air, which powers the turbine; and
4. A plug-and-play microturbine package (turbine, compressor, recuperator, generator, power electronics) powered by the solar heat and, possibly also, co-fired with fossil fuel or biofuel.

A Brayton CSP system can supply power reliably, any time of the day or night, regardless of whether the sun is shining. It is able to do this because the turbine of each module can operate either entirely on the sun, entirely on fuel, or on a combination of both when the heat from the sun needs boosting. As a result of being able to operate independently of the weather, Brayton systems, unlike wind or PV, can be operated like a conventional power plant. Brayton systems can offer excellent reliability and dispatchability based on the inherent redundancy that exists when multiple modules are deployed as a single power plant.

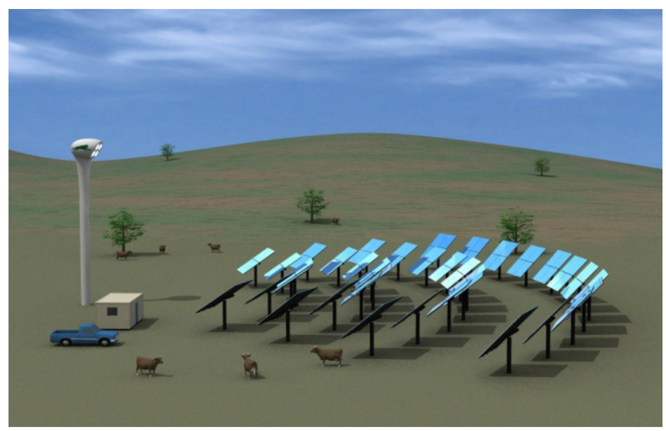

FIGURE 1. A TRADITIONAL BRAYTON POWER TOWER SYSTEM (WITHOUT STORAGE)

Such modular CSP systems also offer continuous industrial-steam-grade heat for a wide variety of applications, such as for absorption chilling (e.g., for refrigerating farm crops); water purification; crop drying; etc. Systems can be stand-alone off-grid or be connected to a grid. Most of the system components use proven, off-the-shelf technologies and can be made in local markets for job creation.

3. WHAT ARE THE RECENT TECHNICAL ADVANCES OF MODULAR BASELOAD BRAYTON POWER TOWER?

[6] 13 hours was required to achieve the Doe target of 75% capacity factor with 85% of the power derived from solar.
[7] "Brayton" refers to the Brayton thermodynamic cycle of an engine. A steam turbine is based on the Rankine cycle; a jet engine is based on the Brayton cycle.

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The principal constraint of the traditional approach to Brayton power towers is the size limitation of systems, which is imposed by the size constraints of their solar receivers. The reason for their size constraint is that they operate at the same high operating pressures of the turbine, i.e., 4 to 12 bar. This means that they must be designed as pressure vessels. A key element of the receiver is the window aperture that faces the heliostat field to let the light in. This same window must contain the high-pressure air. The result is that the window is under substantial pressure while extremely hot and so must be curved. See Figure 2.

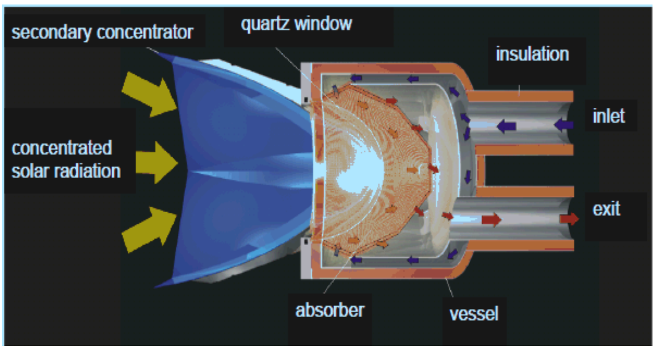

FIGURE 2. CROSS SECTION OF TRADITIONAL HIGH-PRESSURE "VOLUMETRIC" AIR-HEATING SOLAR RECEIVERS, THIS ONE DEVELOPED BY DLR.

As a result of the pressures, the window diameter is constrained to be less than 1 meter and more typically, 60-80 cm (22-29 inches). Coupled with a 4X secondary concentrator to expand the effective area of the aperture through reflection, such a receiver can power a 100kWe turbine when the sun is shining but offers no additional heat for storage to generate off-sun power. Active cooling systems are required for the concentrator, for the window frame, and for the window itself to maintain their integrity during operation. See Figure 3.

Typically, the pressurized air from the turbine's compressor enters the combustor after being first pre-heated in the recuperator. In a high-pressure Brayton power tower system, that compressed air from the recuperator is instead diverted to the solar receiver before entering the combustor, effectively replacing the fuel. It seems simple enough, but the result is that the receiver must be designed as a pressure vessel, as described above, with three active cooling systems that must never break down during operation.

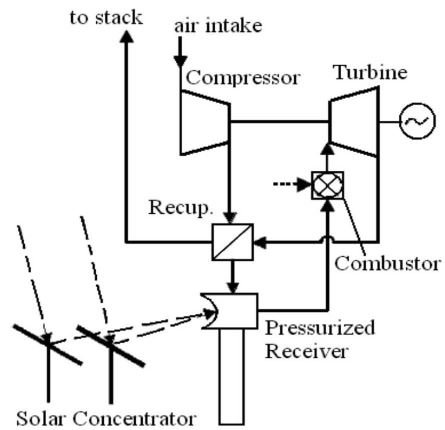

FIGURE 3. SCHEMATIC OF A TRADITIONAL HIGH-PRESSURE BRAYTON CYCLE POWER TOWER SYSTEM (COURTESY OF DLR).

Low-pressure breakthrough

The technical advance in Brayton power towers assessed during the DOE-funded Feasibility Study eliminates the severe limitations caused by high-pressure by modifying the system configuration to enable it to run entirely on near-atmospheric pressure. See Figure 4. The principal system changes from the high-pressure system are a high-temperature heat exchanger, a low-pressure solar receiver, and a low-pressure dry storage system, all resulting in much larger power output with thermal storage for 24/7. Blue lines are normal operation; red lines are storage discharge mode. Green lines show storage charging mode.

The new heat exchanger transfers the heat from the exit air of the solar receiver to the compressed air, which then enters and powers the turbine. With this approach, ambient pressure air from the turbine's exhaust passes through the receiver. No longer having to contain high-pressure air, the aperture of the solar receiver can be a larger diameter without bursting. Where the window aperture diameter of the high-pressure solar receiver is constrained to be less than 1 meter and more typically, 60 cm, the receiver aperture of the low-pressure system is easily 2 meter and may be able to reach 5 meters with further development. Instead of powering just 100kWe during the day, the 2-meter system can power 300-400kWe during the day plus another 10-15 hours at night. A 5-meter system could power more than 2 MWe 24/7. Where high-pressure receivers require three active cooling systems, the low-pressure receiver is completely passive – no active cooling systems and no moving parts.

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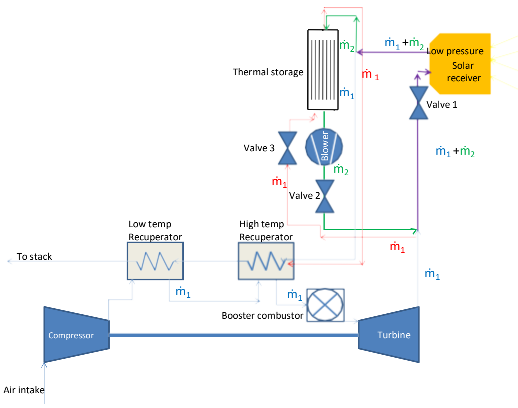

FIGURE 4. SCHEMATIC OF A LOW-PRESSURE BRAYTON SYSTEM CONFIGURATION.

High temperature heat exchanger breakthrough

The principal breakthrough leading to the low-pressure concept was the introduction of a high-temperature heat exchanger. >970ºC, into the system configuration. This heat exchanger transfers the heat from the exit air of the solar receiver to the compressed air, avoiding the passage of high-pressure air through the receiver. With this approach, ambient pressure air from the turbine's exit passes through the receiver, enabling larger receiver diameters.

The introduction of a new high-temperature heat exchanger (HX) into the Brayton power tower cycle was not possible until recently when Haynes International introduced a line of super alloys, including HAYNES® 214® alloy (UNS N07214). This is a nickel-chromium-aluminum-iron alloy, designed to provide the optimum in high-temperature oxidation resistance, while at the same time allowing for conventional forming and joining. It is intended principally for use at temperatures of 1750°F (955°C) and above. The exhaust temperature from the solar receiver is 970ºC, just above the lower figure.

The key performance criterion for such a high-temperature HX is its operating life. Power plants operate for 20 years or more, or ~100,000 hours, assuming a capacity factor of the system of 75% (DOE's targets). To verify that Haynes 214 could perform adequately over tens of thousands of hours, Oak Ridge National Laboratory (ORNL) cycle tested the material. ORNL is one of the United States' foremost materials testing laboratories. The purpose of this testing was to determine the likely operating life of Haynes 214 as it is used in 24/7 solar Brayton systems and, in particular, whether its operating life could approach 100,000 hours. The approach was to conduct accelerated testing. To do this, ORNL cycled a variety of foil thicknesses and types likely to be used through the same temperature extremes that the system will experience, i.e., between ambient and 970ºC. It then characterized the alloy degradation and used best practices to extrapolate the results of that behavior to longer operating times.

ORNL completed cycle testing on various foil thicknesses between 2-10mil (60-260µm) from ambient temperature to 950°C, to 1000°C, and to 1050°C. Over the course of 12 months, they conducted 800 10-hour thermal cycles in dry air for each foil. Aluminum loss of the material, the basis for its degradation, was measured after exposure using EPMA (Electron Probe Micro-Analysis), and aluminum consumption rates were calculated based on the difference between the starting aluminum content and the remaining aluminum content. At 1000°C and 1050°C, the rate was sub-linear with time but not enough data was collected to precisely determine the relationship with time. ORNL concluded [8] that if the reaction rate remains parabolic for 100,000hr (highly unlikely), a 6mil foil may operate for ~100,000hr at 950°C. If the reaction is linear (worst case), a 6mil foil will operate for ~25,000hr at 950°C. Extrapolating to lower temperatures with a linear reaction showed a 6mil foil would likely survive 100,000hr at 900°C.

247Solar took these results to be more positive than what otherwise might be suggested by the data for four key reasons. The first reason is that actual operating experience with heat exchangers is that they perform longer than cycle testing of the metals would suggest. The second is that the inlet temperature of the air from the solar receiver and from the thermal energy storage to the HX will rarely be above 970ºC but more often than not will be below it.

The third reason is that temperature cycling tends to deteriorate most materials, especially metals, more quickly than if they maintain constant temperature. Yet the testing assumed that the 247Solar Plant shuts down completely at least once per day, which does indeed temperature-cycle the metal. However, daily shutdown is not likely, because in most applications the 24x7 system will operate around the clock, and the metal will not cool down every day. Finally, the fourth reason to expect longer operating life than the data may suggest is that it is standard operating procedure to extend the lives of heat exchangers by reversing airflows through them roughly halfway through their projected operating lives. Typically, this is done by physically turning the HX 180 degrees, such that the exit portion of the HX that had

[8] See Assessment of High Temperature Durability of Alloy 214 Foil, November 2013, B. A. Pint, Materials Science and Technology Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6156

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experienced the lower temperatures during initial use, and so is the least degraded, becomes the inlet portion, and the previous inlet portion that had experienced the 970ºC inlet temperatures is now receiving the lower exit temperatures.

Low-pressure solar receiver breakthrough

The second major technical breakthrough is the low-pressure solar receiver. As a reminder, Figure 2 is a cross section of the DLR high-pressure receiver. Figure 5 represents the design of the first low-pressure solar receiver based on this DLR high-pressure receiver design. The major difference is that the air entering this receiver is at or near ambient pressure, i.e., low pressure, rather than the compressor air, which is high pressure. In this design, the air flows from the turbine and/or the thermal storage system around the perimeter of the receiver. It then is pre-heated by flowing through the Inconel wire mesh inlet absorber at the front of the receiver near the window, which is made of high-temperature quartz silica glass. The air is then further heated by passing through the silicon carbide foam-like absorber, and exits through the rear. In a low-pressure configuration (a few millibars), the window needs only to be slightly curved. For an ambient pressure configuration, the window can be made of multiple panes, the configuration of which is independent of pressure considerations. In an initial prototype design the window diameter is 2 meters, compared with 60cm for the DLR high-pressure design. See Figure 6 for photos of the first prototype 2-meter-diameter low-pressure receiver.

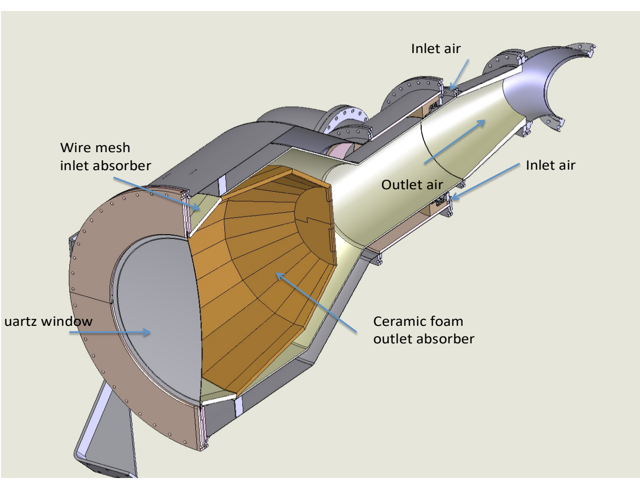

FIGURE 5. 3D CROSS-SECTION OF THE FIRST LOW-PRESSURE SOLAR RECEIVER.

FIGURE 6. THE FIRST PROTOTYPE 2-METER-DIAMETER LOW-PRESSURE RECEIVER: FULLY ASSEMBLED ABSORBER, TOP; OUTER HOUSING OF THE RECEIVER HELD BY A STEEL FRAME, BOTTOM.

Low-pressure thermal storage system

Heat storage is an integral element of CSP systems. The storage material is heated, or charged, during the day by excess solar heat (that which is not used during the day by the system's turbine) and is discharged to power the turbine at night or during cloudy weather. CSP systems typically use molten salts to store this heat, and the hot salt is used to turn water to steam to drive a steam turbine. However, the Brayton thermodynamic cycle is air-driven, not steam-driven. And historically, several applications in various industries that require heat storage also are air-driven. As a result, there is a long history, more than 100 years, of using air both to charge the heat storage and to discharge it. This has been accomplished by passing the hot air through a container filled with small pieces of solid material, around which the air flows. Heat is transferred into and out of the material, the rate depending on the difference in temperature between the air and the material as well as the configuration and composition of the material. Existing concepts include solutions for the

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steel industry (“Cowper” stoves), the glass industry, and some air purification systems. Each approach has its specific merits and drawbacks and can be adapted to the needs of a particular application. Examples of solid storage media include billiard-ball-sized pieces of ceramic (packed beds), honeycomb ceramics, firebricks, and basalt (pebble beds). The general approach is sometimes referred to as regenerative heat storage. See Figure 7.

This storage approach represents a self-evident choice for hot air Brayton power towers. During the day, the solar-heated air flows through a container of solid storage medium with high void fraction (lots of space between the material), which absorbs the heat to be stored. Reversing the flow direction discharges the storage to power the turbine at times of insufficient solar radiation.

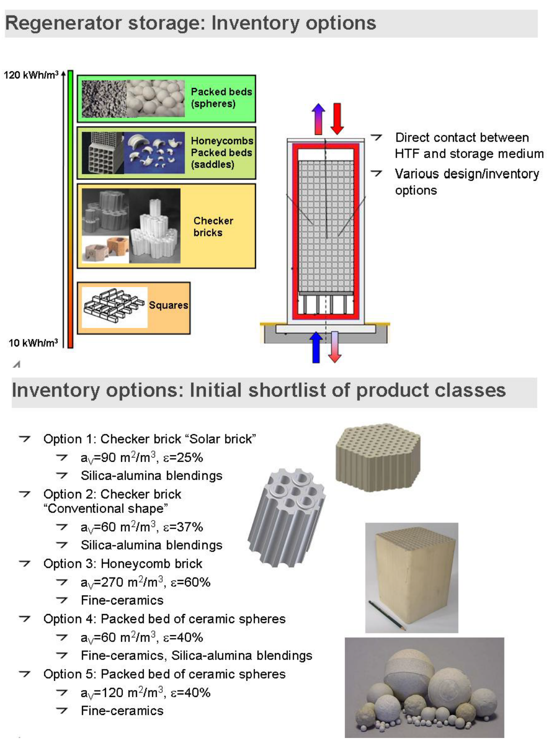

FIGURE 7. REGENERATIVE STORAGE CONFIGURATION, TOP, PROPERTIES OF HEAT STORAGE MEDIA OPTIONS, BOTTOM (COURTESY OF DLR).

In general, heat storage media options with a large heat transfer surface per unit volume offer favorable thermal performance. However, care must be taken in the selection of the media because mechanical stability, durability, cost, and container design all impact the best choice. The applicability and merits of each option depend on the specific design and operating conditions and must be assessed.

Internally applied, high-temperature insulation protects the container, typically steel, from the contained heat while also reducing heat loss. Here, protective and insulating material candidates include, among others, lightweight refractory bricks and ceramic fibers. Typically, combinations of different materials are used. Concrete and related products do not survive at the high operating temperatures of Brayton power towers, >900ºC+.

The heat storage capacity is based on early design decisions for an initial low-pressure Brayton power tower system:

1. The initial solar receiver size of 2 meters in diameter
2. Use of commercially available turbines of 400 kWe
3. Requirement for approximately 13 hours of storage (to achieve DOE’s targeted capacity factor of at least 75%, with at least 85% of the power being provided by solar)

Powering a 400-kWe turbine for 13 hours produces about 3900kWh. After considering heat exchanger and turbine efficiencies as well as the parasitic requirements of the blower and piping system for moving the air, the storage system must be sized to deliver ~16,000kWhth over the course of 13 hours.

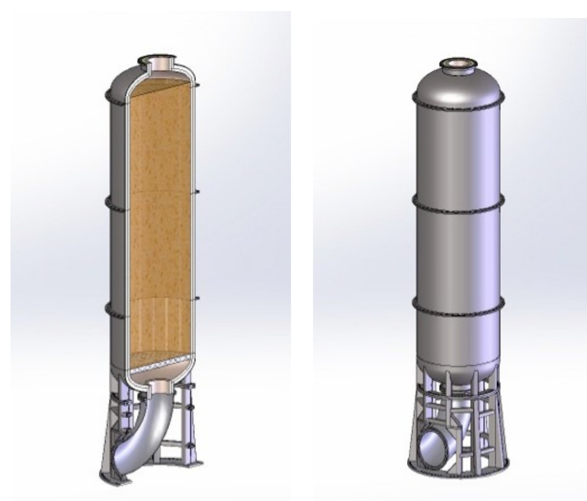

FIGURE 8. CROSS SECTION AND OUTSIDE VIEW OF THE CURRENT DESIGN OF THE 247SOLAR THERMAL STORAGE CONTAINER.

Due to its volume and weight, the thermal storage is located on the ground and separate from but adjacent to the tower. The storage media material is in the silica-alumina family. All-factory production to reduce costs can be achieved with a tank design of steel made in 3-meter sections, each no more than 4

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meters in diameter (respecting road-transport size constraints), insulated in the factory with an insulating refractory material, and shipped to the site. There the sections can be erected on a foundation and filled with ceramic thermal storage media. Such systems would be about 8-10 meters tall and require three or four such sections. Figure 8 shows an example tank configuration.

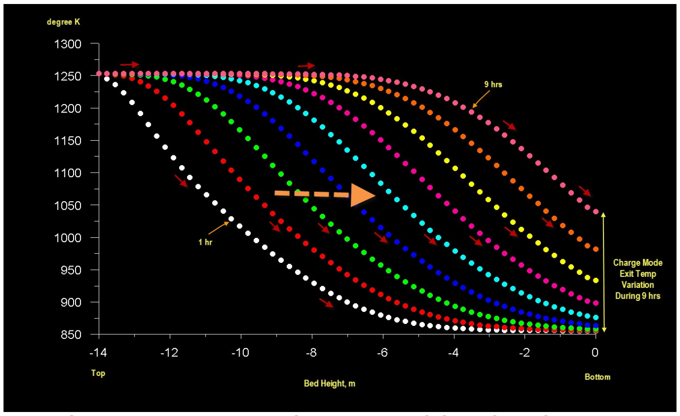

FIGURE 9. THERMAL GRADIENT CONTOURS IN THE TANK DURING 8-9 HOURS OF CHARGING. RECEIVER-HEATED AIR FLOWS FROM THE TOP OF THE TANK (LEFT) TO THE BOTTOM (EXITING RIGHT). THE HEIGHT OF THE TOWER IS IN METERS ON THE X AXIS. TO CONVERT TEMPERATURES FROM KELVIN TO CELSIUS (Y AXIS) SUBTRACT 273.

Hot air from the receiver enters the top of the storage at about 970ºC and exits the bottom about 300ºC cooler. As it flows around the ceramic media it gradually heats it over the course of the day. See Figure 9 for example thermal gradients over the course of a sunny day. To power the turbine at night, the flow is reversed, with the turbine exhaust air entering the bottom at about 650ºC and exiting the top about 300ºC hotter to return to the high-temperature heat exchanger, where it heats the turbine's compressed air before it enters the turbine

In low-cost labor regions, alternative designs could be considered. For example, a container of firebrick built on site of brick, rather than steel, is also a possibility. Such a non-steel tank solution for the container, of course, requires hand labor to build or assemble the container, to line it with several layers of insulating kiln brick or equivalent, and then to lay firebrick or equivalent inside the container in a configuration that allows the air to flow between them. In theory, basalt rock also could be used. It could be considered based on geographical availability and pre-testing of the particular basalt to make sure that it can survive cycling at high temperatures.

4. AN EXAMPLE DESIGN OF A MODULAR BASELOAD BRAYTON POWER TOWER

Figure 10 is an example design of a modular baseload Brayton power tower that is called the 247Solar Plant™. Its solar field of heliostats covers about 4 acres, ~16 million m^2. The low-pressure air-heating solar receiver has a 2-meter diameter, sits on a 35-meter tower and powers a 300-400kWe turbine. The thermal storage system (located inside the tower) powers the Brayton cycle turbine at night for 10-15 hours.

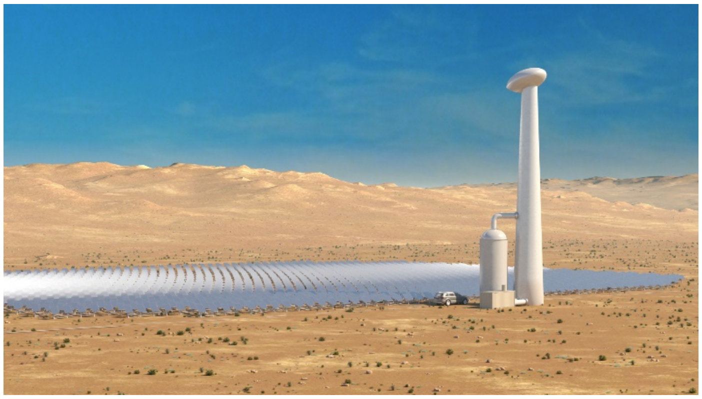

FIGURE 10. AN EXAMPLE DESIGN OF A MODULAR BASELOAD BRAYTON POWER TOWER CALLED THE 247SOLAR PLANT™.

System performance

Solar power towers like 247Solar Plants are point-focusing systems integrated with a multitude, or field, of two-axis tracking mirrors (heliostats) that concentrate solar radiation on top of a central tower where a receiver is installed that absorbs the incoming concentrated radiation. The receiver heats air that drives a gas turbine and/or charges thermal storage.

Due to this complex optical design, a high number of degrees of freedom exist. The power output of every single heliostat depends on the current sun position, the heliostat's position relative to the tower, and blocking and shading from neighboring heliostats.

Thus, the layout and optimization of solar power towers is a complex problem that is preferably analyzed with computer-based simulation. DLR conducted the analysis and used two primary modelling tools: HFLCAL™ and EBSILON™. The first is used to calculate the optics and estimate how much solar energy will be available from the solar receiver for every hour of the year. The second program is used to simulate the operation of the power plant, with the solar energy from the receiver as input. See Figure 11.

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1. HFLCAL was used to determine the output of the “solar” components (heliostat field, tower and receiver);
2. EBSILON determined the output of the air transportation system, the thermal storage system, and the power cycle. Performance curves for the storage were generated by special modelling tools and fed to the EBSILON model.
3. The data flow between the simulation environments as well as the post-processing was managed using Excel.

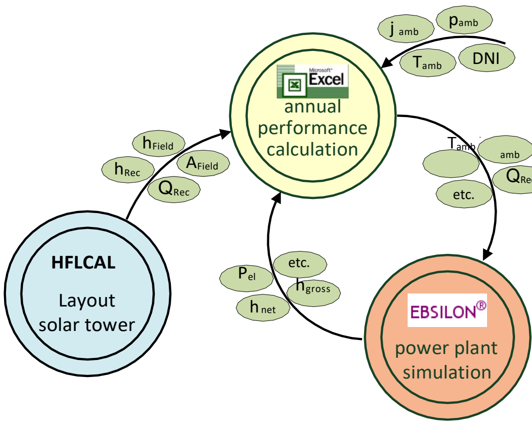

FIGURE 9. THE ANNUAL OUTPUT, OR PRODUCTIVITY, OF THE THREE POWER PLANT CONCEPTS THAT WERE ANALYZED BY DLR REQUIRED A COMBINATION OF HFLCAL, EBSILON, AND EXCEL (COURTESY OF DLR).

As already described, HFLCAL is used for the design optimization of tower systems and heliostat fields. Economic optimization of the solar components is performed on an annual basis. A certain number of characteristic time points that represent statistically the entire year are used to determine the optimum. The complete thermal loss chain at the receiver is taken into account: radiation losses, reflection losses and convective losses. Thus, the net absorbed energy can be calculated. The results are the physical dimensions of the solar components, an hourly resolution of the field efficiency, receiver efficiency and the absorbed receiver energy for the 21st of each month. Thus, the derivation of hourly resolved efficiency and receiver power for an entire year is possible.

In EBSILON, the hourly data of solar field and receiver performance is used to calculate the performance of the entire system. Each of the 8760 hours per year is simulated sequentially in order to integrate the yearly performance results. Each component is modelled by its characteristics in both design and part load situations.

The third model environment is Excel. It couples solar design results with local meteorological data to set up hourly resolved input data for the year. By using Visual Basic scripts, the data transfer to and from EBSILON is realized. Finally, the overall results are evaluated and presented in Excel.

Table 1 summarizes the results of the productivity studies conducted by DLR for three different systems, including the one described here, the low-pressure 300kWe system with 13 hours of thermal storage (LP300). The model assumed full, not partial, power operation of the turbine at all times. As the discharge temperature of thermal storage drops, this operation strategy requires fuel to be added to keep the inlet temperature to the turbine at design point. The result is relatively high fuel input for the two low-pressure cases (including LP1700, a 1700kWe turbine system), even without running any fuel-only hours. It would be possible to further explore the option to operate the turbine in part-load conditions for full utilization of the stored solar energy and to lower the fuel portion. The high-pressure system (HP300) uses less fuel because the calculations for the storage media used honeycomb matrix material as the storage media instead of solar bricks, an extremely expensive option, however.

TABLE 1. PRODUCTIVITY RESULTS FOR THE THREE SYSTEM APPROACHES.

		HP300	LP300	LP17 00
Energy reaching the solar field (DNI)	[GWh]	10.67	10.00	56.81
Energy from the field reaching the tower	[GWh]	5.82	5.88	32.66
Energy leaving the receiver (if no dumping)	[GWh]	4.69	4.7 4	26.7 5
Energy from the receiver actually used	[GWh]	4.66	4.34	24.27
Dumped energy	[GWh]	0.04	0.40	2.48
Energy from fuel	[GWh]	0.7 2	1.7 9	7.39
% energy dumped		0.8%	8.5%	9.3%
Energy from solar and fuel to the power block	[GWh]	5.37	6.13	31 .66
Electricity used for the power block	[GWh]	0.00	0.00	0.00
Electricity used for the blower	[GWh]	0.06	0.18	0.7 1
Total parasitic electricity consumption	[GWh]	0.06	0.18	0.7 1
% parasitic loss in gas turbine cycle		3.4%	8.7 %	6.1 %
Electricity produced	[GWh]	1.7 3	2.02	11.7 7
Net electricity to the grid	[GWh]	1.68	1.85	11.05
"Name plate power" for the turbine at design poi	[kW]	255	251	147 0
full load hours (reference gross)	[hour/year]	657 0	7359	7519
Field efficiency		54%	59%	57 %
Receiv er efficiency		81 %	81 %	82%
Gross turbine efficiency		32%	33%	37 %
Net turbine efficiency		31 %	30%	35%
Net electrical efficiency including ORC		36%	35%	40%
Net DNI to electricity including ORC		18%	21 %	22%
Spec. Heat consumption (fossil)	[kJ/kWh]		3497	2407
Capacity factor		**75%**	**84%**	**86%**
Capacity factor solar		**65%**	**59%**	**66%**

LCOEs

Ultimately, the most important question is the cost of the electricity that a 247Solar Plant produces. This can be done inputting the performance results, the weather data, the CAPEX and OPEX of the system, and a variety of other input parameters into the Solar Advisor Model (SAM), developed by NREL (the US National Renewable Energy Laboratory). DOE established the other inputs into the SAM model and are listed in Table 2. WorleyParsons used all of the inputs to SAM to calculate LCOEs.[9]

The DOE Study team conducted an in-depth analysis of CAPEX and OPEX, both initially and longer-term with volume production. It used a conservative approach to project

[9] Solar Advisor Model (SAM) was developed by NREL (the National Renewable Energy Laboratory) as a tool to estimate costs and performance for solar plants, particularly LCOEs

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declining future manufacturing costs based on industry-accepted cumulative costs learning curves. With 85-90% of the system's costs in factories versus just 10-15% on site, the team estimated cost reductions of 5-7% for each doubling of overall cumulative production.

TABLE 2. INPUTS INTO THE SAM MODEL THAT WERE ESTABLISHED FOR USE IN THE FEASIBILITY STUDY FUNDED BY THE US DOE.

Financial Assumptions	Value	Comments
Analysis Period	30 years	
Inflation Rate	2.0 %	
Real Discount Rate	8.0 %	
Federal Tax	34%/year	NETL 2007
State Tax	6%/year	NETL 2007
Property Tax	0	
Sales Tax	7.75%	
Insurance	0.50%	
Loan term	20 years	
Loan Rate	8.00 %	
Loan (Debt) fraction	50.0%	NETL 2007
Federal Depreciation Rate		MACRS Mid-Quarter Convention for solar
State Depreciation Rate		MACRS Mid-Quarter Convention for solar
PPA Escalation Rate	1%	
Minimum Required IRR	12.0%	NETL 2007
Minimum Required Debt Service Coverage Ratio (DSCR)	1.40	
Incentives: Federal Investment Tax Credit (ITC)	10%	Applied to Solar cases
Cost assumptions	**Value**	**Comments**
Fossil backup fuel cost	$6.75/MMBTU	NETL 2007
Fossil fuel escalation rate (above inflation)	3%/year	DOE/EIA-0383 (2009) http://www.eia.doe.gov/oiaf/aeo/index.html
Contingency	10%	
Engineer, Procure, Construct	16%	SAM default
Project, Land, Misc.	3.5%	SAM default
Percentage of Direct Costs subject to Sales Taxes	80%	SAM default

The LCOE results by WorleyParsons are shown in Figure 11. The initial cost of ~$6000/kWe for a US-deployed system yields an initial LCOE between 11 and 12 cents. Based on cumulative cost learning curve analyses, after a total of 2 GW of factory production and deployment, CAPEX is reduced to under $4000/kWe and LCOEs have fallen to 8 cents. Like PV and wind, costs continue their decline with continued mass production. Of course, costs are expected to be lower in many countries such as India and China.

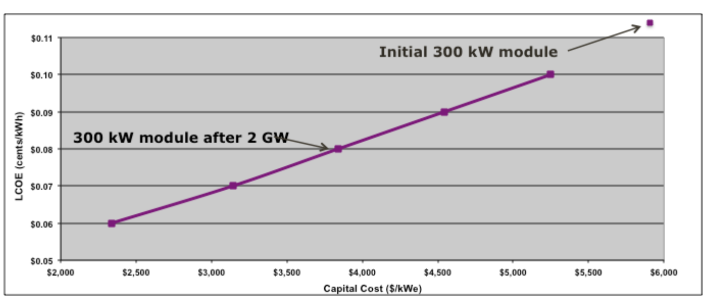

FIGURE 11. LCOE RESULTS FOR THE US FROM THE SAM MODEL EXECUTED BY WORLEYPARSONS FOR A 300KWE LOW-PRESSURE BRAYTON POWER TOWER.

CONCLUSIONS

A successful transition to a low carbon future requires that power be generated all of the time, 24/7, not just when the sun is shining (photovoltaics), or the wind is blowing (wind machines), or when there is sufficient biomass or biofuel.

This technical paper summarizes an Engineering and Cost Feasibility Study funded by the US Department of Energy as well as presents a new breakthrough power generation product based on the Brayton power tower system called 247Solar Plants™.

Such modular concentrated solar power (CSP) systems include thermal energy storage systems and use simple off-the-shelf microturbine packages (using hot air, i.e., no water/steam) that can provide such power dependably and affordably 24/7. When the sun shines, the system's hot air drives the turbine and simultaneously stores heat for later use.

Like wind machines, this modular CSP system is scalable from a few hundred kilowatts to 100s of megawatts. As a distributed 24/7 power source, it also offers about 1,500,000 BTU/hr. of industrial grade process heat for a wide variety of uses (e.g., absorption chilling to refrigerate farm products; water purification; crop drying; etc.) with 24x7 operation.

The major technical advance in Brayton power towers studied during the DOE-funded Study eliminates the severe limitations caused by the high-pressure system configuration of previous systems by modifying it to make it low-pressure through the introduction of a breakthrough high-temperature, >970ºC, heat exchanger at the solar receiver exit. This in turn led to a breakthrough in the solar receiver itself, transforming a severely size-limited, complicated, and costly high-pressure receiver to a significantly larger (7-25% larger by thermal output), simple, low-cost ambient pressure receiver. This in turn led to the introduction, analysis, and preliminary design of a simple, low-cost, highly efficient thermal energy storage system. It was determined that the best module size to develop initially is 300-400 kWe.

The principal conclusion of the DOE-funded Study is that such a system may be able to achieve the Study's two key DOE targets: 1) a capacity factor of at least 75%, of which >85% would be solar with <15% from fuels; and LCOEs <9¢/kWh (US costs). LCOEs under 6¢/kWh may be possible with further development and widespread deployment.

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- Oak Ridge National Laboratory, testing a high-temperature alloy for use in the system's heat exchanger.
- Brayton Energy, co-developing the solar receiver.
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- Keramikblech, development and fabrication of the ceramic absorber structure.
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REFERENCES

Becker, M., Bohmer, M. (Eds.), 1989. GAST—The Gas-Cooled Solar Tower Technology Program. Proceedings of the Final Presentation. Springer-Verlag, Berlin.

Buck, R., Lupfert, E., Tellez, F., 2000. Receiver for solar-hybrid gas turbine and CC systems (Refos). In: IEA Solar Thermal 2000 Conference, 8–10 March 2000, Sydney, Australia.

Buck, R., Brauning, T., Denk, T., Pfander, M., Schwarzbozl, P., Tellez, F., 2002. Solar-hybrid gas turbine-based power tower systems. Journal of Solar Energy Engineering. Transactions of the ASME 124 (February).

Sugarmen C, Ring A, Buck R, Uhlig R, Beuter M, Marcos M J, Fernandez V. Solar-Hybrid Gas Turbine Power System, Proc. 11th SolarPACES Int. Symposium on Concentrated Solar Power and Chemical Energy Technologies, September 4-6, 2002, Zürich, Switzerland.

Schwarzbözl P, Schmitz M, Pitz-Paal R, Buck R. Analysis of Solar Gas Turbine Systems with Pressurized Air Receivers (REFOS), Proc. 11th SolarPACES Int. Symposium on Concentrated Solar Power and Chemical Energy Technologies, September 4-6, 2002, Zürich, Switzerland.

Sugarmen C., Ring A., Buck R., Heller P., Schwarzbözl P., Tellez F., Marcos M. J., Enrile J.. Solar-Hybrid Gas Turbine Power Plants – Test Results and Market Perspective. Proc. ISES Solar World Congress 2003, June 14-19, 2003, Göteborg, Sweden 46.

Arik Ring, Chemi Sugarmen, Joseph Sinai, Gas Turbine Solarization – Development and Testing, Proc. 3rd Israeli Jet Engine Symposium, November 11, 2003, Haifa, Israel.
Heller, P., Pfander, M., Denk, T., Tellez, F., Ring, A., 2005. Test and evaluation of a solar powered gas turbine system. Solar Energy, doi:10.1016/j.solener.2005.04.020.

Amsbeck, L., et al. Development of a tube receiver for a solar hybrid microturbine system, Proc. SolarPACES 2008, Las Vegas, USA; 2008.

Schwarzbözl, P., Pitz-Paal, R., Schmitz, M. Visual HFLCAL - A Software Tool for Layout and Optimization of Heliostat Fields, Proc. SolarPACES 2009, 15.-18.September, Berlin, Germany; 2009.

Giuliano, S., et al. Analysis of solar-hybrid gas turbine cogeneration systems with absorption chillers in hot and dry climates, Proc. SolarPACES 2009, 15.-18.September, Berlin, Germany; 2009.

Amsbeck, L., et al. Test of a Solar-hybrid microturbine system and evaluation of storage deployment, Proc. SolarPACES 2010, Perpignan, France; 2010.

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