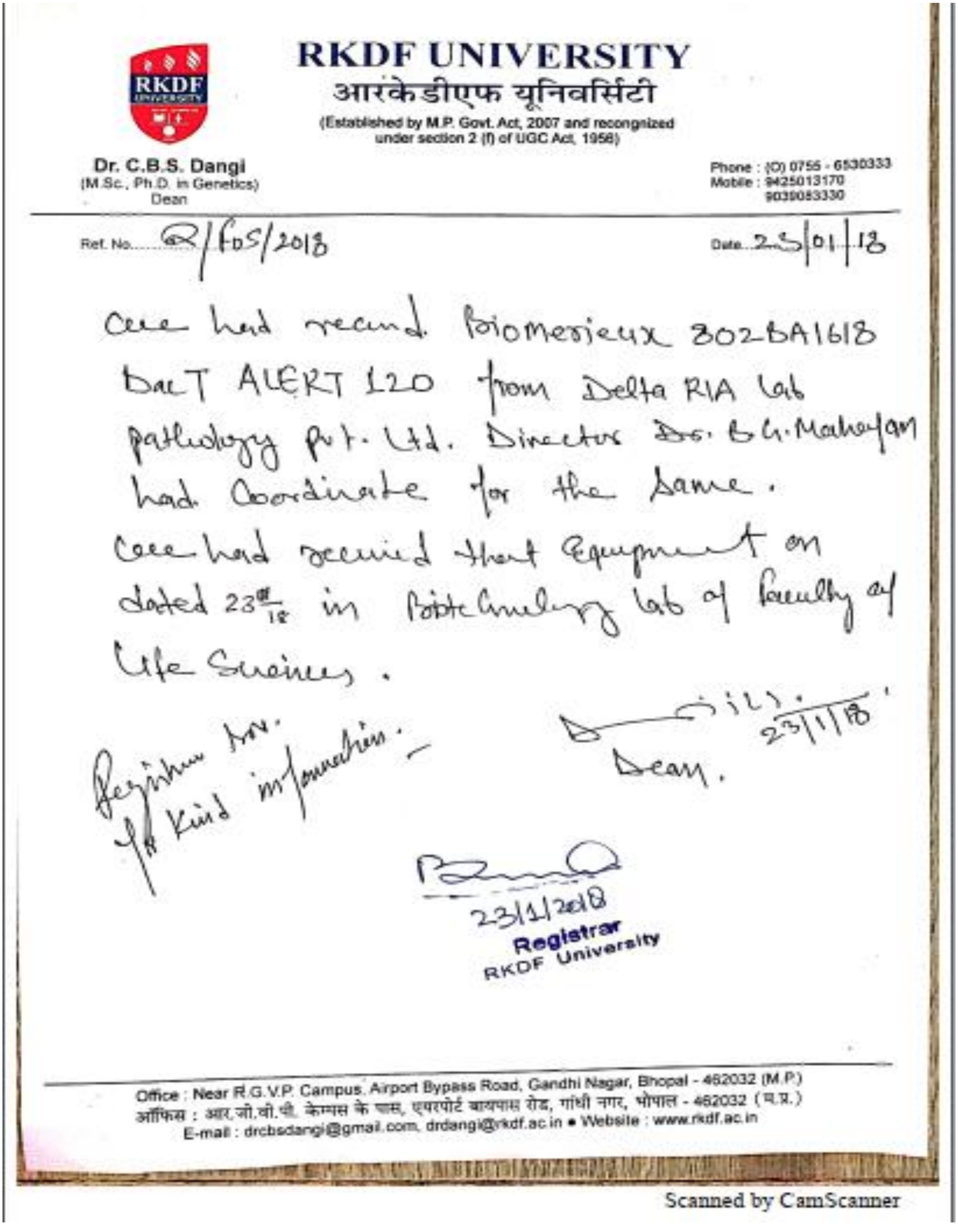
INDEX

3.2.1 Extramural funding for Research



RKDF UNIVERSITY
आरकेडीएफ यूनिवर्सिटी
(Established by M.P. Govt. Act, 2007 and recongnized under section 2 (f) of UGC Act, 1956)

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Ref. No. R/FoS/2018

Date 23/01/18

We had recvd. Biomerieux 302BA1618 BacT ALERT 120 from Delta RIA lab pathology Pvt. Ltd. Director Dr. B.G. Mahajan had Coordinate for the same.

We had received that Equipment on dated 23/1/18 in Biotechnology lab of faculty of Life Sciences.

Registrar Sir.
for kind information.-

23/1/18.
Dean.

23/1/2018
Registrar
RKDF University

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3.2.1.Extra-Mural Funding From Non-Government Organization

M/S DELTA RIA PATHOLOGY PVT.LTD.BHOPAL–Rs. 22.00Lacs worth

BecT Alert120 : Blood Culture Unit

DONATED TO RKDF
UNIVERSITY BHOPAL

Best Practices in Blood Culture Collection

Fluorescent Technology in the BD BACTEC™ Automated Blood Culture System

Detection of blood-borne pathogens is one of the most important functions of the microbiology laboratory. Cultures of blood are essential in identifying bacteria responsible for bacteraemia and sepsis. Several automated blood culture systems are available commercially nowadays. The advantages of all such systems are elimination of the need for blind subculture and the shortening of the usual incubation period of five to seven days. It is very important for the hospitals to choose a reliable system that can give them the best outcome in terms of turnaround time and improves patient outcome by decreasing morbidity and mortality .

The **BD BACTEC™ Automated Blood Culture System** utilizes fluorescent technology in detecting the growth of organisms in the blood culture bottles. When microorganisms are present in the cultured vials, they metabolize nutrients in the culture medium, releasing carbon dioxide into the medium. A dye in the sensor at the bottom of the culture bottles will react with CO_2. This modulates the amount of light that is absorbed by a fluorescent material in the sensor. The instrument's photo detectors measure the level of fluorescence, which corresponds to the amount of CO_2 released by the organisms. Then the measurement is interpreted by the system according to preprogramed positivity algorithms.

The figure next explains how the **Fluorescent Technology** works on the BACTEC™ systems.

❶ Organism metabolic activity releases CO_2 ...

❷ Which reacts with dye in vial sensor.

❸ LED activates fluorescent material in sensor. Fluorescence is modulated by dye in the sensor.

❹ Photo detector reads fluorescence.

❺ Raw data from detector is analyzed by row board ...

❻ And positivity analysis is performed.

❼ Positive vial is announced by audible alert, onscreen indications, and the Positive Vial system indicator.

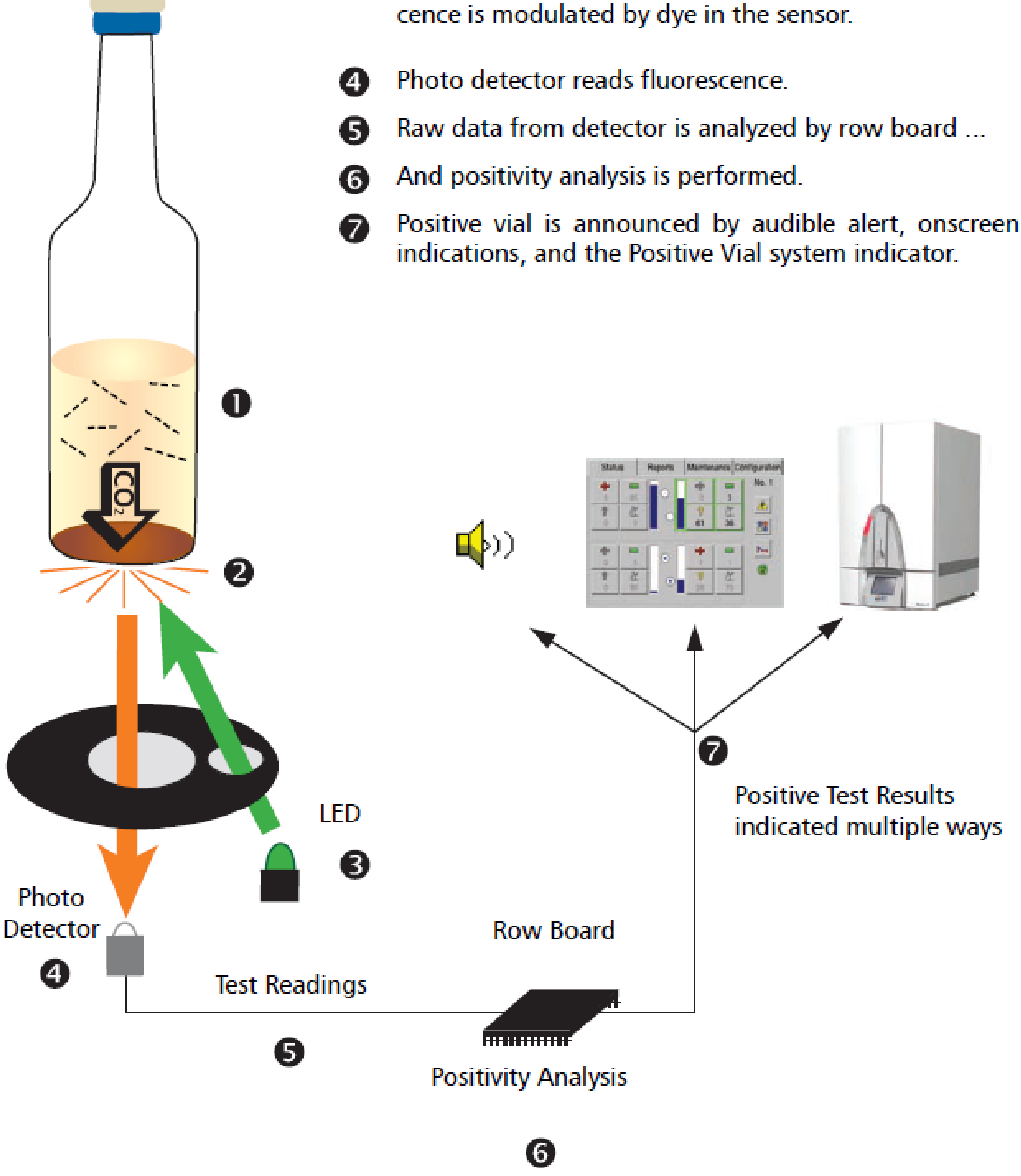

Figure 1 BACTEC Fluorescent Test Technology

The uniqueness of BACTEC™ fluorescence sensor technology allows for fully-automated, walk-away testing using a continuous-monitoring instrument that agitates and incubates BACTEC blood culture bottles, resulting in earlier detection of positives blood culture. The system also provides advance algorithms for each media types, for special circumstances such as low blood volume, pediatric specimens or to detect slow growing organisms such as *Haemophilus* and *Neisseria*. The algorithms provide rapid detection of pathogens in blood culture.

The combination of **media-specific algorithms** with **growth phase-specific algorithms** enhances the sensitivity and time to detection, even in the case of **delayed vial entry** (≤48 hours if are not incubated or held at room temperature) and for bacteria that only generate limited amounts of carbon dioxide (e.g. *Pseudomonas aeruginosa*)

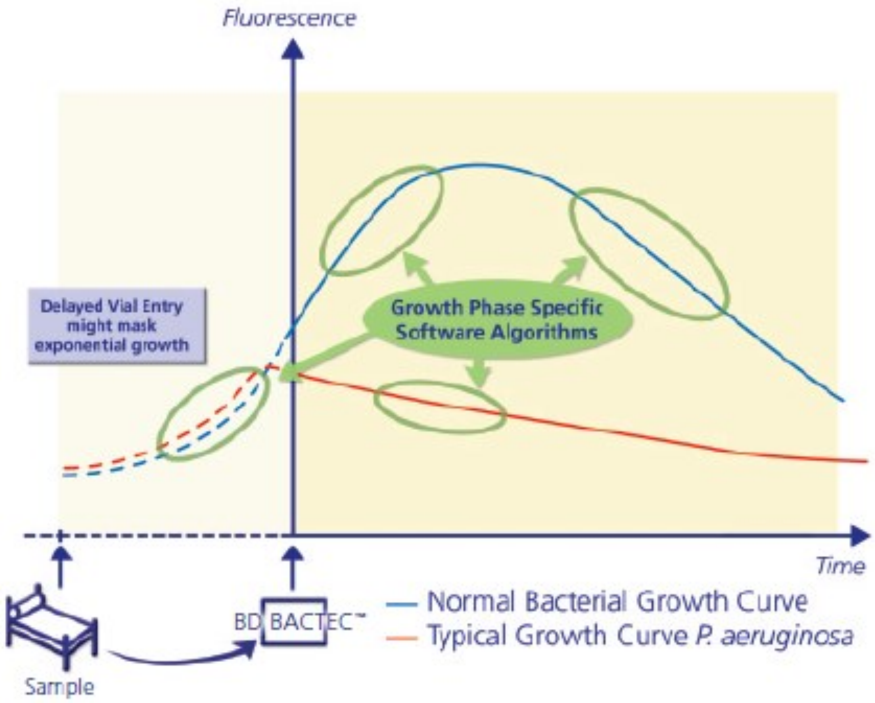

Figure 2 Fluorescent Technology and Sophisticated Algorithms: a Powerful Combination The BACTEC™ blood culture system builds on the proven history of previous BACTEC™ instrumentation, with advanced fluorescence detection technology, exceptional media performance and instrument reliability—adding vial-activated workflow, advanced ergonomics, blood culture observation and customer-focused data management. The easy-to-use workflow comes in a compact, modular design, which can be adapted to multiple space- and time-saving configurations for your laboratory staff.

References: TO FACULTY & STUDENTS OF RKDF UNIVERSITY FOR ACADEMIC

IN-PUT ONLY

1. BACTEC™ Fluorescent Series User's Manual - Received by HOD BIO-TECHRKDF
2. BD BACTEC™ 9000 Systems: A World of Difference in Blood Culture_ e-mail

ENCL: 01

Design, Analysis, Construction and Field Operation Demonstration of a 5 MW Capacity Thermal Storage Module along with a Dispatchable **1.5 MW**$_e$ Solar Power System with 60 MW$_{th}$ Energy Storage Capacity

BY

Ram Krishna Dharmarth Foundation (RKDF) University

&

Rensselaer Polytechnic Institute

110 8th Street, Troy, New York 12180

Proposal

SUBMITTED TO

MNRE for 6 MONTHLY PROGRESS REPORT AS ON MARCH 2020

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Executive Summary

A joint partnership between Rensselaer Polytechnic Institute (RPI), Troy, New York, USA and RKDF University, Bhopal, India proposes to create a megawatt scale concentrated solar power (CSP) test bed in Bhopal, India. Enlys Energy LLC, Edisun Microgrids, Inc. and OPRA Turbines have been designated as the commercial vendors for providing the necessary hardware and field services for building, installation, testing and maintenance of the test bed at the field site in Bhopal, India. Enlys Energy will directly work with Edisun Microgrids, Inc., OPRA Turbines and the relevant entities in India for managing the export control related to all equipment being supplied for this project, custom duty and associated protocols. Partner Institution, RKDF university will provide resources necessary for the test bed construction including, land, utility, labor, civil work services, acquisition of permits and oversight. RPI will provide the necessary fundamental research and engineering design processes for the test bed. RPI and RKDF University will jointly conduct a variety of research and educational programs using the test bed.

The megawatt scale concentrated solar power (CSP) test bed will be built for capturing solar radiation and storing the energy in form of heat inside a thermal energy storage (TES) medium. The heat from the TES will be further used to convert water into steam to generate electrical power using a steam turbine anytime during the day or night. This project encompasses the design, analysis, construction and field operation demonstration of a 5 MW capacity thermal energy storage (TES) module along with a Dispatchable 1.5 MW_e (electric) solar power system with 60 MW_{th} (thermal) energy storage capacity. For the TES plant of 5 MW capacity, the executing agency is a joint venture of Ram Krishna Dharmarth Foundation (RKDF) University Bhopal.

A low-cost and reliable Concentrating Solar Power (CSP) System with integrated Thermal Energy Storage (TES) for distributed on-grid, off-grid, and fringe-of-grid applications is proposed. The system employs proven static solid media sensible energy storage technology and a mature gas turbine engine to provide flexible base load, peaker, and/or grid battery operability. With a nominal power rating of 1.5 MW_e and a storage capacity of 60 MW_{th}, the proposed solution may produce power for up to 16 hours without solar or grid input. The system is suitable for installations in which there is a need for affordable distributed renewable power, energy storage, and energy security; ideal markets include India, Australia, Chile, North Africa and the Middle East.

A full plan for deployment of a first-in-class installation is provided, including the scope of effort, schedule and preliminary budgetary estimate for the development, construction and installation, and commissioning of the system. A knowledgeable team with a passionate commitment to renewable energy and expansive experience in solar collection and concentration, concentrating solar power, gas turbine engine technology, and thermal energy storage is presented. RPI, RKDF University and Enlys Energy propose to work in close partnership with the Madhya Pradesh Power Management Company Limited to achieve success in this program, and to establish manufacturing and services capabilities in Madhya Pradesh province to support this and future installations.

Introduction

Energy storage in form of heat offers a potential pathway for small (local) and large (utility power plants) scale applications. Thermal storage systems provide a unique opportunity to store energy locally in the form of heat that cannot be transported over long distances. Current thermal storage systems are still in its infancy. The most common ones are large, water-heating storage tanks and molten salt-based systems at solar power plants. These systems have been designed based on the economics of water and salt, the heat capacity of water, and the latent heat of salts. Research on a large host of sensible heat storage and phase-change materials have been conducted over the past two decades. The materials parameters that are relevant for this application are: melting point, boiling point, vapor pressure, density, heat capacity, thermal conductivity, latent heat of fusion and chemical reactivity. While it is intuitive that increasing the temperature of storage could pack in more energy, barriers to the development and deployment of high energy density storage remain, including handling materials at high temperatures, associated systems costs, and operating costs. Thus sensible thermal storage systems are cost prohibitive. Phase change materials (PCM) do provide a viable economical solution for higher energy storage density. However, operation temperatures limit current PCM systems; higher temperatures cause chemical instability and reactivity with containers.

Development of affordable high-density thermal storage systems will only be possible by utilizing low cost earth abundant thermal storage materials in conjunction with suitable thermally insulating container materials. Current heat storage systems utilize either *sensible* heat storage (i.e. water in storage tanks) or *latent* heat storage (i.e. phase-change materials such as molten salts). The relatively low operating temperatures of these systems limit their capacity to store thermal energy; storage systems with higher temperatures would be more economical. In this project, we plan to develop and demonstrate an affordable high energy density thermal storage system that can store heat at temperatures approaching 1000 ^{o}C. One of the unique aspects of this system is the solid media based thermal energy storage (TES) for high melting temperature operation and corrosion resistant cheap ceramic container material.

The scope of the proposed project will be to bridge the gap between the initial studies currently underway in demonstrating and measuring the performance of the thermal storage unit test bed at RKDF to a full scale MW_e capacity type electric power generation plant in the future connected to the grid with cost of electricity generation that is grid-parity. The overarching goal of this project is to developing and deploying reliable, cost-effective distributed renewable power solutions that can have a near-term and significant impact by not only reducing the effects of climate change, but also by improving the lives of citizen around the globe. To achieve this, a diverse group of project team members are leveraging decades of experience in alternative energy and Concentrating Solar Power (CSP).

The CSP system proposed here is founded on a long history of experience, successful execution of cutting-edge research projects in the field, and a holistic strategy for complete system definition. Ideally suited for microgrid application and remote and/or developing communities, the system has been developed with an emphasis on Reliability, Simplicity, and Elegance.

The proposed system consists of a field of mirrors (heliostats) which track the sun and focus their reflected sunlight onto a central receiver, located on a tower; an operating example of a system of this type is depicted in Figure 1. The concentrated solar energy is absorbed as heat in the receiver and delivered to a sensible Thermal Energy Storage system at ground level. This storage system enables the dedicated power block to run and generate electricity around the clock, day and night.

Figure 1. The Concentrating Solar Power plant operating at Crescent Dunes in Tovenpah, Nevada, USA [2]

This design is characterized by low-Pressure, low-stress hot components that exhibit long operating lives at low cost. Key parameters describing the proposed system are provided in Table 1. The system as presented is coupled to a nominally 1.5 MW_e power block; this was selected to reduce the total capital cost investment required for initial system deployment, and for the wide range of small-scale distributed communities, neighborhoods, and industrial facilities at which this system could be demonstrated. The fundamental design may be scaled up to integrate with larger power blocks up to 10 MW_e.

Table 1. Overview of the proposed CSP System

PARAMETER	UNITS	VALUE
Nominal Power	**MW_e**	**1.5**
Storage Capacity	**MWh_t**	**60**
Storage Duration	**hrs.**	**16**
Solar Field Power	**MW_t**	**5.8**
Solar Field Area	**ha.**	**2.6**
Capacity Factor:		
Grid Battery Mode	**%**	**100%**
Baseload Mode	**%**	**57%**
Peaker Mode	**%**	**27%**

With up to 16 hours of energy storage, the power block can operate through a large fraction of all off-sun hours. This enables the flexible dispatch of electricity to meet grid loads and user demand, and to provide zero emission power that complements other renewable energy sources and extends the production of clean energy around the clock. The system leverages well-developed and demonstrated static sensible media heat storage in a robust non-pressurized configuration, the operation and performance of which will be showcased by Enlys Energy in conjunction with RPI and RKDF College of Technology in Bhopal through a program funded by the Ministry of New and Renewable Energy.

RKDF and Enlys Energy will work in close partnership with the Madhya Pradesh Power Management Company Limited to identify a suitable site and define an optimal first-in-class demonstration plant to be built and operated. A key element of this effort will also be to define and implement manufacturing and services capabilities in Madhya Pradesh to support this CSP system.

Upon successful completion of this program the key technologies and the supporting manufacturing capacity will be established, enabling the broad distribution of subsequent installations both locally within India and abroad.

Background

Climate Change

Human activity and industrial development is estimated to have already generated a 1.0 (±0.2) ºC rise in global temperatures, with a high likelihood of this number reaching 1.5 ºC well before the end of the century if the current trends continue unabated [3]. The effects of this predicted change are sweeping and profound: an increase in dramatic weather events and natural disasters, widespread changes in the distribution and availability of the natural resources around which human populations have developed, and a global rise in sea level.

The consequences of these changes are devastating. Localized human populations will suffer increased illness and mortality rates due to food and water scarcity, and safety and well-being are threatened as conflicts and migrations arise over access to resources. The economic costs of relief efforts and humanitarian aid, population and industrial relocation, post-disaster repair and restoration efforts, and medical treatments will be massive. Beyond the human toll will be the associated cost to the wildlife, natural beauty and stability of the planet.

The primary vector contributing to these effects is the anthropomorphic generation and emission of carbon dioxide. In May of 2019 atmospheric levels of CO_2 surpassed 415 ppm, 50% higher than the peak levels over the past 800,000 prior to the industrial era [4][5] (see Figure 2). The IPCC recommends immediate reductions in CO_2 emissions in order to limit the effects of anthropomorphic Climate change to levels considered "moderate", noting that major consequences will be unavoidable if reduction goals are not met within the next 12 years.

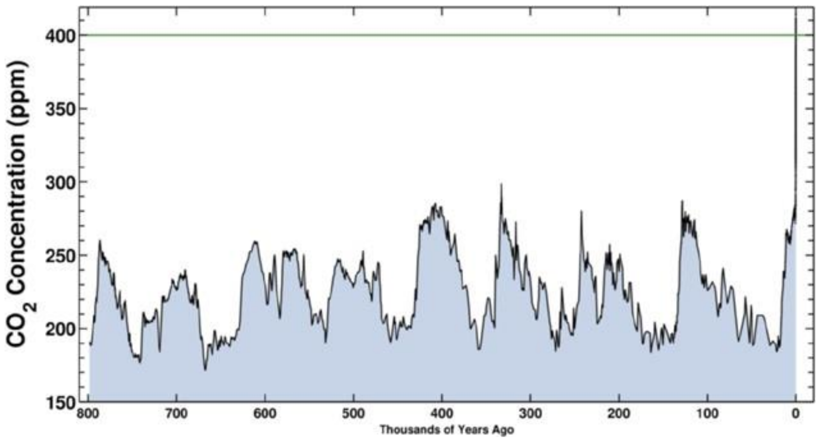


Figure 2. Atmospheric CO_2 concentration data over the last 800,000 years [4,5]

The largest contributing sector – accounting for approximately 25% of the CO_2 currently being emitted through industrialized human activity – is the equipment and infrastructure used to generate the world's heat and electrical power [6]. The near-term adoption of renewable energy sources is therefore critical to not only reduce the levels of greenhouse gas emissions associated with meeting the world's *current* energy needs, but also to address the growing demand for electricity in the world's developing and emerging populations.

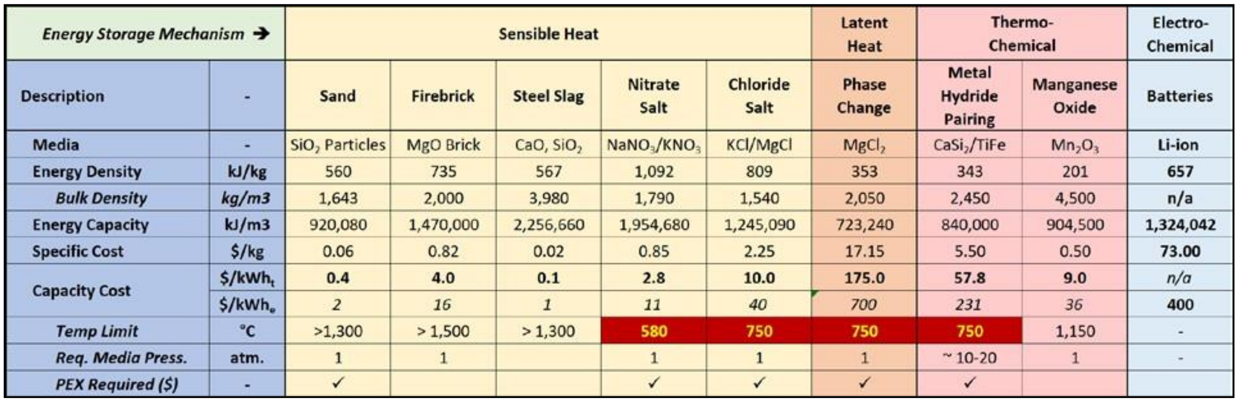
Note that this latter group has a significant advantage with respect to adopting new and renewable energy sources. As opposed to industrialized nations with widespread electrical infrastructures, these populations do not have an incumbent system that is difficult to displace. Rather, they have the opportunity to integrate sustainable and reliable power from the outset.

Energy Storage

The social imperative to adopt renewable sources of electricity – coupled with the low production cost and relative simplicity of photovoltaic-based power solutions – has led to a widespread and growing mismatch between the availability of clean power during the day and the peak energy demand in the hours before sunrise and after sunset. Clean and inexpensive power is abundant when the sun is shining, leading to overproduction of electricity that forces daytime curtailment of non-renewable sources of energy. When the solar resource is absent, these non-renewable sources must quickly respond to increased demand. In this status quo, neither energy source is utilized fully, nor is continuous stress imposed on the grid to maintain a balance between the instantaneous availability of power and the corresponding demand.

The ability to store daytime renewable energy production for later dispatch addresses this issue. Pumped hydropower has long been the preferred energy storage solution as it is relatively inexpensive, efficient, reliable, and is compatible with utility scale capacities. Unfortunately, however, this solution geographically limited, and even those areas long considered favorable face threat from changing water tables due to climate change. Other energy storage solutions have undergone rapid development in recent years, though none has yet emerged as an ideal candidate for large-scale large-capacity power generation applications.

Table 2. Comparative table of Thermal Energy Storage media options for the system under consideration. Sensible, phase change, and thermochemical options are shown, as is an electrochemical battery option [7][8]

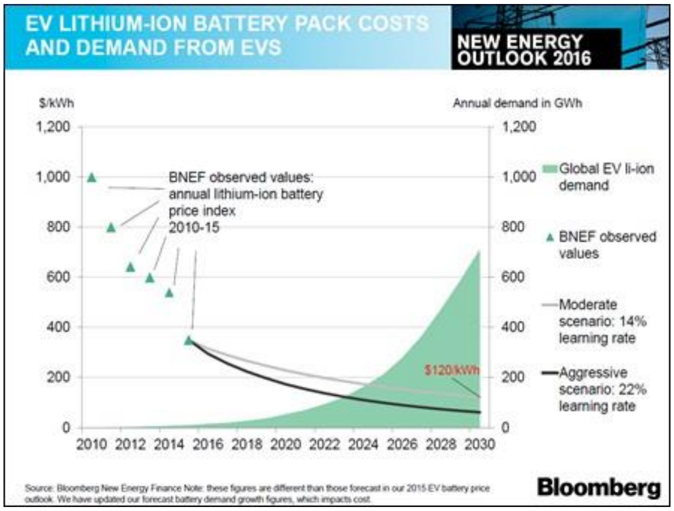


Energy Storage Mechanism ➔		Sensible Heat					Latent Heat	Thermo-Chemical		Electro-Chemical
Description	**-**	**Sand**	**Firebrick**	**Steel Slag**	**Nitrate Salt**	**Chloride Salt**	**Phase Change**	**Metal Hydride Pairing**	**Manganese Oxide**	**Batteries**
Media	-	SiO_2 Particles	MgO Brick	CaO, SiO_2	$NaNO_3/KNO_3$	KCl/MgCl	$MgCl_2$	$CaSi_2$/TiFe	Mn_2O_3	**Li-ion**
Energy Density	kJ/kg	560	735	567	1,092	809	353	343	201	**657**
Bulk Density	*kg/m3*	1,643	2,000	3,980	1,790	1,540	2,050	2,450	4,500	**n/a**
Energy Capacity	kJ/m3	920,080	1,470,000	2,256,660	1,954,680	1,245,090	723,240	840,000	904,500	**1,324,042**
Specific Cost	$/kg	0.06	0.82	0.02	0.85	2.25	17.15	5.50	0.50	**73.00**
Capacity Cost	$\$/kWh_t$	**0.4**	**4.0**	**0.1**	**2.8**	**10.0**	**175.0**	**57.8**	**9.0**	*n/a*
	$\$/kWh_e$	*2*	*16*	*1*	*11*	*40*	*700*	*231*	*36*	**400**
Temp Limit	°C	>1,300	> 1,500	> 1,300	580	750	750	750	1,150	-
Req. Media Press.	atm.	1	1		1	1	1	~ 10-20	1	-
PEX Required ($)	-	✓			✓	✓	✓	✓		

CSP systems – in which solar energy is collected, concentrated, and used to run reliable large scale engines such as steam turbines and/or gas turbine engines – have a significant advantage in that they convert incident sunlight into heat, which is relatively easy and inexpensive to capture and store for extended periods of time. There are multiple heat technologies in various stages of development, including concepts that leverage sensible energy (heat rise), latent energy (phase change), and thermo chemical (chemical reaction) storage. Figures of merit for candidate solutions are shown in Table 2 for the system under consideration. Also shown in Table 2 are the relative metrics for the state-of-the-art in energy storage, electrochemical batteries.

By contrast the Photovoltaic (PV) systems that are widely deployed today convert incident sunlight directly into electricity. As a result, the most suitable form of energy storage for these systems are chemical batteries. Although a mature technology, batteries continue to face a number of major challenges in large-scale power applications:

- Because of the challenges associated with large-scale integration and heat management, they are limited in size and capacity to 4-6 hours of storage only. Incidents associated with these failure modes tend to be dramatic and unsafe, resulting in fires and the wholesale loss of equipment. While the safe timeframes for battery storage are compatible with load-following and grid stabilization applications, they are not suitable for the baseload-power applications that are required to significantly reduce climate change by extending solar power production throughout the day and night
- Over their relatively short service lifetimes – typically 5-8 years – they experience a steady degradation in performance
- Their materials of construction continue to include heavy metals:
    - as the sources of these metals are often in developing and non-industrialized nations, their extraction through mining often has significant negative health and safety impacts on local populations
    - disposal of these heavy metals at the end of their service lifetimes remains problematic, with major safety and environmental concerns still unaddressed



Source: Bloomberg New Energy Finance Note: these figures are different than those forecast in our 2015 EV battery price outlook. We have updated our forecast battery demand growth figures, which impacts cost.

Figure 3. Historical trends and future predictions for the cost of batteries; current pricing is consistent with the trend shown here, indicating 2030 storage costs of \$80-120USD/kWh$_e$ [9]

- Finally, the cost of chemical batteries remains very high, with strong consensus that by 2030 the lower achievable limit is about \$120USD/kWh$_e$.(see Figure 3).

Other technologies – including pumped thermal and flow battery energy storage – show promise, but still require large investments in time and development capital to reach commercialization.

Access to Power and Energy Security

A significant fraction of the world's population does not have access to affordable power, or has access to unreliable power that may be unpredictably intermittent. As these populations industrialize, their need for electrification grows. This added capacity often stresses the existing transmission infrastructure when it exists; in other cases, where there is no existing infrastructure in place, the affected populations are often denied electrification as the capital cost of installing a large or long-distance transmission network is prohibitively large.

Distributed power solutions and microgrids – in which smaller-scale power generating units serve neighborhoods, communities, or industrial entities – are an attractive solution seeing an ever-growing level of acceptance and adoption. Much as the adoption of cell phones in developing nations altogether circumvented the need for a massive wired telecommunications infrastructure, smaller distributed power sources free communities from the cost of long distribution lines and networks. Co-locating generation sources near the end-user also decreases transmission losses.

Distributed power solutions can also provide a level of energy security that does not currently exist in industrialized nations that have long relied on the model of large, utility scale power plants. These centralized systems, while capable of achieving the highest fuel-to-power conversion efficiencies, leverage economies of scale and serve thousands or even millions of customers. Consequently, they represent sole points of failure that can cripple entire states, nations, or economies if successfully attacked. A distributed power network, by contrast, provides a scarcity of attractive targets, and a failure at one site will have a very localized and manageable overall impact to the population as a whole.

Detailed Description of Solution

Integrated System and Overall Performance

To address the environmental, social, and security issues outlined in the previous sections, a renewable CSP power system with energy storage is proposed. The design is highly integrated and has been designed holistically, close-coupling the subsystems while still preserving the driving design priorities of *reliability*, *simplicity*, and *elegance*.

It is critical to note that the system described throughout this proposal has been designed around a nominally 1.6 MW_e gas turbine power block; this decision has several advantages, including the fact that (a) the system is well-suited for distributed power applications for communities, neighborhoods, or industrial clients, and (b) the capital cost required to install the first unit and demonstrate its operation and thermal storage capabilities is relatively modest. That said, it is possible to scale the design up to larger power ratings, though as defined the system is unlikely to be appropriate for utility-scale installations. As a general limit, this system is being presented as well-suited for power blocks no larger than 10 MW_e; exceeding this would require design modifications that forfeit some of the enabling features of the smaller-scale system.

A simplified schematic of the proposed system is shown in Figure 4.

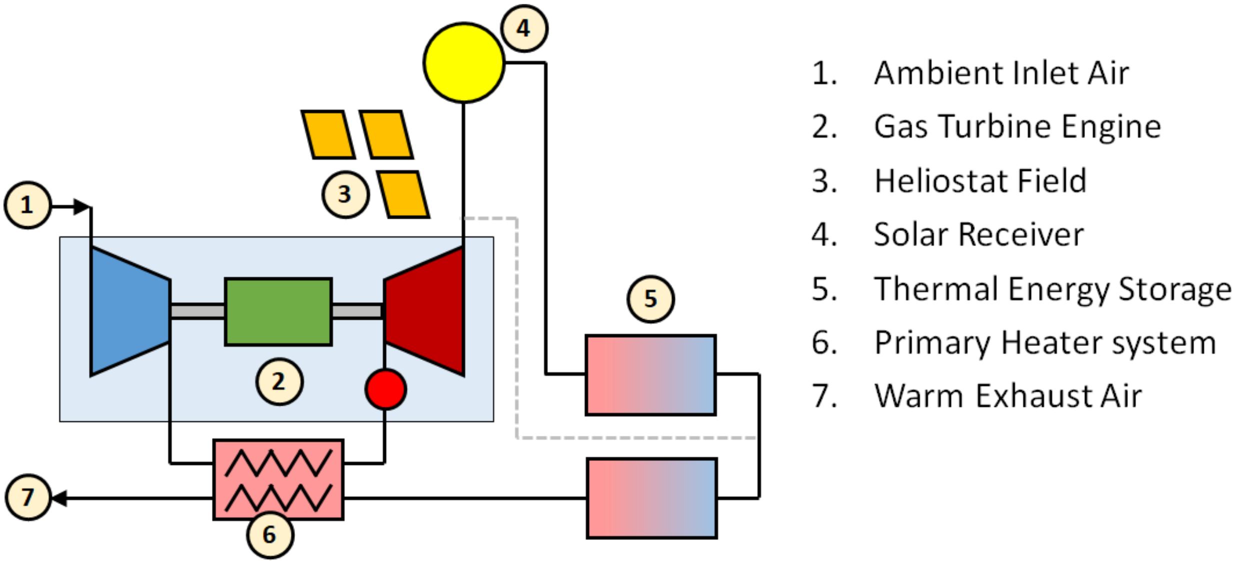


Figure 4. Simplified schematic of the proposed CSP solution, showing the overall integrated system comprised of a commercial heliostat field and power block, solar receiver, thermal energy storage system, and primary regenerator; also depicted are the Technology Readiness Levels of the various subsystems, indicating a high level of technical maturity in the constituent elements of the design

A short overview of the system is as follows, with enumerated points corresponding to the labels in Figure 3, is provided below:

1. The use of **Ambient Inlet Air** as a working fluid simplifies the design as there is no requirement for hermetic seals and overboard leaks do not impact the environment at large, reduces cost as there is no expense associated with a specialized working fluid, and enables the use of a standard gas turbine engine and generator to produce electricity

2. A commercially-available **Gas Turbine Engine** is used as the system's power block. By using an off-the-shelf design with proven reliability and known operating characteristics, high development costs and long development times are eliminated. Furthermore, by retaining the engine's conventional combustor, the ability to operate the system during periods of extended solar deficit or in fast transient conditions is preserved.

3. The solar collection and concentration is achieved through the use of emerging **Heliostat Field** technology. These next-generation heliostats are lower-cost and better-performing than previous designs, enabling the design of the proposed CSP to prioritize reliability over efficiency while still achieving an overall low cost of electricity

4. The **Solar Receiver** is designed leveraging multiple decades of CSP experience. Because of its integration downstream of the power block, the receiver operates at near-ambient pressure, eliminating the pressure stresses that induce failure at high temperatures.

5. The **Thermal Energy Storage** system, consisting of a solid media and utilizing sensible heat storage, is at ambient pressure like the solar receiver; this feature is critical to the economics of the system. Even the most energy-dense thermal energy storage system will be volumetrically large for any sizable capacity, and the cost of reacting any internal pressure above ambient becomes prohibitively large. An integral electric heater system also enables the system to convert all of its electrical energy into heat, thereby eliminating all power export while still charging the storage system.

6. The **Primary Heater** is used to deliver high temperature heat energy from the storage system into the gas turbine engine, allowing the power block to run off solar energy exclusively. Rather than use a high-temperature heat exchanger as has been employed in other systems, this primary heater is a modular valved regenerator system. This eliminates the expensive nickel-based Inconnel or Haynes alloys and the specialized manufacturing processes typically used in high temperature heat exchangers. Instead, low-cost insulated modules containing with sensible energy storage media are used to alternatingly absorb heat from the TES and deliver it to the power block.

7. The working fluid then exits the system as **Warm Exhaust Air**. This air can be vented to atmosphere without any carbon emissions, used for local water or space heating requirements, or used to run a coupled water desalination unit that produces clean and potable water.

The subsystems above are described in more detail in the following sections.

Note that the solar and TES elements are downstream of the turbine exhaust; as a consequence, the solar receiver and the thermal energy storage are at near ambient pressure. This is a critical enabling consideration, in that it reduces pressure-induced stresses in the highest temperature sections to negligible levels, and enables ultra-low-cost containment of the thermal energy storage system. Both of these are critical to the reliability and economics of the system. The challenge this configuration imposes is that all downstream components must be designed for minimal pressure drops in order to maximize the expansion ratio across the turbine (and thereby maximize the power generation).

When operated in conjunction with a larger microgrid or full-scale grid that has excess daytime electrical capacity, the TES electric heating elements can be engaged to absorb excess power and convert it to heat for storage and later dispatch. By sizing the TES accordingly and storing both thermal energy from the receiver and electrical energy from the grid, the system can generate power 24 hours a day.

Figure 5 shows the hourly electrical export of the system for an installation in Bhopal India throughout three different days of the year: the equinox (green), the summer solstice (yellow), and the winter solstice (blue). Two different operating modes are depicted:

- **Maximum Storage Efficiency** (shown as solid lines), in which the system produces less power but stores thermal energy from the cycle during the day, increasing the net electrical output as compared to the amount of grid electricity stored.
- **Maximum Power Generation** (shown as dotted lines), in which the system forgoes excess thermal storage from the cycle during the day in favor of greater electrical output. The

result is more electrical power overall, but for a correspondingly greater fraction of electrical energy absorbed from the grid to achieve it.

The yellow shaded area in Figure 5 approximately indicates the on-sun hours of operation of the system (seasonal variations neglected). The grey areas indicate off-sun operation.

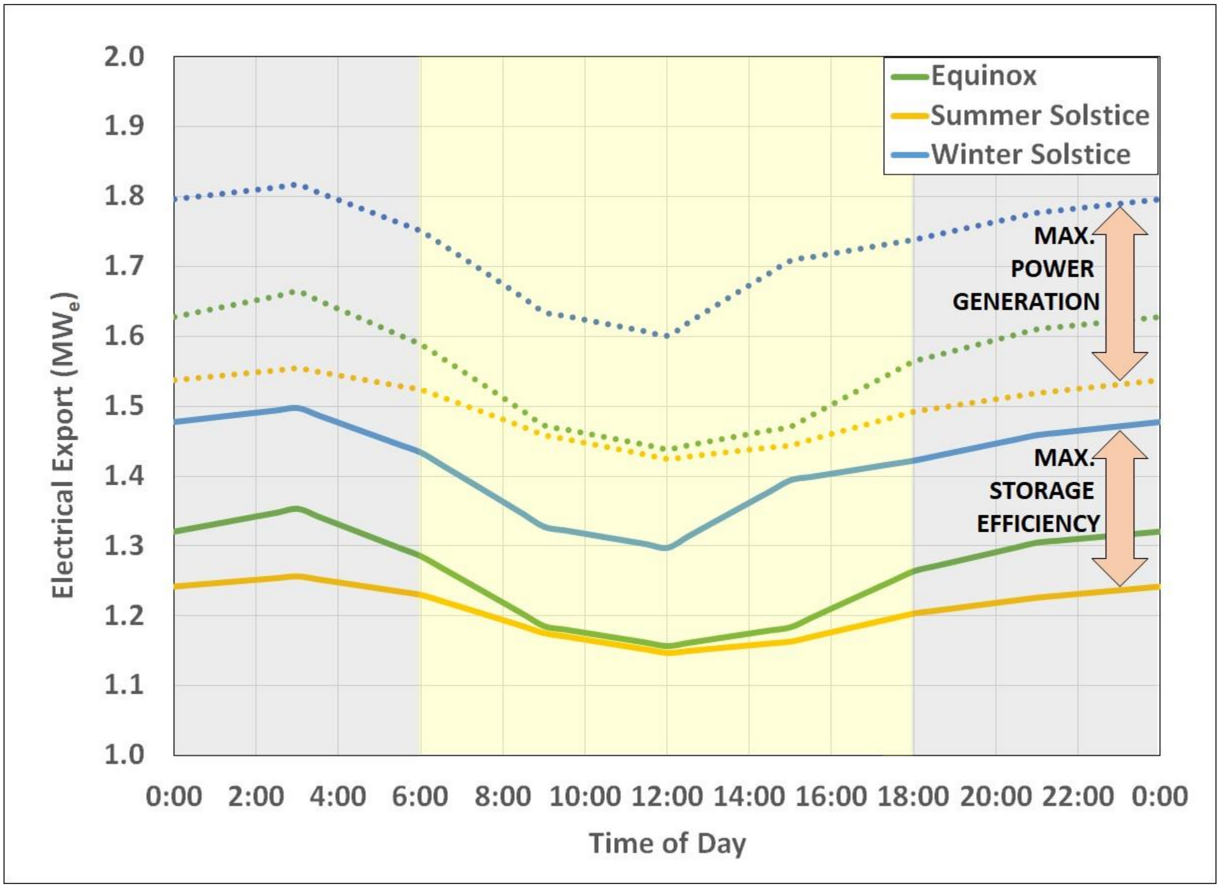


Figure 5. Grid-battery mode operating profiles, showing the daily electrical export for the equinox (green), summer solstice (yellow), and winter solstice (blue) days. Two different operating modes are shown: "Maximum Storage Efficiency" (solid lines), in which the system returns the most power to the grid compared to what it accepts, and "Maximum Power Generation" (dotted lines), in which the round-trip efficiency is less critical than maximizing electrical output. The shaded regions of yellow and gray indicate the approximate on-sun and off-sun operation of the system, respectively

When operating in this grid battery mode, electrical power absorbed from the grid is converted to thermal energy via electric heating and captured in the thermal energy storage system. When used to dispatch electricity at a later time, it does so at a 35% round trip thermal-to-electrical efficiency; this high efficiency is achieved due to the effective recuperation effected in the primary regenerator system. Because of the supplemental "free" solar energy being captured and used to run the engine during the day – and deliver thermal energy to the TES when desired – the equivalent conversion efficiency from the perspective of the grid is much higher. That is, the solar contribution increases the energy delivered to the grid. These results are summarized in Table 3.

Table 3. Performance summary for three days throughout the year (equinox, summer solstice, and winter solstice) and two different operating profiles (maximum storage efficiency and maximum power generation). For each case the daily electrical energy generation is shown, along with the energy that must be stored from the grid to enable 24-hour running. The equivalent "battery" efficiency – the energy delivered to the grid as compared to the energy absorbed by the grid – is also shown

PARAMETER	UNITS	MAX. EFFIC.	MAX. POWER
EQUINOX			
Electrical Gen.	**MWh$_e$**	30.8	38.1
Grid Storage	**MWh$_e$**	34.6	51.4
Equiv. Efficiency	**%**	89.0%	74.2%
SUMMER SOLSTICE			
Electrical Gen.	**MWh$_e$**	29.5	36.6
Grid Storage	**MWh$_e$**	27.8	43.7
Equiv. Efficiency	**%**	106.2%	83.9%
WINTER SOLSTICE			
Electrical Gen.	**MWh$_e$**	34.7	42.4
Grid Storage	**MWh$_e$**	41.0	59.2
Equiv. Efficiency	**%**	84.5%	71.6%

Alternatively, the system may operate entirely independently without any larger grid infrastructure. Figure 6 shows a series of example power curves for the system operating in this continuous "standalone" and "full power" mode in Bhopal India at the equinox. Daytime hours are presented with the light yellow background, and off-sun hours are shown with a grey background. These curves are all for operating profiles in which daytime generation is desired, and depict the tradeoff between power export and how long constant power delivery can be extended into the night.

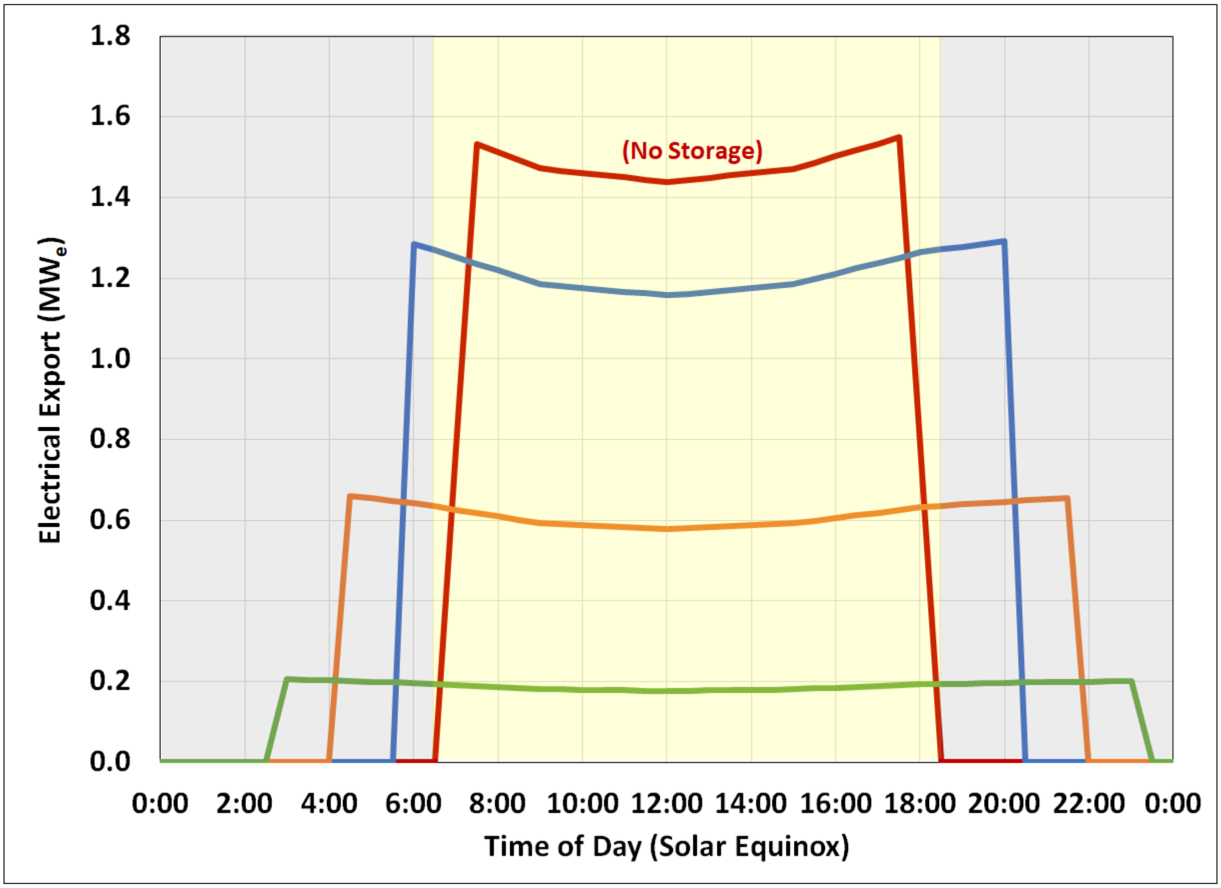


Figure 6- Example "constant power" operating profiles for Bhopal, India on the Equinox

The period between sunrise and sunset is indicated by the yellow background. Reducing the constant power setting allows the system to extend operation further into the off-sun hours

Figure 7 shows a series of example power curves for the system operating in "standalone" and "peaker mode" in Bhopal India at the equinox; during this operation power export during the day is deferred in favor of greater off-sun dispatch capacity. Daytime hours are shown with the light yellow background, and off-sun hours are shown with a grey background. For all of these curves shown the engine is operating continuously during the daytime hours; however, all electricity at these times is being converted into thermal energy to increase the overall storage rate. These curves also depict the tradeoff between power export and how long power delivery can be extended into the night.

Note that the system is not limited to the power profiles presented in Figure 6 and Figure 7. in all cases, however, the system will be constrained by how much thermal energy is stored during the day, as that represents the limit of energy that can be dispatched at night. That dispatch can be at high power for shorter durations, or at lower power throughout more of the night, depending on the needs of the end user. Understanding the application and needs of the customer is critical to defining how the engine operates and optimizing its profitability and/or utility.

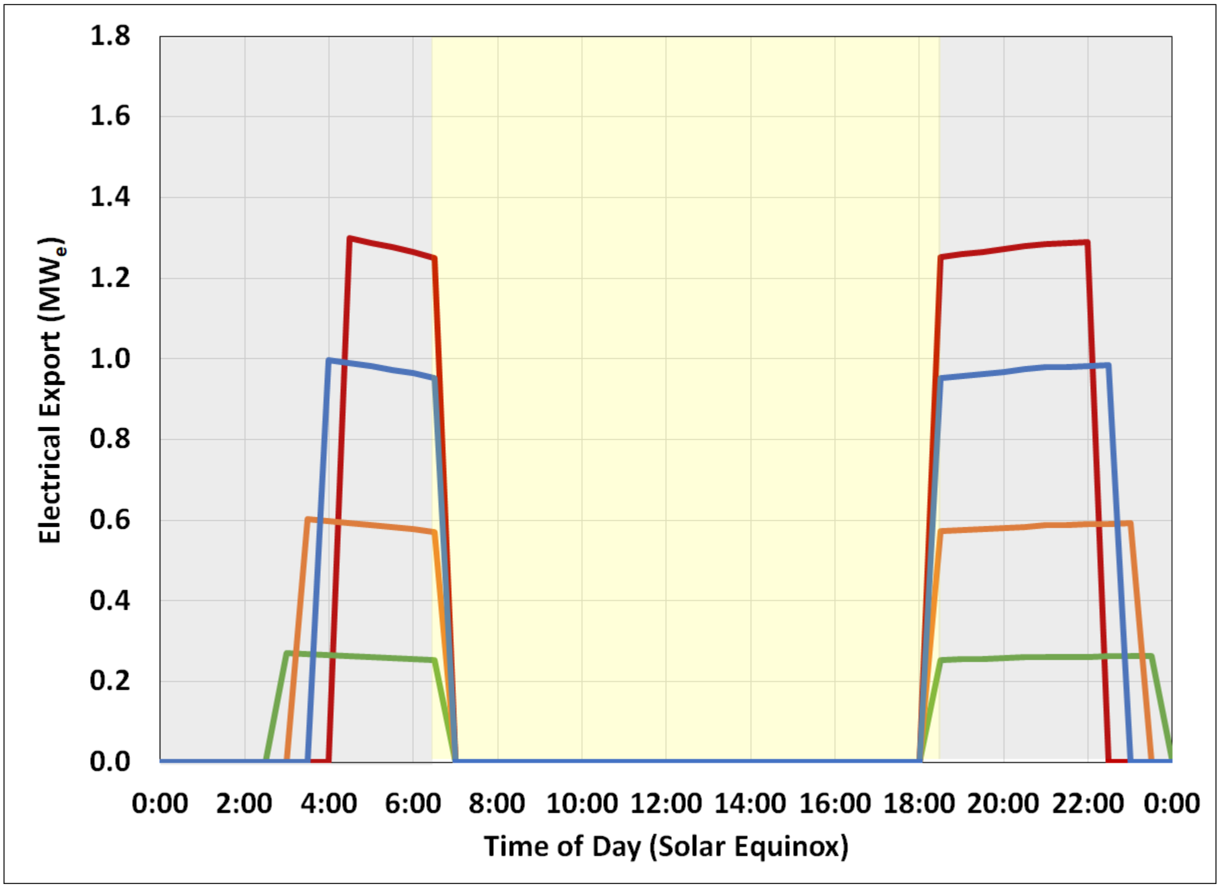


Figure 7- Example "peaker-type" operating profiles for Bhopal, India on the Equinox. The period between sunrise and sunset is indicated by the yellow background. In all cases the system runs throughout the day, but all thermal and electrical energy is stored (net zero export) for use during off-sun hours

This integrated system has been specifically designed with the focused intent to be:

- ***Inherently safe***, employing benign air as a working fluid and limiting pressurized components only to the hot section of the commercial gas turbine
- ***Reliable***, prioritizing robust operation and high availability to ensure the consistent delivery of electricity to the end user
- ***Flexible***, able to operate day or night and over a broad range of operating (generating, charging, discharging, etc.) profiles to meet the demands of the local or greater grid
- ***Efficient***, such that the overall Levelized cost of electricity provided by the system is competitive with the local rates
- ***Low-cost***, being sized for distributed power applications, employing mature technologies that do not require development time or cost, and using inexpensive and thin -walled materials wherever possible

- ***Socially beneficial***, enabling the use of local materials, manufacturing, industry, and service throughout several key subsystems and the technology deployment as a whole
- ***Autonomous***, eliminating the need for the on-site oversight or operation that would challenge the overall system economics
- ***Environmentally friendly***, avoiding the use of materials or heavy metals that are damaging, corrosive, or toxic
- ***Deployable in the near term***, employing mature technologies wherever possible and avoiding the long development times or advanced manufacturing techniques

Heliostat Field

Historically solar collection and concentration has been a cost-challenged element of CSP systems, with dish and heliostat solutions contributing up to 50% or more of the overall system capital cost. Minimizing the solar collector area has traditionally been the driving mechanism to lower energy costs, enforcing a reliance on riskier, more expensive receiver, power block, and TES designs that push the envelope of system efficiency at the expense of reliability and operating flexibility.

However, emerging solar field solutions are now approaching costs of \$100USD/m^2 of reflector area, a price regime that changes the economics of optimizing the entire system. Maximum efficiency designs are no longer the sole path to economic viability, and designs that emphasize reliability, dependability, and flexibility can now produce low-cost energy.

One such emerging heliostat design is being produced by Edisun, whose technology is a descendent of eSolar's 10 years of cutting-edge solar collector development and expertise. Edisun has engineered a small-scale (~2 m^2 reflective area) focused heliostat (see Figure 8) that introduces multiple significant innovations, including

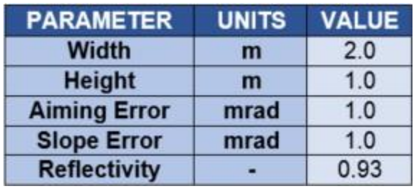
- A non-traditional tracking mechanism that simultaneously reduces drive component stresses and increases aiming fidelity
- Leveraging these benefits to incorporate lower-cost production material and manufacturing techniques, significantly reducing the heliostat's cost
- A breakthrough mounting solution that produces the focusing curvature of the reflector surface without coefficient-of-expansion mismatches that have historically been root causes of heliostat de-lamination and optical degradation

Figure 8- Edisun's ~2 m^2 heliostat design, incorporating multiple design innovations that simultaneously improve reliability and reduce cost. The faceted outline serves to eliminate reflector area in the regions of greatest shading and blocking in the optimally-packed heliostat field, thereby further reducing the overall cost-per-kW-delivered

- A wireless-capable drive system that can enable lower cost installation and control of the entire heliostat field.
- A closed-loop control system that enables the system to monitor each heliostat's aimpoint in real-time and make continuous adjustments.

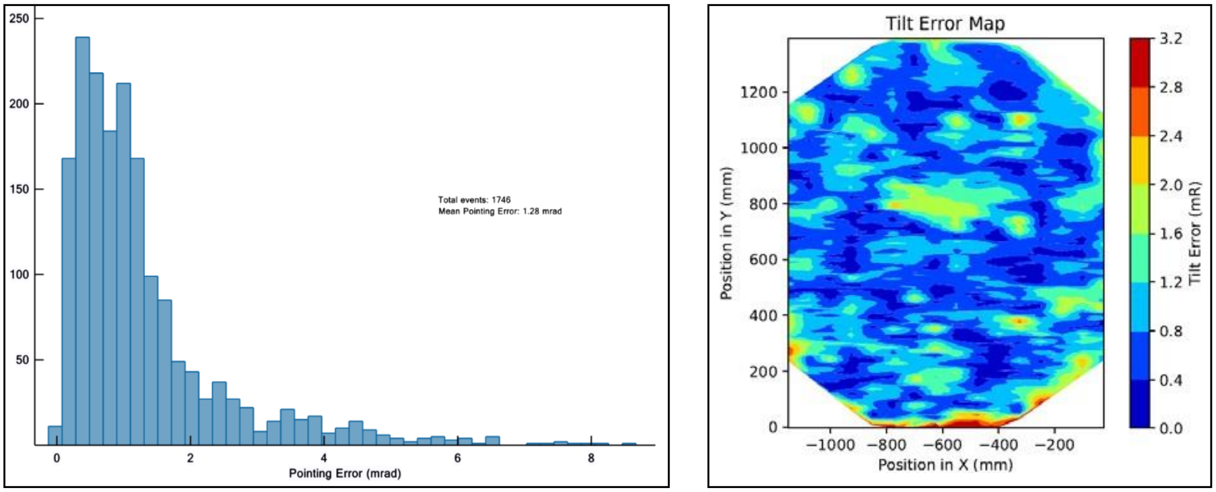
The heliostats are designed to be either mounted via driven pedestals or on ballasted pedestals, which provides an additional degree of freedom for specific installations. There small size enables further cost reductions as the structural requirements to maintain high optical performance under wind loads are minimized.

Table 4. Optical and performance characteristics of the Edisun heliostat



PARAMETER	UNITS	VALUE
Width	m	2.0
Height	m	1.0
Aiming Error	mrad	1.0
Slope Error	mrad	1.0
Reflectivity	-	0.93

The units are demonstrating excellent performance, as summarized in Table 4. Figure 9 depicts test data for both (a) aiming accuracy and (b) surface quality. These performance characteristics are being further improved through aiming algorithm refinement and manufacturing process development, respectively.



(a)

(b)

Figure 9. Performance measurements for the Edisun heliostat; (a) a frequency histogram of aiming errors taken over a 1-month period, demonstrating a mean pointing error of 1.28 mrad, and (b) a map of the surface quality

While any and all heliostat designs will be considered while engineering the proposed system, Edisun's technology is considered a well-understood, cost-effective, and high-performance unit. Its operating characteristics, controls fidelity, and pathway to cost-effective solar collection and concentration are considered to be at the cutting edge of the industry, and their design has been used in all scoping and evaluation studies supporting this proposal. Furthermore, Enlys Energy has prior experience working with Edisun technology, making it easier to incorporate the sub-system design into the megawatt scale test bed.

Solar Receiver

The solar receiver absorbs the concentrated sunlight being reflected from the heliostat field and conveys it into the working fluid of the system. In accordance with the prevailing design philosophy applied throughout the entire system, the design of the solar receiver emphasizes reliability and simplicity over unproven emerging technologies.

This system employs a cavity receiver design, wherein the solar field focuses its power through an open aperture and illuminates the absorbing surface inside the cavity. This allows for a large receiver surface – an important feature given the large frontal flow area needed to minimize the pressure drop of the low near-ambient working fluid pressure – without excessively large radiation and convection losses to ambient. This overall configuration would be impractical for large power ratings, but is enabled by the modest size of the proposed solar field.

In general, cycle efficiency improves and receiver efficiency decreases with increasing operating temperature. This is shown schematically in Figure 10, with the typical operating temperature ranges for steam Rankine and air Brayton power cycles depicted as shaded regions. Note that the typical optimal operating range is in the 650-900 ºC temperature range, which corresponds to the conditions in the proposed system.

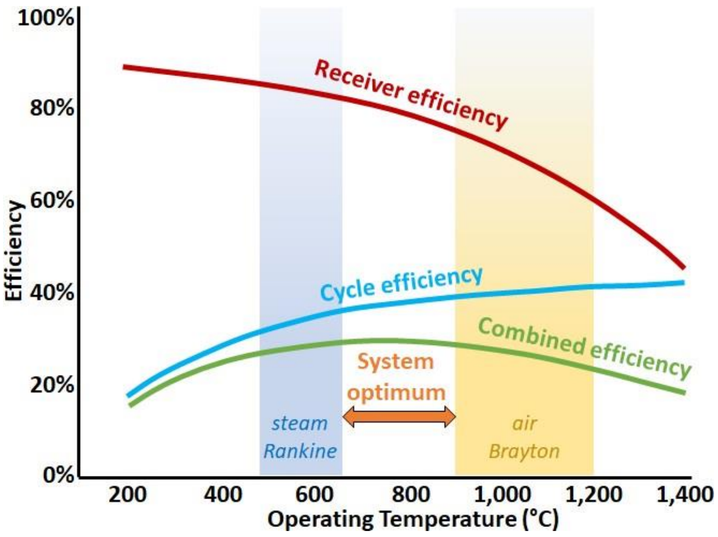


Figure 10. Schematic depicting the tradeoff between cycle efficiency and receiver efficiency, resulting in an optimal CSP system performance in the temperature range of interest

Within the receiver the working fluid is conveyed in silicon carbide tubes or channels. Silicon carbide is stable to temperatures above 1350 degree C, and has a low coefficient of thermal expansion that reduces thermal stresses on irradiated surface

The ends of the receiver tube are captured between metal manifold blocks that are connected via spring-loaded tie rods located outside of the high-temperature cavity. The slight compressive load provides sealing and prevents leakage, in large part due to the negligible pressure differential between the working fluid and the environment. This system also eliminates the need for hermetic ceramic-to-metal connections that are historically unreliable.

Receiver control features required to ensure the desired flow distribution within parallel working fluid paths is effected upstream of the receiver, enabling the use of standard off-the-shelf high-temperature air valves.

Thermal Energy Storage

Thermal energy storage represents a unique enabling technology that differentiates CSP from other renewable energy sources such as PV and wind. The relative simplicity with which heat can be captured – be it through sensible temperature rise, melting or boiling phase change, or the forming or dissolution of thermochemical bonds – provides a means of storing the concentrated energy of the sun for later use. This enables the dispatch of solar energy at any time, providing capacitance to an electrical grid and providing a means of matching the supply of electricity to the load.

The challenge with TES systems has been to achieve cost-effective integration with the CSP system as a whole. In many cases the actual thermal storage media may be inexpensive: steel slag or silica sand for sensible storage, nitrate salts or eutectic metals for latent energy storage, or any number of materials experiencing oxidation, hydrogenation, or other chemical reactions in the operating range of interest. In each of these cases, however, the prohibitively high costs have often been a consequence of (a) the containment of the working fluid, which is often at elevated temperature and pressure, (b) the provisions for achieving effective heat transfer to and from the storage media, and/or (c) failure modes associated with the media itself, such as corrosion, hydrogen permeation, and sintering.

The TES system employed in the proposed solution avoids containment costs by operating at the near-ambient pressures downstream of the turbine, and leveraging direct fluid-to-media contact to achieve highly effective heat transfer. By also selecting an inert media that is thermally stability at temperatures far above the operating conditions of the system, reactivity concerns are eliminated.

The net result of these design choices is that the TES is no longer incentivized to be as physically small as possible. Containment costs can be negligible when there is no stress from internal pressurization, and direct thermal contact reduces the mass of costly metal or ceramic needed to effectively convey heat into and out of the system. Given that CSP plants already require relatively significant land area to accomplish the required solar collection, there is little implication to a large TES system beyond ensuring appropriate Surface Area-to-Volume ratios and adequate insulation to minimize heat loss to the environment.

One embodiment of the proposed system can be described as follows:

- Multiple large, thin-walled, well-insulated shells are constructed; note that these shells may be formed of rigid material above ground, or may simply consist of excavated cavities lined with insulating ceramic firebrick.
- Each shell is filled with a network of ceramic firebricks that, when stacked regularly, form defined channels with both ample cross-sectional flow area and heat transfer area for the working fluid. An example of stacked firebrick of the type described here is shown in Figure 11.

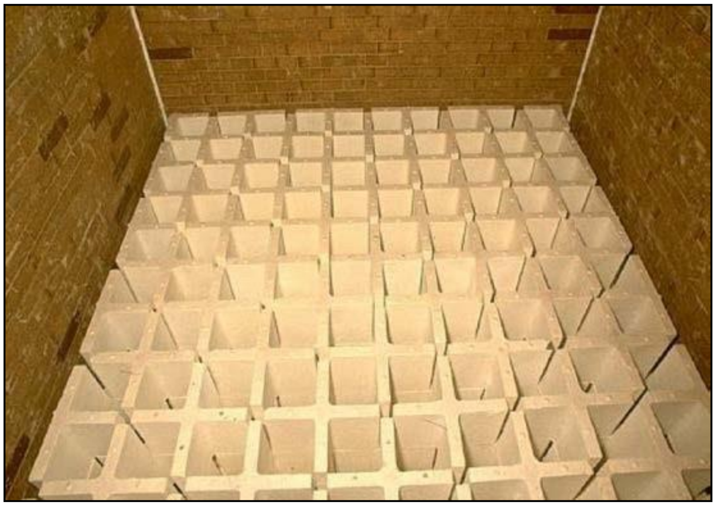


Figure 11. A stacked arrangement of cruciform-shaped firebrick of the type described in [10]

- Electric heaters are integrated within the System as well; these are either radiative heating

Elements with direct line of sight to the storage media, or process flow heaters located upstream of the shells and capable of heating the airflow to system operating temperatures
- The shells are plumbed at both inlet and outlet with valving to ensure that they can be flowed singly or in parallel.

Detailed discussion and favorable analysis of this configuration is provided in [10]. Note that the above description presupposes the use of a formed high-temperature firebrick in the TES. Alternatively, a number of other low-cost materials may be employed in packed bed configurations; these may be considered attractive options if they may be locally-sourced (ceramic, stable natural minerals, etc.) or obtained for negative cost (as may be the cost with steel slag). Images of steel slag and alumina are shown in Figure 12 and Figure 13, respectively.

Figure 12. Steel slag, a low-cost candidate sensible thermal energy storage material

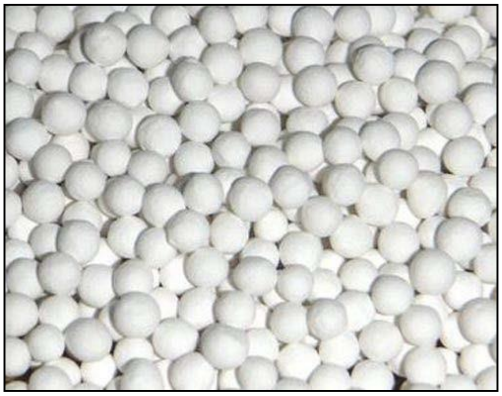


Figure 13. Alumina balls, a high-temperature candidate sensible thermal energy storage material

In any of these embodiments, however, the same enabling features are retained: superior material stability in the operating temperature range, near-atmospheric working pressures, and direct fluid-to-media heat transfer. In all cases the shells are sized so as to ensure both low pressure drops during operation, as well as acceptable flow distribution throughout.

These principles are being tested currently under a program funded by the Indian Ministry of New and Renewable Energy [11]. A small-scale TES system – characterized by low pressure air working fluid, direct fluid-to-media heat transfer, and low-cost thermally-stable sensible media options – is being assembled. This system – shown schematically in Figure 14 – will be coupled to a Scheffler Dish-based Solar Steam Generation at RKDF University in Bhopal, India (Figure 15) for the purpose of demonstrating and de-risking a TES solution suitable for large-scale installations. Testing is scheduled to begin during summer of 2020.

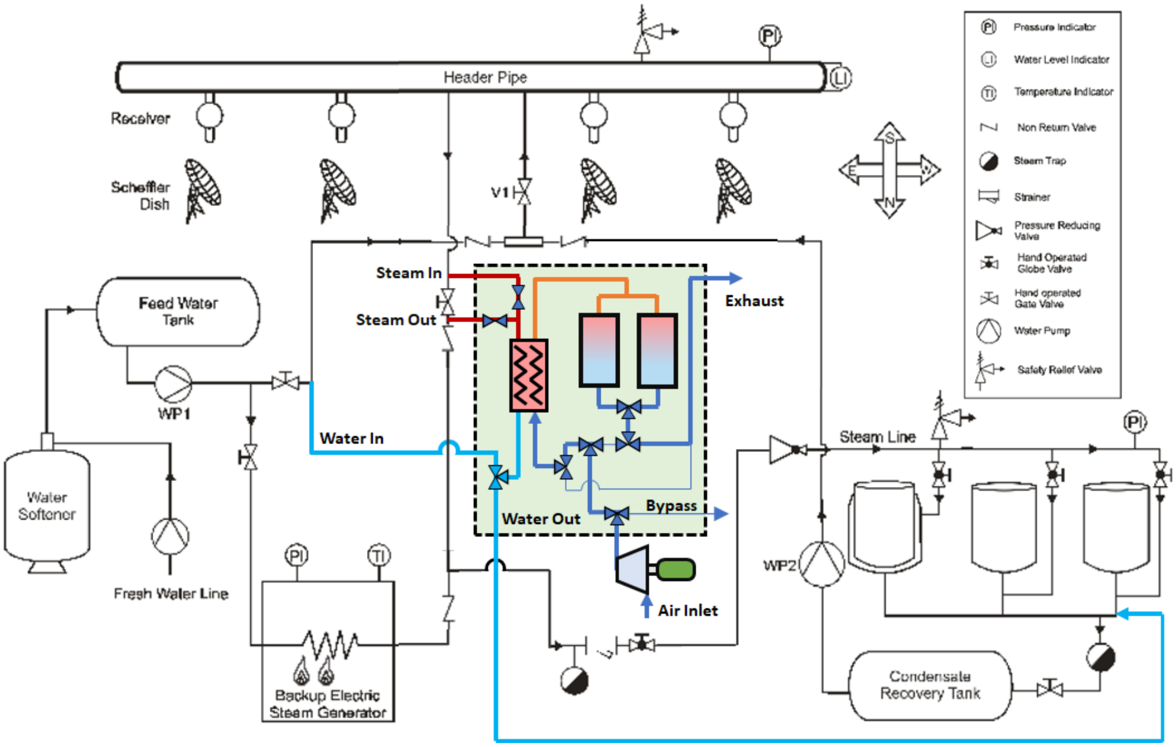


Figure 14. Schematic for the TES system being assembled by Enlys Energy LLC for testing at RKDF University in conjunction with a Scheffler Dish Solar Steam Generator. The program is funded by the Indian Ministry of New and Renewable Energy (MNRE), with the purpose of demonstrating and evaluating a TES suitable for large-scale applications, as described in this proposal [11]

Figure 15- Solar-powered Scheffler Dish steam generation system at RKDF University (MNRE funded project)

In addition to benchmarking the available TES media, the development of a high solar absorptivity, stable TES medium from earth abundant materials will be pursued in this project and tested in the Phase 3 of the project in the test bed. These materials can store heat at temperatures greater than 700 °C as required for Gen 3 CSP systems. One of the proposed class of novel TES materials are organic-inorganic composites engineered using large carbon chain molecules ($>C_{50}$) phase change materials (PCM) like bitumen and asphalt, sand, fly ash and metals. The high optical absorptivity (black mass, Figure 16a), high latent heat of fusion (~ 450 kJ/kg), inertness with container materials, high temperature stability (> 700 °C) and lower cost compared to solar salts are attractive features of these materials and hence they could be a potential candidate for TES material in future CSP plants.

Another class of engineered TES media based on earth abundant materials was demonstrated in a prior MNRE funded project in the 2015-2017 time-frame (*System Design, Erection, Testing & Commissioning of 40* kW_{th} *and 10* kW_{e} *pilot plant aiming at the Feasibility Study of* MW_{e} *Scale Concentrated Solar Thermal Plant integrated with 24 x 7 Thermal Energy Storage; Project Funded by MNRE, New Delhi (2015-2017): PI: Partha Dutta, RPI, Co-PI: V.K. Sethi, RKDF University*). Within the scope of this project, an affordable high energy density thermal storage system that can store heat at temperature around 1000 °C was developed. The unique aspect of this system is alkali halide salt and oxides that withstand high melting temperature and a corrosion resistance to container material. The thermal storage unit could be coupled with a high solar concentrator system (1000 – 10,000 x). Figure 16b shows a photo of high temperature salts used in preliminary field demonstration at the RKDF University, Bhopal, India test bed. In field trials, the TES could be heated locally to 1400 °C using a novel Fresnel lens based solar concentrator as shown in Figure 17. Laboratory tests of such TES material show long duration thermal energy storage capability (Figure 18). *All of these prior experiences with the pilot scale modular CSP system research will be used in optimization of the megawatt scale CSP plant design in this project.*

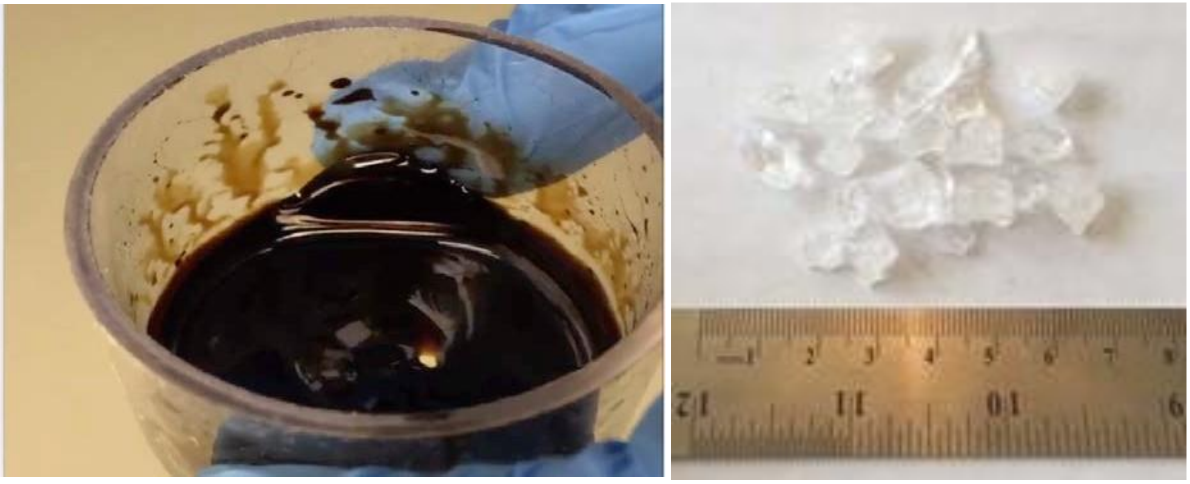
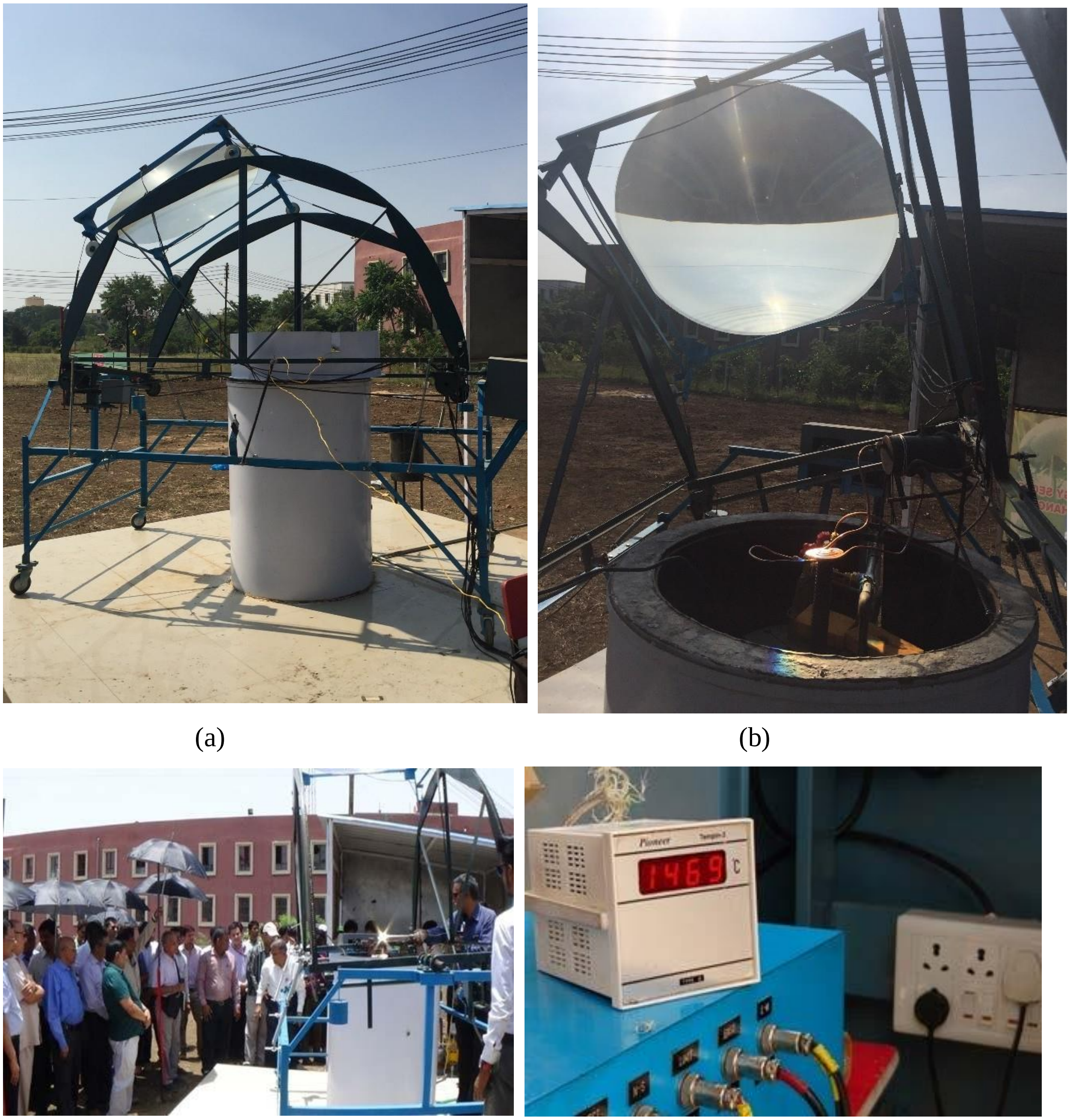

(a) (b)

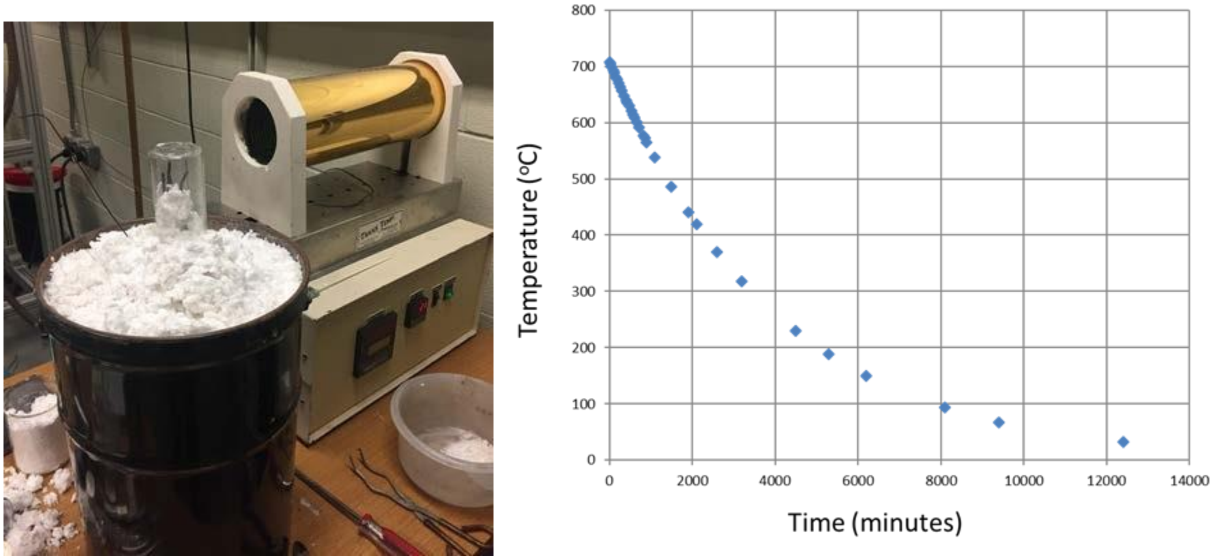
Figure 16- (a) Engineered high absorptivity organic-inorganic hybrid TES, (b) alkali halide based TES crystals. Both of these TES were developed at RPI in PI's laboratory



(a) (b)

(c) (d)

Figure 17- (a) Fresnel lens based modular CSP pilot system developed during the MNRE funded project (2015-2017) for the Design and Economic Feasibility Analysis of a 1MWe capacity solar thermal energy storage system with volumetric energy density exceeding 300 kWh/m^3*, capable of operating at high temperatures up to 1000* ^{o} *C, (b) demonstration of high solar concentration ratio (> 1000 x), (c) field demonstration of the system, (d) high local temperature of TES (~ 1400* ^{o}*C) observed at the collection point of the system*



(a) (b)

Figure 18. (a) Laboratory TES analysis system, (b) experimental data of thermal energy storage duration (temperature-time profile) measurements at RPI in PI's laboratory

Power Block

A key shortcoming of many prior CSP system development efforts has been to insist on a custom power block design specifically tailored for the application. As alluded to previously in this submission, a driving consideration in this has been the historically unfavorable costs of the solar collector field, the minimization of which has mandated the highest overall efficiencies possible in every other system component. Significantly modifying existing gas turbine engine designs for a specialized application such as CSP may take a year of more of engineering effort and entail a high engineering cost penalty to the program economics. A custom power block design, tailored to a specific application and capable of maximizing the overall engine efficiency, results in long-term (typically multi-year) engineering efforts costing millions of dollars US, and produces a design that is unproven, unreliable, and not flexible to any variations in the system found in subsequent installations.

With the relaxed sensitivity to efficiency that accompanies the emerging lower-cost heliostat solutions, the adoption of well-developed, reliable, and cost-effective engines that are essentially off-the-shelf product offerings becomes possible. Instead of tailoring the engine to fit an integrated CSP system, this program recognizes that relying on a well-developed, proven gas turbine technology is key to overall system economics and, more importantly, system reliability.

For the proposed system there are several key power block requirements:

- A well-developed, commercially-available design with a proven track record of reliability
- A power rating of less than 10 MW_e, ideally in the 1-6 MW_e range
- A nominal turbine inlet temperature between 600 and 1000 C, corresponding to the limits of solar receiver designs that exhibit long-life and high efficiency

- High efficiency, as performance continues to have significant impact on the system economics through the solar field, receiver, and thermal energy storage sizings
- Operational flexibility, with good turn-down/part-power performance characteristics
- Compelling transient performance, including short cold-start times and fast ramp-up/ramp-down capabilities to provide load-following and on-demand power according to the immediate requirements of the grid or microgrid.

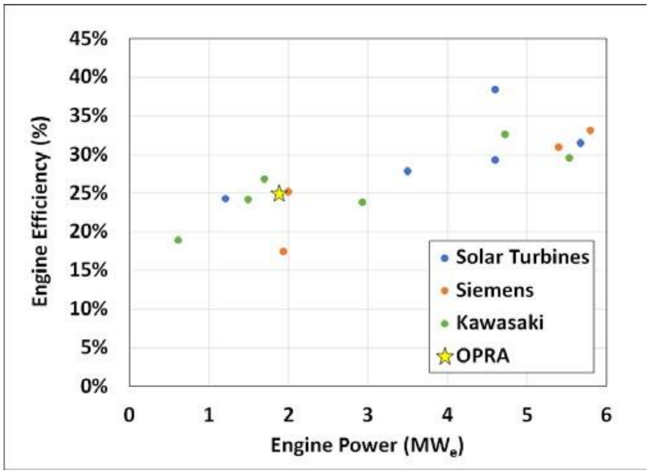


Figure 15. Off-the-shelf commercially-available gas turbine solutions with proven performance in the 1-6 MW_e power range of interest for this application

There are a number of commercial gas turbine manufacturers that have a product that meets most or all of the above requirements, including Kawasaki (GPB06, M1A-13A, M1T-13A), Siemens (KG2-3), Solar Turbines (Saturn 20, Centaur 40), and OPRA Turbines (OP16). The performance of these candidate is presented in Figure 19. The current proposal favors the OP16 offering from OPRA Turbines (shown in Figure 20), for several reasons:

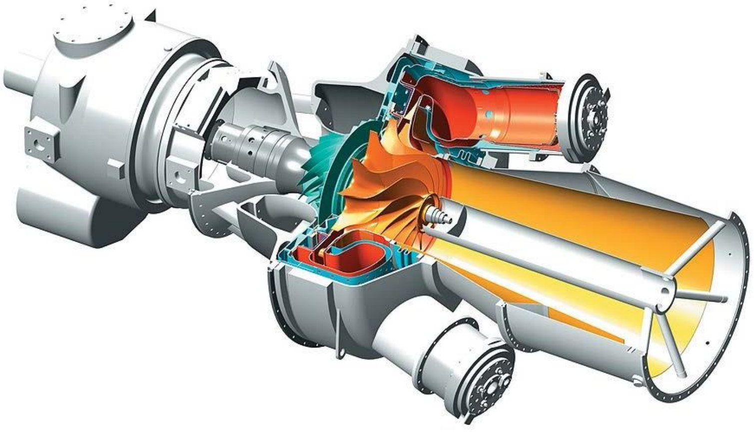


Figure 20. Cross section view of the OPRA 1.6 MW_e Gas Turbine Engine, used as the baseline power block option for the engineering development of the integrated system

- The nominal engine power rating of 1.6 MW_e is small enough to make first-deployed-system capital costs – which include the costs not only of the engine but the size of the heliostat field, receiver, TES – reasonable and attractive.
- The power rating is simultaneously large enough to sustain a sizable microgrid, suitable for distributed power applications capable of servicing whole neighborhoods, communities, or industrial customers.
- The OP16 has a high cycle efficiency at its nominal power rating, reducing the solar field and the TES capacity needed for a specified system

- The engine has broad turndown capabilities, and is capable of operating with any load between 0% and 100% indefinitely. Power and Heat Rate curves down to 60% power are shown in Figure 21. This flexibility is critical to the integrated solution being proposed here.
- The turbine inlet temperature ranges between 900 C and 1000 C, in line with the solar receiver requirements.

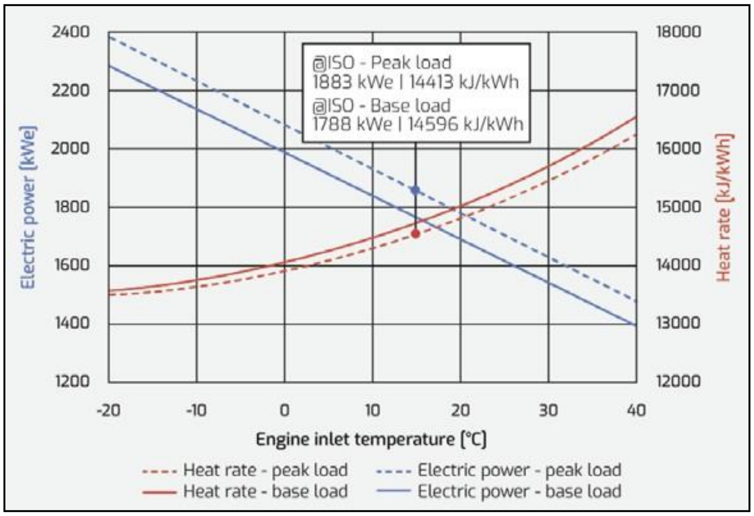


Figure 21- Power and heat rate curve for the OPRA 1.6 MW_e gas turbine engine [12]

- The unit is a robust, proven design that is commercially available in a range of configurations. Figure 22 shows the unit in packaged form, with the generator and electronic controls all contained within an environmental enclosure.

Figure 22. Typical package view for the OPRA 1.6 MW_e engine, including engine, generator, environmental container, and controls electronics

- Lastly, this engine has seen prior integration in CSP systems, demonstrating its flexibility and suitability in these renewable energy applications [13].

In its standard gas-fueled configuration, the engine exhibits excellent transient behavior, including:

- A typical cold start-up time of 90 seconds for installations with 10 m exhaust duct length
- A maximum start-up time of 200 seconds for installations, observed in installations with much longer exhaust ducting lengths.
- Ramp-up rates of up to 1,000 kW/s

In the proposed system, the engine will retain these capabilities as the system may operate in gas-fueled mode if an especially rapid response is required. During operation within the integrated solar/TES configuration these characteristics will be modified due longer duct lengths and the thermal inertia of the primary regenerator. Estimated start-up time if constrained to this mode of operation is approximately 300 seconds, with comparable 1000 kW/s allowable ramp rates.

Power Block Heat Addition

The heat addition required to run the engine occurs via one of two systems:

- The standard power block fueled combustor; the aforementioned OPRA OP16 engine will retain its can combustor system. This enables the engine to operate on natural gas or diesel during periods of extended solar resource deficit, during field/receiver/TES maintenance, and during startup operation. A backup heating source is considered imperative for a system that must have high availability.

- Via a proprietary regenerator system that enables the power block to run off heat supplied by the TES. The regenerator system contains a high-temperature capable static media that alternates between absorbing heat from the TES and delivering heat to the engine cycle; with multiple regenerator section operating in parallel, both of these functions can be performed simultaneously, allowing the engine to run off stored energy indefinitely.

Historically, primary heat exchangers have also served this heat transfer functionality; however, like the custom power block, there has never been an economically successful custom heat exchanger developed for a CSP application. To achieve high effectiveness and thereby maximize system efficiency, the heat exchanger must be large in size; this has always required a large mass of expensive high-grade high-temperature metal alloy – typically a nickel alloy. Furthermore, advanced and specialized manufacturing processes must be employed, which entails large non-recurring engineering and tooling costs, and usually precludes the manufacture of the unit using industry local to the site of system deployment.

By contrast, a regenerator may use relatively low-cost materials, some of which may be sourced and produced using local resources. The design employed here minimizes the use of metal and advanced manufacturing methods, thereby enabling local manufacture and assembly of this key enabling component.

Auxiliary Components

In addition to the major subsystems addressed above there are a number of ancillary components critical to the design and operation of the system. As with the power block, a guiding philosophy has been to utilize, wherever possible, off-the-shelf commercially available products that have been tested, fielded, and proven reliable in the operating conditions required for this application. This not only reduces the capital investment costs needed to deploy the first system, but also incorporates system reliability at all levels of the design.

Production instrumentation – including thermocouples and pressure transducers – will be standard configurations. Piping and tubing will consist of standard sizes with external insulation, eliminating the engineering, manufacture, complexity of coaxial or internally-insulated fluid transport solutions. Up-tower componentry is limited to the solar receiver only, minimizing its structural requirements and simplifying its design, foundation, and construction.

Valves are a critical component that are used throughout the system; solenoid and motorized control valves are a well-understood familiar technology that exhibit robust operation and long-life when used in accordance with their design. The proposed CSP system eschews the use of moving parts wherever possible as they add complexity and points of failure, instead favoring reliable valve solutions to accomplish actuation and control the system. The design also prioritizes a layout that leverages low-temperature valve solutions, further improving the overall system reliability by employing those designs that are most widely-produced and deployed.

That said, the proposed system does require hot valves in order to control the flow of receiver outlet air through the TES modules, and to modulate flow through the primary regenerator. Multiple commercial options suitable for the required operating temperature range have been identified; these include the 1000 ^{0}C-rated Batley BV10000 valve [14] (Figure 23) and the 950 ^{0}C-rated Cera KST-X-HT valve [15] [16] (Figure 24).

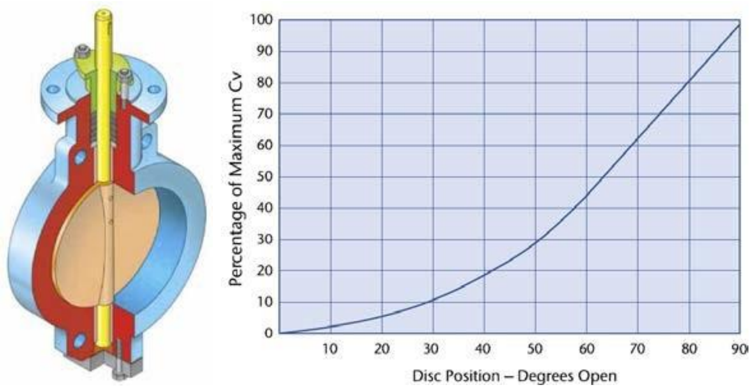


Figure 23. Batley BV10000 valve rated to 1000 ^{0}C

Design Flexibility and Options

The basic design as described above represents an integrated solar power system with thermal energy storage that is capable of dispatching electricity when needed, day or night. Several “upgrades” or design modification recommend themselves for eventual integration with the system. Each entails additional cost and development, but addresses an installation-specific need that may exist. These options include:

- **Up-Sized Storage** – the system presented is tailored to operate within comfortable temperature, pressure, and load limits throughout. A more aggressive design may alternatively be employed to increase the rate of storage and the resulting duration and/or level of dispatchable power. This may be achieved by introducing a multi-pass receiver design, or by increasing the operating receiver temperature. Both of these options are viable but require additional engineering development work.

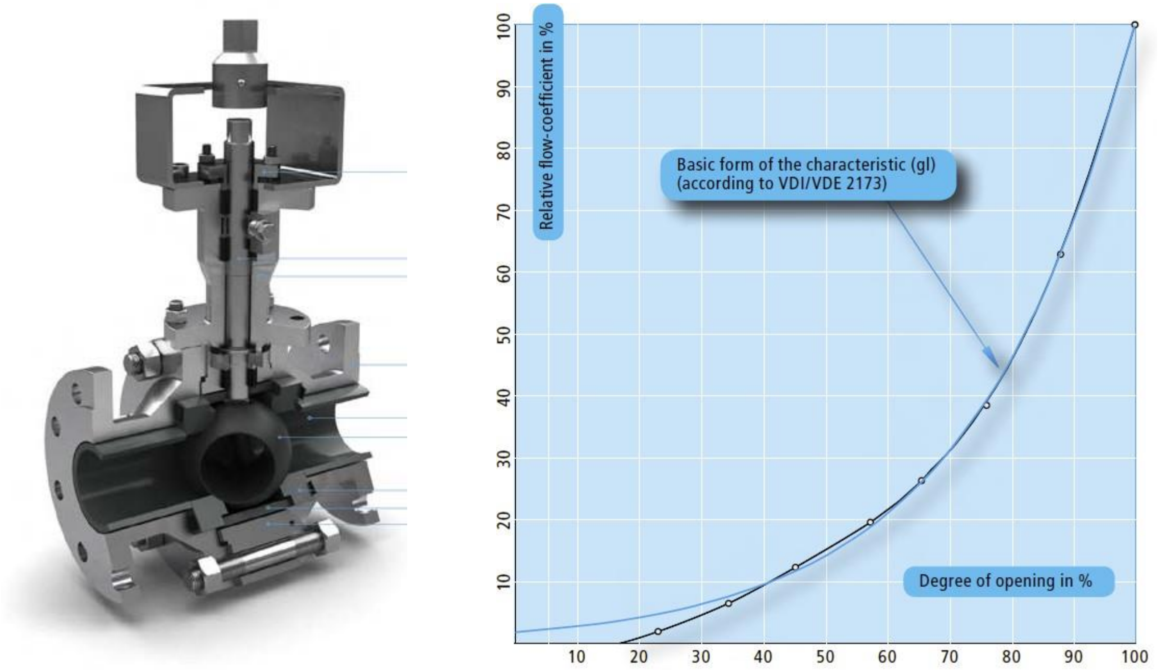


Figure 16. Cera Valve KST-X-HT valve, rated to 950 ºC

- **Independent Power Block** – the integrated system uses the power block working fluid as the heat transfer fluid within the receiver; furthermore, the engine itself is used as the circulator, which delivers the air to the receivers and thermal energy storage system. Alternatively the power block may be separated from the solar absorption and thermal energy storage components by transitioning to a separate heat transfer fluid loop. This separate loop would require additional engineering development and its own circulator which will, necessarily, add capital cost and consume a significant amount of electricity during TES charging operation, making it better suited for peaker-type applications than constant-power applications.

- **Local Space and Water Heating** – the 300 ºC exhaust flow from the system represents a significant source of thermal energy that can be applied to various heating applications, including (a) steam generation, (b) air heating, and (c) water heating for commercial, industrial, or residential applications. As a source of water heating, for example, the system delivers 1.7 to 2.1 MW_t of water heating potential (assuming a target water temperature of 50 ºC).

- **Water Distillation** – that same 300 ºC exhaust flow can also be coupled to a multi-flash or multi-effect distillation system to purify and deliver clean water. With nominal exhaust conditions a coupled system has the capacity to provide between 1,200 and 5,000 m^3 (1.2M to 5.0M liters) of clean, potable water (depending on the technology used and its system efficiency) per day (assuming 14 hours of engine runtime).

- **Long-Duration Storage –** The receiver outlet conditions may be appropriate for coupling to a Manganese Oxide trickle-charged thermochemical energy storage system. In this concept, a small flow of receiver discharge gas is passed through a bed of static Mn_2O_3 to endothermically drive off oxygen (producing Mn_2O); once charged this bed may be sealed to isolate it indefinitely. To discharge the stored energy engine compressor discharge flow may be fed into the Mn_2O, where oxygen re-bonds with the media bed and in an exothermic reaction that heats the flow to the desired temperature [17]. The result is an environmentally-benign, high-energy-density, long-term heat storage system capable of dispatching its energy days, months, or even years after it is initially charged. This is envisioned as, for example, a backup system that enables the system to run through extended weather interruptions.

Impact

Social and Climate Benefits

The proposed solution represents a fundamental step towards global sustainability, emphasizing renewable energy that is accessible around the clock as well as social responsibility. As a solar energy system with integrated energy storage, this system delivers electrical power to end users without contributing to the greenhouse gas emissions driving climate change. When used to displace existing fossil-fueled energy sources, it actively reduces emissions, moving society towards the recommendations of the International Panel on Climate Change. It furthermore accomplishes this while simultaneously promoting the well-being of its end users via:

- Enhancing quality of life and promoting economic growth
- Providing energy security by decentralizing the electrical power infrastructure
- Eschewing the use of toxic materials and heavy metals that have a lasting and pernicious effect on local populations

The International Panel on Climate Change has identified key Sustainable Development Goals (SDGs) that move society towards a just, secure, and equitable model that emphasizes not only human rights and opportunity but also effective and sustainable stewardship of the earth and its natural resources [3]. These goals are listed in Figure 25, along with their relative trade-offs and synergies with respect to the key enabling metrics of Energy Supply, Energy Demand, and Land. The two primary impacts of this program – SDG7 Affordable and Clean Energy and SDG 11 Sustainable Cities and Communities – are highlighted in green, and are shown to have dramatic synergies with few-to-no trade-offs. Note that two other SDGs – specifically SDG 6 Clean Water and Sanitation and SDG Industry, Innovation, and Infrastructure – are not highlighted, but have a very high potential for integration with this system, further enhancing its societal benefits.

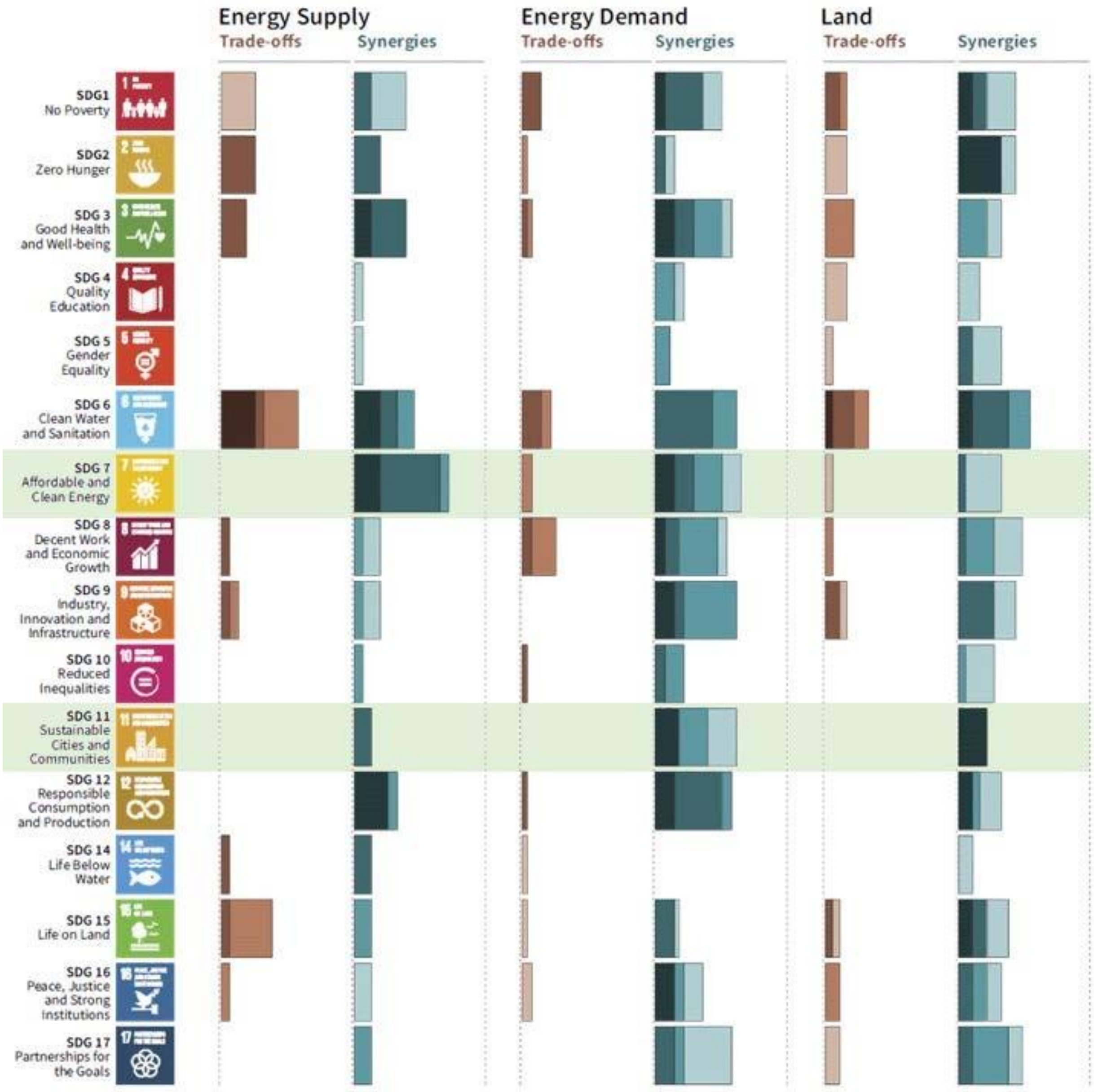


Figure 17. IPCC Sustainable Development Goals (SDGs), showing the relative synergies and trade-offs with respect to the key metrics of Energy Supply, Energy Demand, and Land. The proposed Enlys solution specifically targets SDG 7 and SDG 11 (highlighted in green), providing clean and affordable energy in a distributed and sustainable fashion to communities. Note that these SDG exhibit large synergies with the other goals with minimal trade-offs. Also note that the proposed system has the opportunity to engage SDG 6 (via waste heat driven distillation/desalination processes) and SDG 9 (via local manufacturing and workforce engagement)

The energy provider is benefited by the adoption of this system as well:

- Distributed electrification of new areas does not require a large capital investment in transmission and distribution networks between communities

- Flexible operation allows it to respond to the needs of the grid, varying its dispatch and storage profiles to respond to changing demands and transient load profiles

Engagement with Local Manufacturing

The proposed system – consisting of a next-generation heliostat field, a commercially-available power block coupled to a primary regenerator-type heater, a central tower and receiver, and a high-capacity energy storage system – has been designed with the intent of leveraging local materials and engaging the local workforce. Historically the most successful technical adoptions have been those that engage the hearts and minds of the local populations, and instill a sense of ownership, pride, and satisfaction to those who live alongside the products of their efforts.

A short non-exhaustive list of potential manufacturing, industrial, and specialist services that may engage the Madhya Pradesh workforce in the support of this program and future instances of the technology includes but is not limited to:

Heliostat Assembly and Installation

Each instance of the proposed design requires thousands of small-scale heliostats. Traditionally the most economic means of deploying these critical components is to have their parts delivered to the site for local assembly, thereby eliminating the need for costly packaging and the risk of breakage during shipping. Once assembled the heliostats are transported to their precise point of deployment and installed (either via a driven pile or a ballasted frame) and wired for power and/or communications, depending on the specific design.

Edisun would provide the necessary service to manage the deployment of the first heliostat field, but use local personnel to assist in the critical assembly, transport, and installation tasks. They would also convey key learning to a team of local lead engineers, such that follow-on installations could be assembled with progressively less on-site direct support by Edisun personnel. Ultimately there could be a local center of excellence boasting a team capable of installing, commissioning, debugging, programming, and maintaining next-generation heliostats anywhere in the country.

Thermal Energy Storage Media Fabrication

The Thermal Energy Storage system, due to its Megawatt-scale power level and multi-hour capacity requirement, is physically large. More than 8 metric tonnes of sensible heat storage media is required for every MWh_t of storage.

As envisioned in this project, that sensible heat storage media consists of formed units of firebrick that are produced *en masse*, transported to the site, and installed within the integrated system. This requires a fabrication facility capable of producing the large volume of high-temperature capable formed material, an industry that could be supplied entirely by the local workforce using locally sourced materials.

Primary Heater Module Fabrication

The proposed system employs a modular regenerator system to convey heat from the Thermal Energy Storage system into the Gas Turbine Engine power block. These regenerator modules consist of a metal vessel, insulation, and an internal sensible storage media; altogether the modules must be capable of transferring more than 5 MW_t on a continuous basis for each instance of the proposed design.

The fabrication of these modular units – which consists of vessel fabrication, insulation installation, and solid media packing – can all be performed using the local workforce and, in large part, locally-sourced materials. Also note that as a modular design that is flexible in terms of its working fluid and operating temperature and can be scaled to a broad range of heat transfer rates, this subcomponent assembly may be a viable product offering to other industries both domestic and abroad.

System Installation and Commissioning

Although there will be specialized components that must be specially sourced (e.g. the gas turbine engine), much if not all of the actual on-site assembly can be performed by a trained local workforce. Site preparations, tower and engine foundations, tower assembly, receiver mounting, piping and insulation, instrumentation, electrical interconnections, TES installation, and system commissioning can be performed by a trained local workforce.

Service and Operations

While the overall system is designed to be reliable and autonomous, there will still be a need for periodic inspection, maintenance, calibration, and service. As deployment of the system expands throughout the country and other regions there will be a need for a qualified service center that can monitor installations and dispatch personnel for these periodic and scheduled needs.

In the case of regenerator and thermal energy storage subcomponent production, local technical and business leadership will be needed to set up initial manufacturing capacity. It may also be advantageous to co-locate the thermal energy media production with local raw material resources, reducing the transportation costs of raw material and enabling the lower-cost transport of finished product.

Economic Potential

Cost-effective integration and deployment has remained the primary challenge facing wide adoption of CSP with TES. However, in recent years there has been a steady and significant decline in the levelized cost of electricity from CSP plants, such that "by 2020 commissioned CSP plants will increasingly be delivering electricity at a cost that is within the lower end of the fossil fuel-fired cost range [18]. There is a large untapped global market that is hungry for this type of solution. As described previously, this technology is unique in its ability to address multiple social, environmental, and economic needs simultaneously.

Figure 26 shows key regions across the globe for which this technology is ideally suited, and which provide key initial markets in which to grow and export this solution.

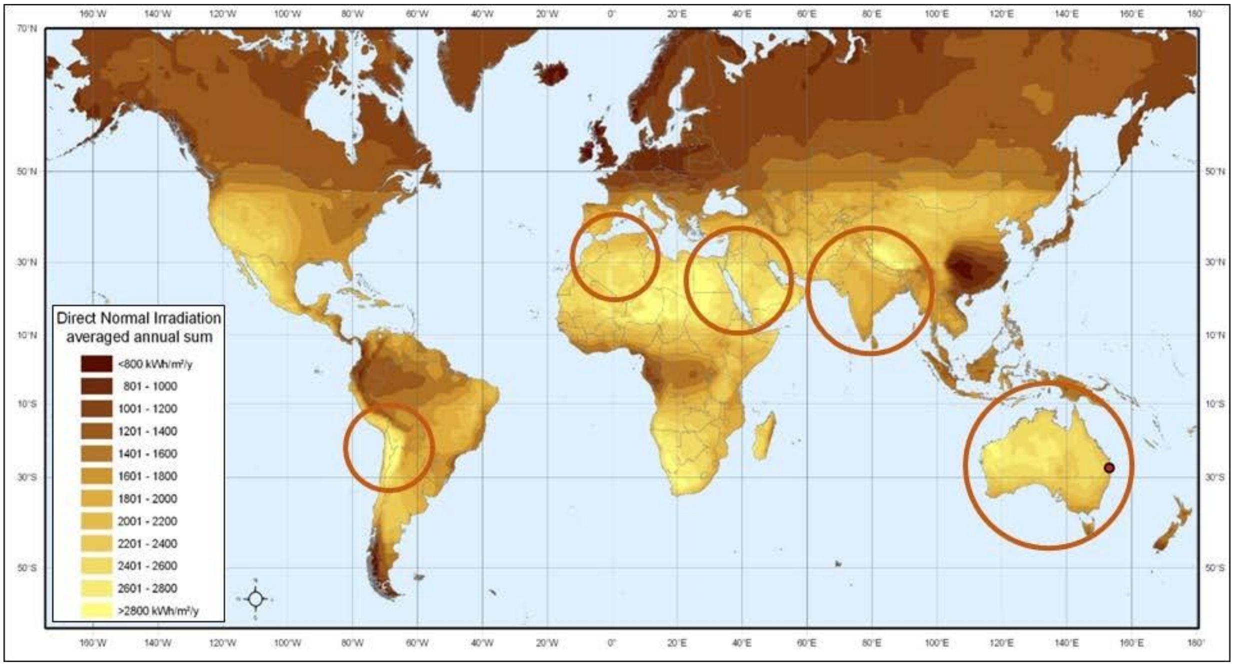


Figure 18. A map of the global Direct Normal Irradiation solar resource, with highlighted regions indicating large areas of the world that are ideal markets for the proposed system; these regions are characterized by (a) a favorable solar resource, (b) leadership and popular support for renewable energy technologies, and (c) a electrical infrastructure (or lack thereof) that favors reliable, distributed, secure power generation solutions

Among these India is considered a primary first market opportunity for the proposed solution, as its near-term Renewable Energy targets require more than 70 GW of new solar energy capacity within the next few years; this is motivated in part by the fact that India has an abundant India also has an abundant solar resource (as can be seen in Figure 27). However, successful and reliable deployment of new solar energy on the desired scale is only possible in the context of rigorous grid controls, which is greatly enhanced by integrated energy storage. Furthermore, with many communities still off the national grid system, a relatively small scale distributed power system has a broad applicability and potential to bring electricity and economic growth potential to millions of people.

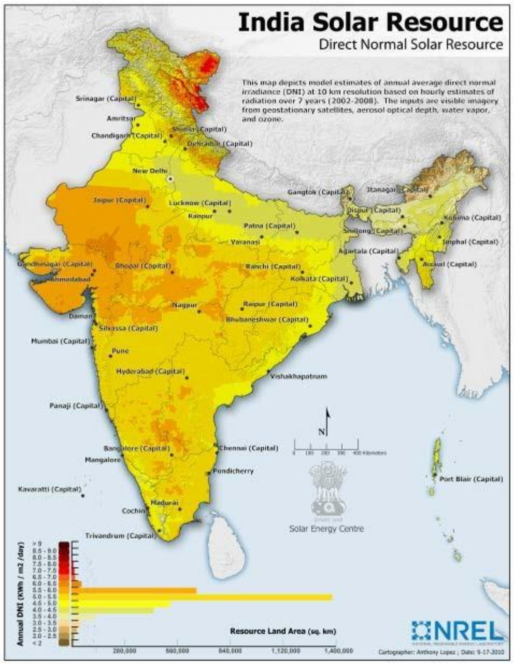
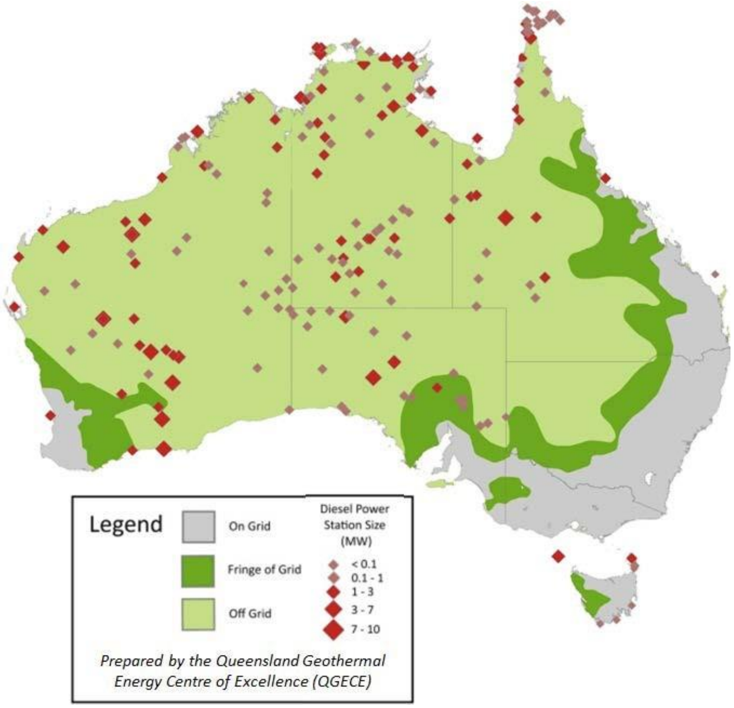


Figure 27. A map of India showing its abundant and free natural Direct Normal Radiation solar resource [19]

The interior of Australia is viewed as another primary market opportunity. Its electrical infrastructure is primarily along the coasts, but there is an extensive distributed power demand (approximately 2,000 MW_e) in mining installations alone; the vast majority of these require between 1 and 10 MW_e of power (see Figure 28). These facilities currently rely on the costly import and transport of diesel fuel from the coasts, and are actively seeking renewable and reliable energy sources to supplement or replace their incumbent gensets.



Prepared by the Queensland Geothermal Energy Centre of Excellence (QGECE)

Figure 19. Market potential for a distributed CSP system with storage throughout Australian interior [20]

Through partnership in the initial deployment and operation of the system, Madhya Pradesh will be established as the experienced first-to-market source for the supply of trained personnel and industry support relating to this technology. This experience and expertise can be leveraged to transform Madhya Pradesh into a Center of Excellence for this type of system, supporting the renewable expansion of its own growing electrical needs but also exporting this skillset to support growth in other states within India, and to other countries in the region.

Programmatic Details

Scope

The program is divided in three (3) phases. The Phase 1 will encompass the system design efforts, system specification and engineering development. RPI and RKDF university will work closely with Enlys to accomplish the goals as presented below. The Phase 2 will include the Procurement, Fabrication, Installation and System Commissioning contingent upon successful execution and favorable results from Phase 1 (System and Site Specification and Engineering Development). Based on the results of the Phase 1, various commercial vendors will be used in Phase 2 for execution of the field work as discussed below. The Phase 3 will consist of joint research between RPI and RKDF University using the megawatt scale test bed in Bhopal, India. For the TES plant of 5 MW capacity, the executing agency is a joint venture of Ram Krishna Dharmarth Foundation (RKDF) University, Bhopal & Siddhartha Kapoor Infrastructure Pvt. Ltd., (SKIPL) Bhopal.

PHASE 1 – System and Site Specification and Engineering Development – 15 months

- Defining the CSP test bed research topics
- Site selection and full system definition
    - Work in close partnership with MPPMCL to identify the installation site for the first-in-class demonstration facility
        - Initiate site land acquisition, permitting, preparation, etc. as necessary
    - Specify the target CSPwS system characteristics (including power rating, storage capacity, typical operation, outlying operating modes, etc.)
    - Define system operating profile according to the need of the end users or local grid
    - Engage Project Management Officer (PMO) and Engineering/Procurement/ Construction (EPC) company to execute actual site installation; EPC company may be designated by MPPMCL or by RPI and RKDF in accordance with customer needs
- Perform subsystem engineering development efforts in accordance with finalized targets and the specific installation details
    - *Solar Collector Field*
        - Optimize solar collector field layout for the site
        - Generate annualized power delivery and receiver incident flux profiles
        - Generate full solar collector field cost, including hardware, on-site installation, and required wiring for power, controls, etc.
    - *Solar Receiver*
        - Specify receiver layout in accordance with solar collector field output and receiver efficiency, pressure drop, and life targets
        - Generate updated receiver performance model
        - Generate updated annualized receiver performance results
        - Generate full Receiver subsystem Bill of Materials
    - *Riser/Down-Comer*
        - Specify low-DP piping layout in accordance with Power Block outlet conditions, receiver outlet conditions, and thermal loss and pressure drop requirements
        - Generate full piping subsystem Bill of Materials
    - *Thermal Energy Storage*
        - Specify TES layout in accordance with receiver performance, storage capacity, and pressure drop requirements
        - Generate updated TES system performance model
        - Generate full TES subsystem Bill of Materials
    - *Primary Regenerators*
        - Specify primary regenerator layout in accordance with TES performance, Power Block requirements, and target performance and pressure drop requirements
        - Generate updated regenerator performance model
        - Generate regenerator subsystem Bill of Materials
    - *Power Block*

        - Provide engine operating details to vendor to finalize any controls, instrumentation, and or component swap-outs required to optimize performance in the site-specific installation
        - Power Block manufacturer to provide modified compressor discharge flow path design to enable integration with primary regenerator upstream of fueled combustor
- Integrate site-specific critical subsystem designs into full system performance model
    - Reconcile discrepancies to finalize subsystem/subcomponent designs
    - Generate annualized system performance (energy capture, storage, electrical delivery, etc.) for the full system given the defined operating profile
    - Identify the limits of system operability
    - Incorporating detailed BOM estimates from each constituent subsystem, finalize an updated full system capital cost
    - Generate Levelized cost of Electricity, Internal Rate of Return, Payback, and other financial metrics
- Installation and Operation Preparations
    - Produce pseudo-code controls logic for operation of the integrated system, including mitigation or protection for handling all cases encountered in risk register
    - Generate preliminary commissioning plan to bring installation on-line
- Finalize first-unit local manufacturing plan opportunities
    - Establish manufacturing entity startup plan (location, organization, personnel, necessary capital equipment, etc.) to be initiated upon start of Phase 2 for:
        - Producing regenerator modules
        - Fabricating TES storage media elements (firebrick, formed ceramic, alkali halide salt, etc.)

PHASE 2 – Procurement/Fabrication, Installation, and System Commissioning – 15 months

- Execute site preparations
    - Clearing and Grading
    - Excavation work (if TES is to be located underground)
    - Tower and power (and TES if aboveground) foundation
    - Back-up fueled engine combustor infrastructure (if specified)
    - Electrical interconnections and tie-ins to grid/micro-grid/local load
- Enact local manufacturing plan developed in Phase 1 to bring production capacity on-line
- Finalize Operational preparations
    - Full controls development, including integrated control of solar field, receiver/TES/ regenerator valves, and power block
    - Generate finalized commissioning plan for bringing the installation on-line
- Procure critical components and subsystems (including international shipping where required)
    - *Solar Field* – via US-based vendor Edisun, with the potential to export on-site fabrication, installation, controls development, and service/maintenance capabilities to an affiliated team in India for suture installations
    - *Power Block* – place purchase order for delivery for gas turbine engine with environmental enclosure, controls/component upgrades specific to the application,

    and compressor discharge flow path modification to accommodate primary regenerator heat input during operation via TES discharge
  - *Receiver* – the first unit will be a custom design, fabrication location to be determined (primary candidates are US-based fabrication, fabrication in Australia, or fabrication in India in conjunction with local industrial partner)
  - *Riser/Down-comer/Piping* – fabrication to be performed in India
  - *Thermal Energy Storage* – media to be fabricated in India in accordance with manufacturing plan outlined above. Media may be produced locally, or from a centralized location with transport to site
  - *Primary Regenerators* – to be fabricated in India in accordance with manufacturing plan outlined above.
- Full installation on Site
  - Local workforce will be safely and productively engaged to the greatest extent possible throughout the installation process
  - First-unit heliostat field installed in accordance with vendor coordination
  - Tower to be designed and installed by EPC in coordination with PMO
  - Receiver/Riser/Down-comer/TES/Regenerator to be installed by EPC in coordination with PMO/Enlys Energy
  - Power Block installation to be coordinated and managed between Gas Turbine Manufacturer, PMO, and MPPMCL
  - Electrical connections and interfaces to be managed by MPPMCL in coordination with PMO
- System Commissioning to be performed in accordance with plan drafted in Phase 1 and finalized in Phase 2. Commissioning to be coordinated through Enlys Energy, PMO, and MPPMCL to ensure that startup and shake-down occurs in compliance with all safety and regulatory guidelines.

PHASE 3 – CSP Testbed Research – 30 months

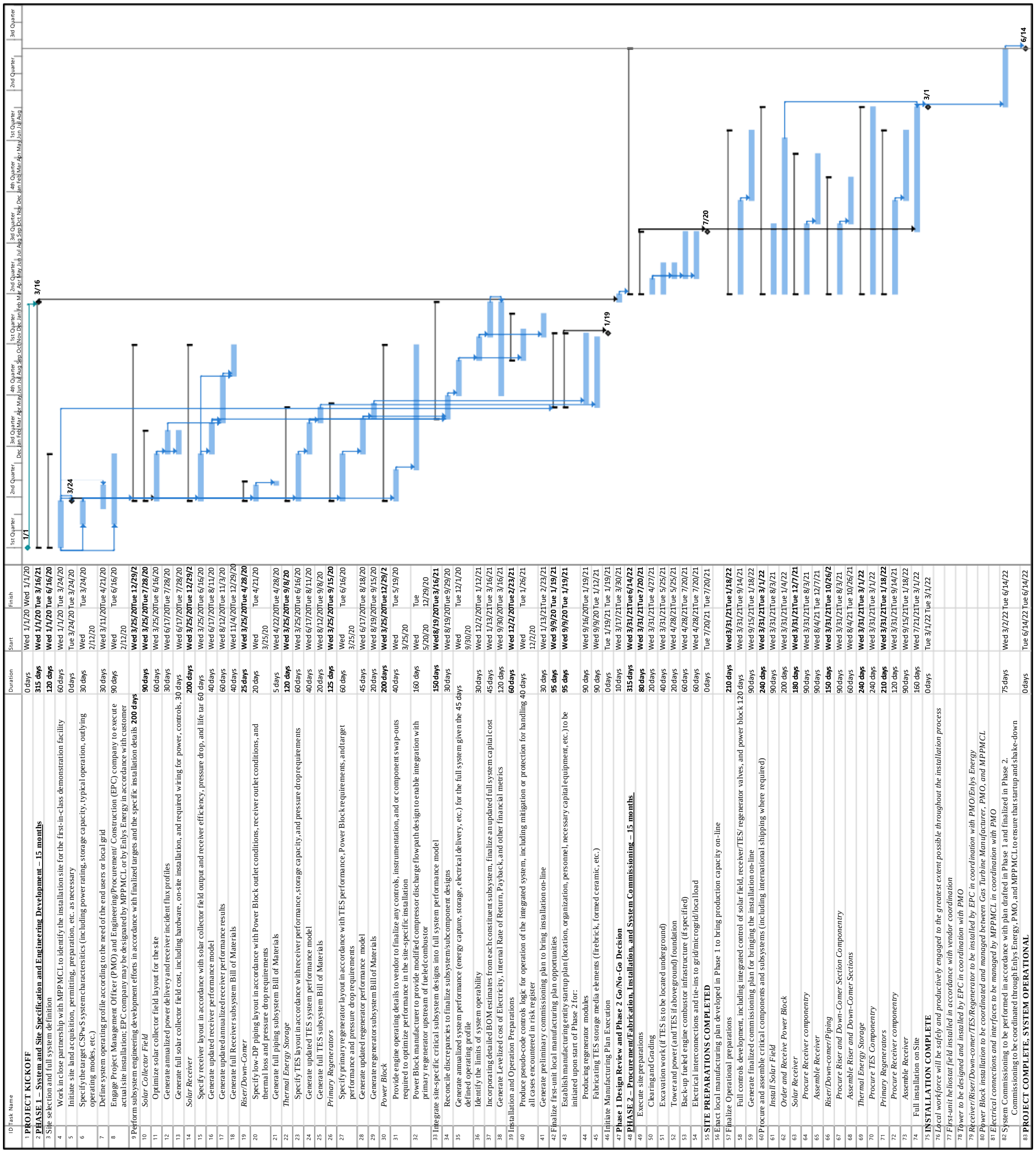
- Quantify the seasonal energy capture over a period of 2 years
- Quantify the thermal energy storage duration useful for electric power generation and direct heating applications
- Quantify the cost of energy versus operating cost and capital cost
- Quantify the efficiency of thermal storage in various earth abundant, commercially available and novel materials based TES media
- Quantify the degradation in infrastructure and performance due to weathering and operation, and estimate the projected lifetime of the CSP megawatt scale plant
- Publish the results in scientific journals to benefit the global community with experimental field data directly gathered from a megawatt scale CSP system.

Schedule for Phase 1 and Phase 2

A screenshot of the preliminary 30-month project plan is provided in Figure 29, consisting of two distinct two consecutive Phases:

1. A 15-month engineering and design Phase, wherein the installation site is selected and engineering efforts specific to that installation are performed, and

2. A 15-month procurement, assembly, delivery-to-site, installation, and commissioning Phase that results in a fully-operational CSP system with integrated power block and TES.



ID	Task Name	Duration	Start	Finish
1	**PROJECT KICKOFF**	0 days	Wed 1/1/20	Wed 1/1/20
2	**PHASE 1 – System and Site Specification and Engineering Development – 15 months**	**315 days**	**Wed 1/1/20**	**Tue 3/16/21**
3	Site selection and full system definition	**120 days**	**Wed 1/1/20**	**Tue 6/16/20**
4	Work in close partnership with MPPMCL to identify the installation site for the first-in-class demonstration facility	60 days	Wed 1/1/20	Tue 3/24/20
5	Initiate site land acquisition, permitting, preparation, etc. as necessary	0 days	Tue 3/24/20	Tue 3/24/20
6	Specify the target CSPwS system characteristics (including power rating, storage capacity, typical operation, outlying operating modes, etc.)	30 days	Wed 2/12/20	Tue 3/24/20
7	Define system operating profile according to the need of the end users or local grid	30 days	Wed 3/11/20	Tue 4/21/20
8	Engage Project Management Officer (PMO) and Engineering/Procurement/ Construction (EPC) company to execute actual site installation; EPC company may be designated by MPPMCL or by Enlys Energy in accordance with customer	90 days	Wed 2/12/20	Tue 6/16/20
9	Perform subsystem engineering development efforts in accordance with finalized targets and the specific installation details	**200 days**	**Wed 3/25/20**	**Tue 12/29/2**
10	*Solar Collector Field*	**90 days**	**Wed 3/25/20**	**Tue 7/28/20**
11	Optimize solar collector field layout for the site	60 days	Wed 3/25/20	Tue 6/16/20
12	Generate annualized power delivery and receiver incident flux profiles	30 days	Wed 6/17/20	Tue 7/28/20
13	Generate full solar collector field cost, including hardware, on-site installation, and required wiring for power, controls,	30 days	Wed 6/17/20	Tue 7/28/20
14	*Solar Receiver*	**200 days**	**Wed 3/25/20**	**Tue 12/29/2**
15	Specify receiver layout in accordance with solar collector field output and receiver efficiency, pressure drop, and life tar	60 days	Wed 3/25/20	Tue 6/16/20
16	Generate updated receiver performance model	40 days	Wed 6/17/20	Tue 8/11/20
17	Generate updated annualized receiver performance results	60 days	Wed 8/12/20	Tue 11/3/20
18	Generate full Receiver subsystem Bill of Materials	40 days	Wed 11/4/20	Tue 12/29/20
19	*Riser/Down-Comer*	**25 days**	**Wed 3/25/20**	**Tue 4/28/20**
20	Specify low-DP piping layout in accordance with Power Block outlet conditions, receiver outlet conditions, and thermal loss and pressure drop requirements	20 days	Wed 3/25/20	Tue 4/21/20
21	Generate full piping subsystem Bill of Materials	5 days	Wed 4/22/20	Tue 4/28/20
22	*Thermal Energy Storage*	**120 days**	**Wed 3/25/20**	**Tue 9/8/20**
23	Specify TES layout in accordance with receiver performance, storage capacity, and pressure drop requirements	60 days	Wed 3/25/20	Tue 6/16/20
24	Generate updated TES system performance model	40 days	Wed 6/17/20	Tue 8/11/20
25	Generate full TES subsystem Bill of Materials	20 days	Wed 8/12/20	Tue 9/8/20
26	*Primary Regenerators*	**125 days**	**Wed 3/25/20**	**Tue 9/15/20**
27	Specify primary regenerator layout in accordance with TES performance, Power Block requirements, and target performance and pressure drop requirements	60 days	Wed 3/25/20	Tue 6/16/20
28	Generate updated regenerator performance model	45 days	Wed 6/17/20	Tue 8/18/20
29	Generate regenerator subsystem Bill of Materials	20 days	Wed 8/19/20	Tue 9/15/20
30	*Power Block*	**200 days**	**Wed 3/25/20**	**Tue 12/29/2**
31	Provide engine operating details to vendor to finalize any controls, instrumentation, and or component swap-outs required to optimize performance in the site-specific installation	40 days	Wed 3/25/20	Tue 5/19/20
32	Power Block manufacturer to provide modified compressor discharge flowpath design to enable integration with primary regenerator upstream of fueled combustor	160 days	Wed 5/20/20	Tue 12/29/20
33	Integrate site-specific critical subsystem designs into full system performance model	**150 days**	**Wed 8/19/20**	**Tue 3/16/21**
34	Reconcile discrepancies to finalize subsystem/subcomponent designs	30 days	Wed 8/19/20	Tue 9/29/20
35	Generate annualized system performance (energy capture, storage, electrical delivery, etc.) for the full system given the defined operating profile	45 days	Wed 9/30/20	Tue 12/1/20
36	Identify the limits of system operability	30 days	Wed 12/2/20	Tue 1/12/21
37	Incorporating detailed BOM estimates from each constituent subsystem, finalize an updated full system capital cost	45 days	Wed 1/13/21	Tue 3/16/21
38	Generate Levelized cost of Electricity, Internal Rate of Return, Payback, and other financial metrics	120 days	Wed 9/30/20	Tue 3/16/21
39	Installation and Operation Preparations	**60 days**	**Wed 12/2/20**	**Tue 2/23/21**
40	Produce pseudo-code controls logic for operation of the integrated system, including mitigation or protection for handling all cases encountered in risk register	40 days	Wed 12/2/20	Tue 1/26/21
41	Generate preliminary commissioning plan to bring installation on-line	30 days	Wed 1/13/21	Tue 2/23/21
42	Finalize first-unit local manufacturing plan opportunities	**95 days**	**Wed 9/9/20**	**Tue 1/19/21**
43	Establish manufacturing entity startup plan (location, organization, personnel, necessary capital equipment, etc.) to be initiated upon start of Phase 2 for:	**95 days**	**Wed 9/9/20**	**Tue 1/19/21**
44	Producing regenerator modules	90 days	Wed 9/16/20	Tue 1/19/21
45	Fabricating TES storage media elements (firebrick, formed ceramic, etc.)	90 days	Wed 9/9/20	Tue 1/12/21
46	Initiate Manufacturing Plan Execution	0 days	Tue 1/19/21	Tue 1/19/21
47	**Phase 1 Design Review and Phase 2 Go/No-Go Decision**	10 days	Wed 3/17/21	Tue 3/30/21
48	**PHASE 2 – Procurement/Fabrication, Installation, and System Commissioning – 15 months**	**315 days**	**Wed 3/31/21**	**Tue 6/14/22**
49	Execute site preparations	**80 days**	**Wed 3/31/21**	**Tue 7/20/21**
50	Clearing and Grading	20 days	Wed 3/31/21	Tue 4/27/21
51	Excavation work (if TES is to be located underground)	40 days	Wed 3/31/21	Tue 5/25/21
52	Tower and power (and TES if aboveground) foundation	20 days	Wed 4/28/21	Tue 5/25/21
53	Back-up fueled engine combustor infrastructure (if specified)	60 days	Wed 4/28/21	Tue 7/20/21
54	Electrical interconnections and tie-ins to grid/microgrid/local load	60 days	Wed 4/28/21	Tue 7/20/21
55	**SITE PREPARATIONS COMPLETED**	0 days	Tue 7/20/21	Tue 7/20/21
56	Enact local manufacturing plan developed in Phase 1 to bring production capacity on-line			
57	Finalize Operational preparations	**210 days**	**Wed 3/31/21**	**Tue 1/18/22**
58	Full controls development, including integrated control of solar field, receiver/TES/ regenerator valves, and power block	120 days	Wed 3/31/21	Tue 9/14/21
59	Generate finalized commissioning plan for bringing the installation on-line	90 days	Wed 9/15/21	Tue 1/18/22
60	Procure and assemble critical components and subsystems (including international shipping where required)	**240 days**	**Wed 3/31/21**	**Tue 3/1/22**
61	*Install Solar Field*	90 days	Wed 3/31/21	Tue 8/3/21
62	*Order and Receive Power Block*	200 days	Wed 3/31/21	Tue 1/4/22
63	*Solar Receiver*	**180 days**	**Wed 3/31/21**	**Tue 12/7/21**
64	*Procure Receiver componentry*	90 days	Wed 3/31/21	Tue 8/3/21
65	*Assemble Receiver*	90 days	Wed 8/4/21	Tue 12/7/21
66	*Riser/Down-comer/Piping*	**150 days**	**Wed 3/31/21**	**Tue 10/26/2**
67	*Procure Riser and Down-Comer Section Componentry*	90 days	Wed 3/31/21	Tue 8/3/21
68	*Assemble Riser and Down-Comer Sections*	60 days	Wed 8/4/21	Tue 10/26/21
69	*Thermal Energy Storage*	**240 days**	**Wed 3/31/21**	**Tue 3/1/22**
70	*Procure TES Componentry*	240 days	Wed 3/31/21	Tue 3/1/22
71	*Primary Regenerators*	**210 days**	**Wed 3/31/21**	**Tue 1/18/22**
72	*Procure Receiver componentry*	120 days	Wed 3/31/21	Tue 9/14/21
73	*Assemble Receiver*	90 days	Wed 9/15/21	Tue 1/18/22
74	Full installation on Site	160 days	Wed 7/21/21	Tue 3/1/22
75	**INSTALLATION COMPLETE**	0 days	Tue 3/1/22	Tue 3/1/22
76	*Local workforce will be safely and productively engaged to the greatest extent possible throughout the installation process*			
77	*First-unit heliostat field installed in accordance with vendor coordination*			
78	*Tower to be designed and installed by EPC in coordination with PMO*			
79	*Receiver/Riser/Down-comer/TES/Regenerator to be installed by EPC in coordination with PMO/Enlys Energy*			
80	*Power Block installation to be coordinated and managed between Gas Turbine Manufacturer, PMO, and MPPMCL*			
81	*Electrical connections and interfaces to be managed by MPPMCL in coordination with PMO*			
82	System Commissioning to be performed in accordance with plan drafted in Phase 1 and finalized in Phase 2. Commissioning to be coordinated through Enlys Energy, PMO, and MPPMCL to ensure that startup and shake-down	75 days	Wed 3/2/22	Tue 6/14/22
83	**PROJECT COMPLETE, SYSTEM OPERATIONAL**	0 days	Tue 6/14/22	Tue 6/14/22

Figure 20. Preliminary project plan, showing successful execution in 3 years; plan consists of an 18-month engineering and design phase, followed by an 18-month procure, assemble, install, and commission phase

As presented the two Phases are performed sequentially, with the second Phase initiation being contingent on a Go/No-Go decision after Phase 1. The enables a complete technical review of the system design prior to the beginning of construction. Alternatively, site preparations and construction may be initiated prior to the completion of all design tasks in order to reduce overall program duration. With Phase overlap the overall program duration may be reduced to less than 24 months.

Budget Requested and Justification

Table 5 provides the budget allocation (Total: $30,000,013) for the research activities to be conducted by RPI as well as the expenses related to the CSP testbed construction. Enlys Energy LLC will be used as the preferred vendor for the testbed construction, equipment supply, shipping, installation and testing and manual training at site. Enlys Energy will directly work with the relevant entities in India for managing the export control related to all equipment being supplied for this project, custom duty and associated protocols. RPI will allocate the necessary funding for all these activities to Enlys Energy as indicated in Table 5.

RPI research budget will be used for the following purposes: (a) supporting 5 FTE graduate students, 2 FTE postdoctoral fellows, 1 FTE research engineer and part of PI’s time during summer, (b) equipment such as a furnace, air blower and temperature monitoring device to conduct TES temperature retention capability, (c) furnace to synthesize TES media, (d) raw material for TES synthesis, (e) travel expenses to visit the site in Bhopal, India, national and international conferences on CSP and (f) publication cost for research papers.

A preliminary budgetary estimate for the engineering development, construction, installation, and commissioning of the modular 1.5 MW_e Concentrating Solar Power system with 60 MWh_t Thermal Energy Storage capacity for grid-battery, off-frid, and fringe-of-grid applications is shown in Table 6. Engineering development, EPCM (Engineering, Procurement, and Construction Management company) contract cost, and system hardware costs are given by Phase. The total capital cost of the equipment used in the CSP testbed system is approximately $14,000,000. The total cost of the TES media is approximately $25,000 at $0.4/$kW_{th}$ using low cost ceramic refractory (e.g. alumina) or cast ceramic forms. Not included in the costs shown are those associated with permitting, land acquisition, site preparation (clearing, grading, foundations, services, etc.), and the actual Construction/Installation; these are highly site-specific and dependent on local labor rates, and therefore cannot be included in this initial estimate. These costs will be covered by the budget allocation for RKDF University.

Values shown in Table 6 are considered conservative and represent an upper bound on the cost for installing Unit One. Note that the cost of subsequent system installations will decrease dramatically; engineering development costs will be almost entirely eliminated as only minor modifications or site-specific allowances may need to be performed, and EPCM contract costs will be dramatically lower as the bulk of system definition and process development will have been completed. Multiple follow-on installations will also benefit from volume pricing.

Table 5. Preliminary conservative budgetary estimate numbers for the proposed 1.5 MW_e Concentrating Solar Power system with 60 MWh_t of Thermal Energy System

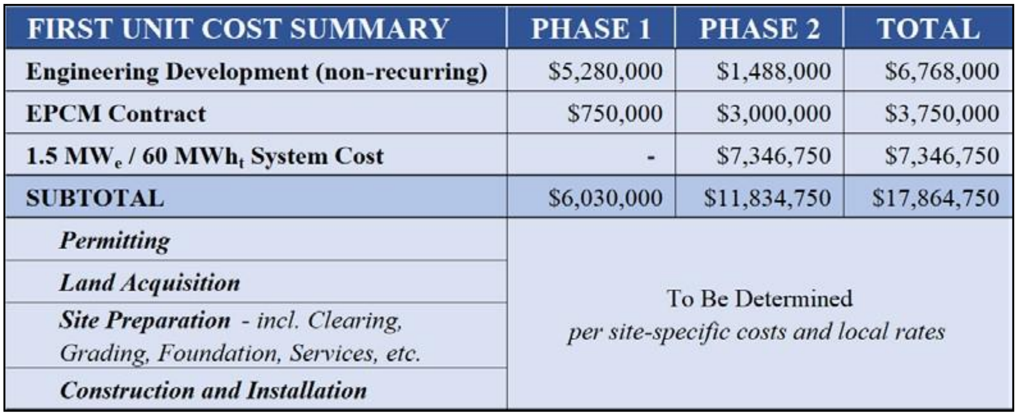
Rensselaer Polytechnic Institute

Cost Estimate Summary: Five Years

Period: 6/1/2020 - 5/30/2025

Proposal No. 20-0436						**Apr-20**
	Year One	**Year Two**	**Year Three**	**Year Four**	**Year Five**	**Total**
PERSONNEL						
Principal Investigator (Partha Dutta)						
academic - 9 mos @ %	$0	$0	$0	$0	$0	$0
summer - 10 wks @ 100%	39,344	40,131	40,933	41,752	42,587	204,747
Co-Principal Investigator ()						
(Engineer 1)						
calendar - 12 mos @ 100%	91,650	93,483	95,353	97,260	99,205	476,951
(Engineer 2)						
calendar - 12 mos @ 100%	0	0	0	0	0	0
()						
Postdoctoral Associate (TBD 2)						
calendar - 12 mos @ 100%	101,833	103,870	105,948	108,066	110,228	529,945
Graduate Research Assistant(s)						
tuition (5, 5, 5, 5, 5)	182,520	189,820	197,412	205,309	213,522	988,582
stipend (5, 5, 5, 5, 5)	161,359	167,820	174,520	181,515	188,755	873,969
Graduate Assistance	0	0	0	0	0	0
Undergraduate Assistance (URP)	0	0	0	0	0	0
Undergraduate Assistance	0	0	0	0	0	0
TOTAL PERSONNEL PAYMENTS	**$576,706**	**$595,124**	**$614,166**	**$633,902**	**$654,297**	**$3,074,194**
FRINGE BENEFITS @ 29.24%	68,079	69,440	70,829	72,246	73,691	354,285
EQUIPMENT						
Description	150,000	0	0	0	0	150,000
TRAVEL						
Domestic: meetings & conferences	10,000	10,000	10,000	10,000	10,000	50,000
Foreign: description	15,000	15,000	15,000	15,000	15,000	75,000
OTHER DIRECT COSTS						
Lab Supplies	225,000	250,000	150,000	120,000	75,000	820,000
Enlys Energy	6,060,000	11,834,000	1,300,000	152,250	159,750	19,506,000
Publication Costs	3,000	3,000	3,000	3,000	3,000	15,000
Consultant Services	0	0	0	0	0	0
Computer Services	0	0	0	0	0	0
Subcontracts/Subgrants						
SC1	0	0	0	0	0	0
SC2	0	0	0	0	0	0
SC3	0	0	0	0	0	0
TOTAL DIRECT COSTS	**$7,107,785**	**$12,776,564**	**$2,162,995**	**$1,006,398**	**$990,738**	**$24,044,479**
INDIRECT COSTS @ 26%	1,761,569	3,272,554	511,052	208,283	202,076	5,955,534
TOTAL PROJECT COSTS	**$8,869,354**	**$16,049,118**	**$2,674,047**	**$1,214,681**	**$1,192,814**	**$30,000,013**

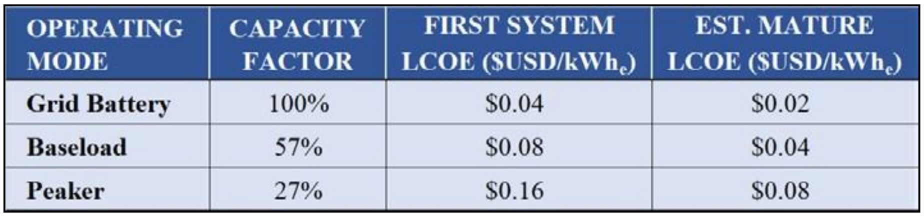
Table 6. Preliminary conservative budgetary estimate numbers for the proposed 1.5 MW_e Concentrating Solar Power system with 60 MW_{th} of Thermal Energy System. Permitting, Land Acquisition, Site Preparation, Construction and Installation will be partly covered by RKDF portion of the project funds



FIRST UNIT COST SUMMARY	PHASE 1	PHASE 2	TOTAL
Engineering Development (non-recurring)	$5,280,000	$1,488,000	$6,768,000
EPCM Contract	$750,000	$3,000,000	$3,750,000
1.5 MW_e / 60 MWh_t System Cost	-	$7,346,750	$7,346,750
SUBTOTAL	$6,030,000	$11,834,750	$17,864,750
Permitting	To Be Determined *per site-specific costs and local rates*		
Land Acquisition			
Site Preparation *- incl. Clearing, Grading, Foundation, Services, etc.*			
Construction and Installation			

Levelized Cost of Electricity

Table 7. LCOE as a function of system operating mode and assuming a 20-year operating life. Estimates are provided for both the first system and a mature system with higher volume production levels. Note that the costs of permitting, land acquisition, site preparation, construction, and installation are not included



OPERATING MODE	CAPACITY FACTOR	FIRST SYSTEM LCOE ($USD/$kWh_e$)	EST. MATURE LCOE ($USD/$kWh_e$)
Grid Battery	100%	$0.04	$0.02
Baseload	57%	$0.08	$0.04
Peaker	27%	$0.16	$0.08

With the estimated system hardware costs and EPCM contract costs shown above, the Levelized Cost of Electricity for the First System with various operating modes and an assumed 20-year operating life is shown in Table 7. Note that the numbers shown do not include the unknown permitting, land acquisition, site preparation, and construction and installation costs; these LCOE numbers will be updated as that information becomes available. Estimated mature system LCOEs are also provided, reflecting increased production volumes, cost savings, and EPCM streamlining.

Team and Qualifications

PI Qualification (RPI):

Principal Investigator (PI), Professor Partha S. Dutta of Rensselaer Polytechnic Institute brings 30 years of research experience in materials, devices and systems development for energy, optoelectronics, and medical applications. He has over 15 years of entrepreneurship experience translating small scale laboratory research into large scale industrial products. His involvement with real world projects for “engineering for a better world” initiative addressing societal challenges has led to the collaboration with RKDF university. Dr. Dutta will provide overall direction, insight and guidance in addressing the specific needs of the Indian market, as well as access to extensive university facilities suitable for scientific and technical evaluation of potential thermal energy storage solutions.

PI Qualification (RKDF University):

Principal Investigator (PI), Dr. V.K. Sethi of RKDF University, Bhopal, India brings 40+ years of career experience in the power energy industry. He has held many high level positions within the Indian Power Sector, prior to his academic positions at the Vice Chancellor and Director Levels. He will provide the high level coordination for this project with various stakeholders.

Preferred Vendor Qualification:

The preferred Commercial vendor, Enlys Energy LLC is a USA-based engineering research and development company with a mission to advance cost-effective, practical renewable power solutions that can be widely deployed throughout the world and help curb climate change. President and CEO Shaun Sullivan brings over 20 years of experience in advanced energy systems, including modeling, analysis, and innovation in gas turbine engine design, combined heat and power solutions, biomass energy systems, advanced high-performance heat exchanger design, low-emissions combustion, and hybrid vehicle development. Specific to the needs of this program, Shaun has focused on concentrating solar power solutions for over 10 years, most recently having been Principal Investigator for three successfully-executed high-profile United States Department of Energy projects. Shaun also holds engineering degrees from Rensselaer Polytechnic Institute (RPI) and the Massachusetts Institute of Technology (MIT), has received multiple patents, has authored multiple journal articles, is on the advisory board of the European Micro Gas Turbine Forum (EMGTF), and was an invited speaker at the 2019 Center for Future Energy Systems Technology Conference. The principals at Enlys Energy have both depth and breadth of engineering and development experience in the fields critical to the successful deployment of a CSP system with integrated energy storage and power system. A brief overview of their advanced technology development projects in fields of specific relevance to this program is presented in Table 8. Complementing its fundamental and applied engineering expertise and capabilities, the team at Enlys also leverages broad experience in specialized manufacturing processes (including metal forming, brazing, and CNC machining), design-for-production, project management, and business development. Enlys Energy is currently engaged in a small-scale project in conjunction with RKDF University in Bhopal India to demonstrate the Thermal Energy Storage system being proposed in this application. Funded through India’s Ministry or New and Renewable Energy, this project will integrate with a Scheffler-dish based solar-powered steam drying system. Although that latter system operates at an elevated pressure with steam, the Enlys project has been specifically designed to operate through an intermediate heat exchanger to demonstrate the low-pressure sensible media heat storage and dispatch considered imperative for large-scale economically-viable deployment. Testing of that system should be complete by the end of 2020.

The preferred Commercial vendor, Edisun Microgrids, Inc. brings a wealth of experience in small-scale heliostat design and controls to the project. Their core technology team that has been pioneering advances in this field for over a decade, many of them initially operating under the eSolar banner as early as 2007. Their innovative hardware design, innovative closed loop controls, and design-for-low-cost-manufacturing efforts have resulted in a compelling product that is reliable, robust, accurate, and economical. Their engineers will specify the solar field based on the site location identified and oversee manufacture and installation of the first field.

The preferred Commercial vendor, OPRA Turbines is a leading manufacturer of small high-efficiency gas turbine engines. Committed to finding green energy applications for their technology, OPRA has been providing extensive off-design engine operating parameters for the purposes of modeling the integrated system and is enthusiastic to contribute to potential clean energy solutions.

RKDF University (Project Site) Qualification:

RKDF is one of the growing Universities of central India with over 40,000 students and 1,500 faculty offering a wide range of undergraduate, postgraduate and doctoral programs in Engineering, Management, Health sciences, and Science and Humanities. The R&D base of RKDF University is in the area of Renewable Energy, Climate change, Drug Delivery, Medicinal plants and Bio informatics, Internet of Things (IOT), Machine Learning, Big DATA. SKIPL, Bhopal is engaged in developing & consulting for Infrastructure project, Agriculture project & Renewable Energy Project across India. The University is perusing India’s 1st carbon capture project on coal based plant sponsored by Ministry of power (CPRI) and a solar thermal storage project through technology transfer from RPI USA, sponsored by MNRE GoI.

Agency’s experience on similar type of assignments:

The promoter of this company has very keen interest in installation and promotion of renewable Energy. MP State’s First 500 KW rooftop solar plant was installed at RKDF University, Bhopal. It was also MP state’s first Net Metered Plant.

About the product/solution offered by Agency:

The Thermal energy storage consists of Halide salt particles for high temperature heat transfer medium and TES for temperatures above 1400°C. A key benefit of these particles is the high energy density in excess of 300 kWh /m3 and ability to transport heat via low-cost particles which are chemically inert.

Advantages and Disadvantages of Different storages solutions:

The biggest advantage with this product that it will not leave any carbon footprint in environment as in case of Lithium-Ion Battery. The high energy density material developed through Transfer of technology will be produced in the university lab indigenously as per deliverable of the project of MNRE at RKDF University.

Experience sharing from different countries/utilities on Energy Storage solution:

This Thermal Storage technology was developed by RPI, USA having MOU with RKDF University for Department of Energy (DOE) USA with the objectives of providing TES at lower cost, higher efficiency, and improved reliability compared to current state-of-the-art technologies. These projects explore new concepts explore new operation system designs and innovative concepts in the collector, receiver, thermal storage, heat transfer fluids, and power cycle subsystems, advancing the state-of-the-art. The Technology focuses on the objective of development of megawatt-scale test system. The Plant will absorb energy from a solar field and deliver it into a thermal energy storage system, storing nine megawatt-hours (per MW) of heat at a temperature of 750 °C for a minimum of ten hours. The energy then moves into a working fluid that could have a round-trip efficiency of 95-99 percent, creating a CSP solution that enables on-demand renewable energy. In India the TES has tested at RKDF University and it can store energy of 1400 °C temperature. This plant was developed with jointly RPI University, USA and it was financially supported by Ministry of New & Renewable Energy (MNRE) GoI in the year 2015-2016.

Suggestion from agencies for successful implantation of Manufacturing and energy storages services in MP:

As Madhya Pradesh is an energy surplus state having conventional as well as achieving new heights in augmentation of renewable power generation sources. Despite intermittency issues with wind and solar power generation, these energy sources have had wide acceptance among generators. Wind and solar power generation, when mapped, largely serve the off-peak base load (mid-day and late night)—that is, the lowest time-of-day pricing. This current scenario can be altered substantially by the application of Energy storage mechanism, wherein renewable generation could be stored and discharged during peak hours. The proposal envisaged is Thermal Storage of Solar thermal field.

This project encompasses the design, analysis, construction and field operation demonstration of a 5 MW capacity thermal energy storage (TES) module along with a dispatchable 1.5 MW_e (electric) solar power system with 60 MW_{th} (thermal) energy storage capacities. For the TES plant of 5 MW capacity, the executing agency is a joint venture of Ram Krishna Dharmarth Foundation (RKDF) University, Bhopal & Siddhartha Kapoor Infrastructure Pvt. Ltd., (SKIPL) Bhopal.

The following characteristics of modular storage solution (5 MW) will be demonstrated by the participants:

Maximum Response time from cold start: Rapid startup and cool down in the range of within 45 minutes for capacity of 5 MW. Time reduces as we increase our plant capacity.

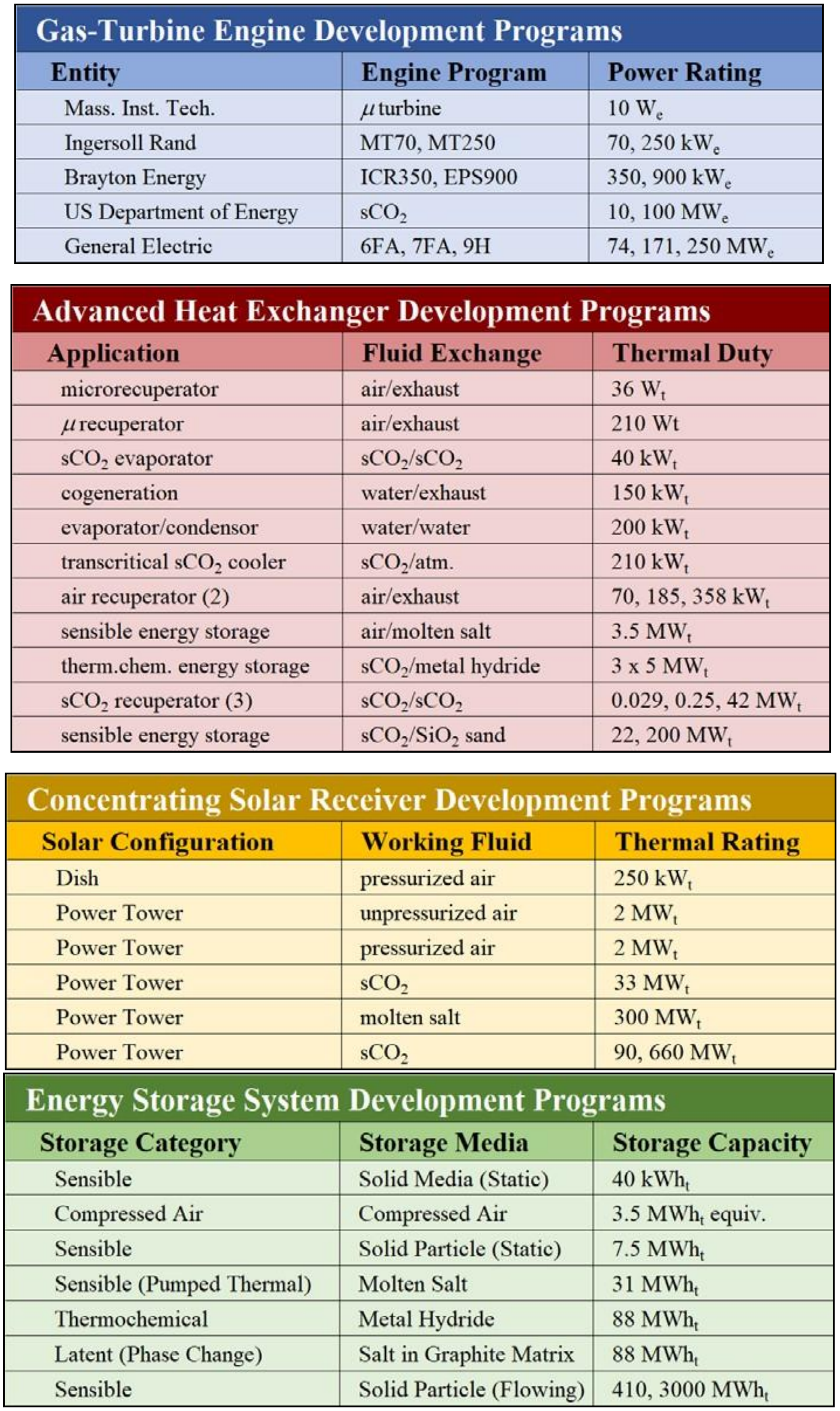
Ability to operate and in grid forming and grid following modes: On Grid A/C supply

Maximum Ramp up Response time in operating conditions: 25 minutes

Maximum Ramp down Response time in operating condition: 15 minutes

Requirements for setting up manufacturing capacity, location of manufacturing plants, Technology used: A Land Area of 8 Acre has been acquired at the IT Park behind the university premises opposite to Mahavir Institute of Medical Science (MIMS). A 33 kV Grid is just adjacent to this Area.

Table 8. Program experience in fields relevant to a CSP system with integrated power block and energy storage



Gas-Turbine Engine Development Programs

Entity	Engine Program	Power Rating
Mass. Inst. Tech.	μturbine	10 W_e
Ingersoll Rand	MT70, MT250	70, 250 kW_e
Brayton Energy	ICR350, EPS900	350, 900 kW_e
US Department of Energy	sCO_2	10, 100 MW_e
General Electric	6FA, 7FA, 9H	74, 171, 250 MW_e

Advanced Heat Exchanger Development Programs

Application	Fluid Exchange	Thermal Duty
microrecuperator	air/exhaust	36 W_t
μrecuperator	air/exhaust	210 Wt
sCO_2 evaporator	sCO_2/sCO_2	40 kW_t
cogeneration	water/exhaust	150 kW_t
evaporator/condensor	water/water	200 kW_t
transcritical sCO_2 cooler	sCO_2/atm.	210 kW_t
air recuperator (2)	air/exhaust	70, 185, 358 kW_t
sensible energy storage	air/molten salt	3.5 MW_t
therm.chem. energy storage	sCO_2/metal hydride	3 x 5 MW_t
sCO_2 recuperator (3)	sCO_2/sCO_2	0.029, 0.25, 42 MW_t
sensible energy storage	sCO_2/SiO_2 sand	22, 200 MW_t

Concentrating Solar Receiver Development Programs

Solar Configuration	Working Fluid	Thermal Rating
Dish	pressurized air	250 kW_t
Power Tower	unpressurized air	2 MW_t
Power Tower	pressurized air	2 MW_t
Power Tower	sCO_2	33 MW_t
Power Tower	molten salt	300 MW_t
Power Tower	sCO_2	90, 660 MW_t

Energy Storage System Development Programs

Storage Category	Storage Media	Storage Capacity
Sensible	Solid Media (Static)	40 kWh_t
Compressed Air	Compressed Air	3.5 MWh_t equiv.
Sensible	Solid Particle (Static)	7.5 MWh_t
Sensible (Pumped Thermal)	Molten Salt	31 MWh_t
Thermochemical	Metal Hydride	88 MWh_t
Latent (Phase Change)	Salt in Graphite Matrix	88 MWh_t
Sensible	Solid Particle (Flowing)	410, 3000 MWh_t

Summary

RPI and RKDF University is proposing to work closely with Madhya Pradesh Power Management Company Limited and commercial vendors, Enlys Energy, Edisun Microgrids and OPRA Turbines to deploy a first-in-class robust and economical 1.5 MW_e Concentrating Power System with 60 MW_{th} Energy Storage for distributed on-grid, off-grid, and fringe-of-grid applications. The project encompasses the design, analysis, construction and field operation demonstration of a 5 MW capacity thermal energy storage (TES) module along with a dispatchable 1.5 MW_e (electric) solar power system with 60 MW_{th} (thermal) energy storage capacity. For the TES plant of 5 MW capacity, the executing agency is a joint venture of Ram Krishna Dharmarth Foundation (RKDF) University, Bhopal & Siddharth Kapoor Infrastructure Pvt. Ltd., (SKIPL) Bhopal. This project will facilitate the establishment of local manufacturing and services capabilities to support the first system as well as subsequent installations in India and in USA.

The proposed system employs proven static solid media sensible energy storage technology and a mature gas turbine engine to provide flexible base load, peaker, and/or grid battery operability. Ideally suited for microgrid application and remote and/or developing communities, the system has been developed with an emphasis on Reliability, Simplicity, and Elegance A full plan for deployment of a first-in-class installation is provided, including the scope of effort, schedule and preliminary budgetary estimate for the development, construction and installation, and commissioning of the system.

The broader impact of this project is developing and deploying reliable, cost-effective distributed renewable power solutions that can have a near-term and significant impact by not only reducing the effects of climate change, but also by improving the lives of citizen around the globe. To achieve this, a highly qualified team with decades of experience in solar collection and concentration, concentrating solar power, gas turbine engine technology, and thermal energy storage will work together with Madhya Pradesh Power Management Company Limited towards the fulfillment of India's ambitious renewable energy goals and to build a shared clean energy future.

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