

RE<C: Brayton Project Overview

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Introduction

RE<C was a Google initiative to drive innovation in renewable energy, with the goal of making renewable energy cheap enough to compete head-to-head with coal-fired power plants. Hence the name RE<C - "renewable energy cheaper than coal." As part of this initiative, Google formed an engineering team to develop promising technologies in the field of solar energy power generation. After evaluating many technologies, we focused our engineering efforts on concentrating solar power (CSP) because we felt it was an area where we had the biggest opportunity to innovate.

CSP is a proven means of solar power generation and new technologies are lowering its cost curve, but a common characteristic of current CSP technologies is the use of steam turbines for power generation. Steam turbines, although well understood, consume large amounts of water and require extensive balance-of-plant equipment. CSP works best in regions with a lot of sun year-round, and these tend to be desert areas where water is in short supply and permission to use water may be difficult or impossible to obtain.



Examples of different types of CSP: tower, trough, and dish

Our goal for the power conversion part of a CSP plant was to create a new approach that was water-free, modular, and less expensive than steam-based CSP. This led us to examine the Brayton power cycle as a possible solution.

Brayton-Cycle Engines

In a basic Brayton cycle engine, ambient air is compressed, heated, then expanded through a turbine. The turbine expansion reduces the temperature and pressure of the air and produces shaft power. The power from the turbine drives the compressor, and the power left over drives a generator which converts that power into electricity. The air exiting the turbine is exhausted to the atmosphere, and the only cooling required is for the oil that lubricates the bearings.

Jet engines and gas turbines are examples of Brayton cycle engines. These engines have been manufactured in a wide range of sizes, from model airplane sizes to power-plant sized generators. Brayton cycle engines conform to our design goals: waterless, scalable to almost any size, and potentially inexpensive when produced in volume. The biggest challenge with Brayton engines is that very high temperature (above 900C) is needed for efficient operation.

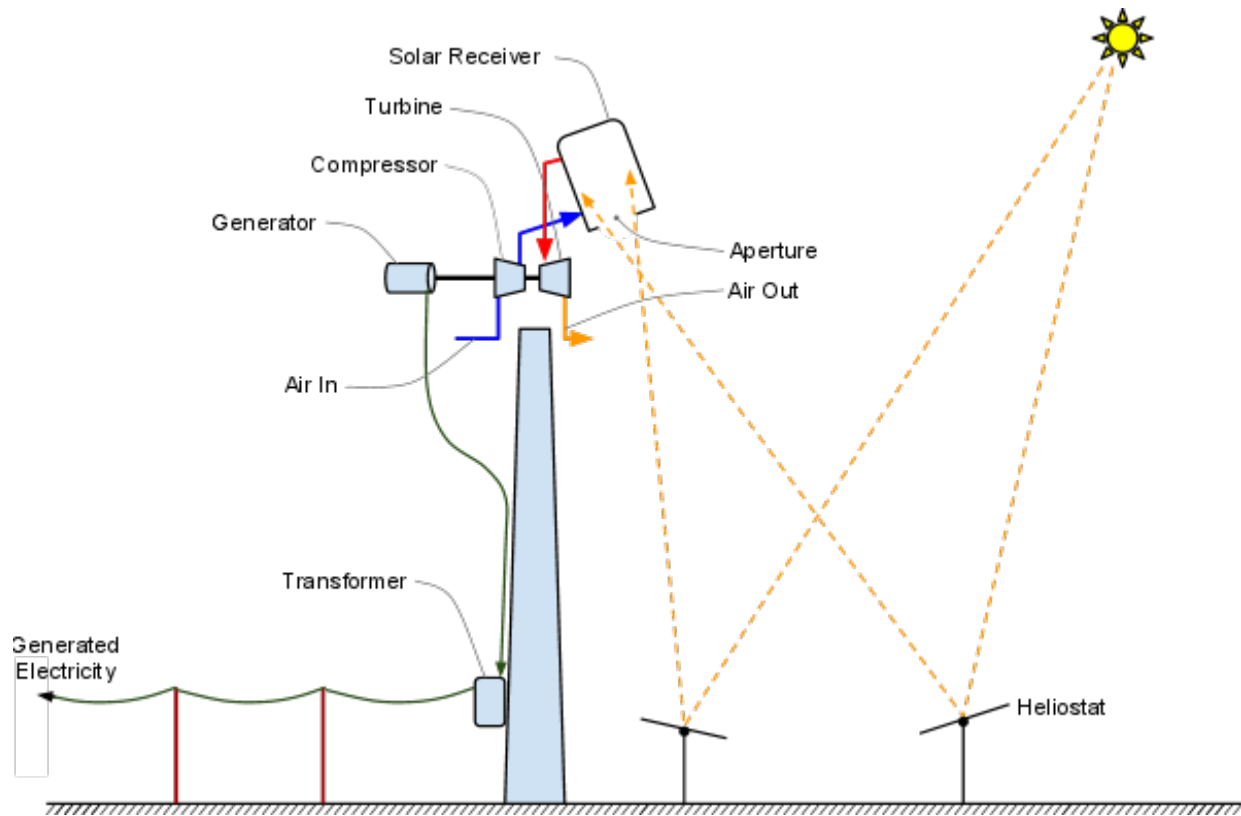
We found that there had been a few prior attempts at Brayton-based CSP and most of these projects had attempted to modify existing engines that had been designed for aircraft or distributed generation applications. We decided to design a new Brayton cycle engine from scratch, specifically tailored for a CSP application. Google partnered with [Brayton Energy](#) to design and develop a new purpose-designed Brayton cycle engine for tower CSP applications.

Google's Brayton CSP Engine Goals

We initially decided to start with an engine power rating of 1 megawatt (MW). We felt this was a reasonable compromise: it was big enough to potentially build large power plants composed of multiple engines and heliostat fields, yet it was small enough to be feasible to develop and test with a reasonable amount of time and investment. Our design goals for this engine were:

- **High efficiency over a wide range of solar input:** The amount of solar energy collected by the field varies substantially depending on the time of day and season. We wanted the engine to operate efficiently over as wide a range of input power as possible.
- **Robust and controllable enough to operate through rapid changes in solar input:** The engine and receiver must be able to operate through the inevitable rapid changes in solar input that occur when clouds pass overhead, shading the field of mirrors.
- **Low cost when produced in volume:** The cost of a complete Brayton CSP power plant would have to be much lower than a more conventional solar photovoltaic (PV) power plant in order to be a viable choice. The cost goals proved to be a moving target during the course of our project as the cost of solar photovoltaic panels continued to drop.

Our design configuration concept was to place a Brayton engine at the top of a tower. The only connections to the tower would be for electricity and data.



Major components of a Brayton CSP system

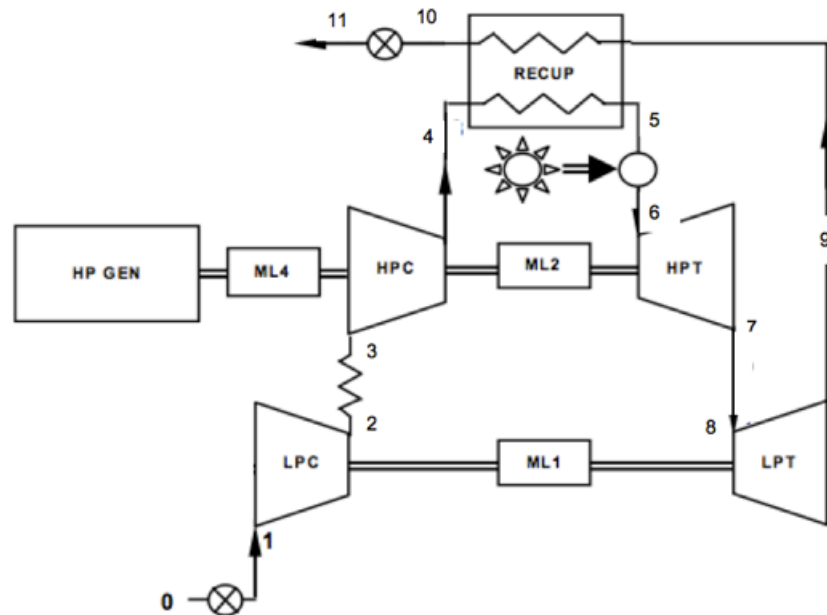
Engine Configuration Selection

We decided early on to utilize radial-flow turbomachinery, similar to a turbocharger or a microturbine. Radial-flow compressors and turbines can achieve pressure ratios of four to five in a single stage, whereas axial-flow turbomachinery found in aircraft engines needs multiple stages. In order to achieve good efficiency over a wide range of input power and to increase the power per amount of air mass flow (specific power), we decided to use two stages of compression and expansion, which would allow an overall pressure ratio of between 10 and 20.

The final design point parameters for the engine are shown below. The power rating of 890 kW was chosen in order to allow the use of a large off-the-shelf turbocharger for the low pressure spool.

Engine	
TIT HP (K)	1175
TIT LP (K)	883
Tamb (K)	298.2
Pamb (kPa)	93.8
PRL x PRH	10.95
massflow (kg/s)	4.828
LP power (shaft)	0.00
HP power (shaft)	949.8
Elec power (kW)	890.0
engine efficiency	33.96%

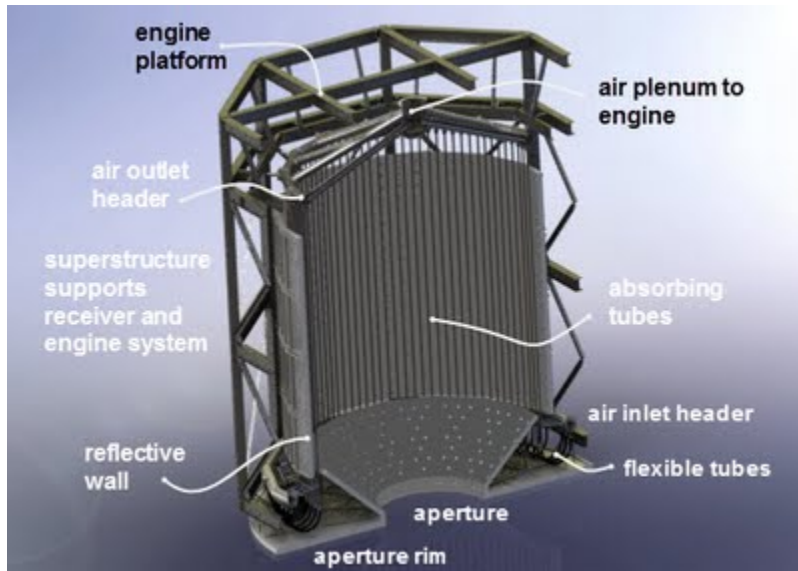
State Points	P (kPa)	T (K)
0	93.8	298.2
1	93.3	298.2
2	362.1	468.5
3	352.7	311.8
4	995.4	443.8
5	975.5	693.9
6	921.8	1175.0
7	234.6	882.7
8	234.6	882.7
9	96.9	721.7
10	94.3	473.1
11	93.8	473.1



<p><i>LP</i> refers to low pressure <i>HP</i> refers to high pressure <i>C</i> denotes compressor <i>T</i> denotes turbine <i>ML</i> refers to mechanical losses <i>RECUP</i> is a recuperator that transfers residual exhaust heat back into the engine airflow</p>	<p><i>GEN</i> is for generator <i>TIT</i> is turbine inlet temperature <i>Tamb</i> and <i>Pamb</i> are ambient temperature and pressure <i>PRLxPRH</i> is the product of the pressure ratios of the <i>LPC</i> and <i>HPC</i> An intercooler is located between 2 and 3. The solar receiver is between points 5 and 6.</p>
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Final design point parameters and engine configuration

Air enters from a circular manifold at the bottom and is distributed through vertical absorbing tubes. The air is collected at one point at the top where it flows directly into the high pressure turbine (HPT). A cutaway view of the solar receiver and a rendering of the engine in its entirety are shown below.



Cutaway view of the solar receiver

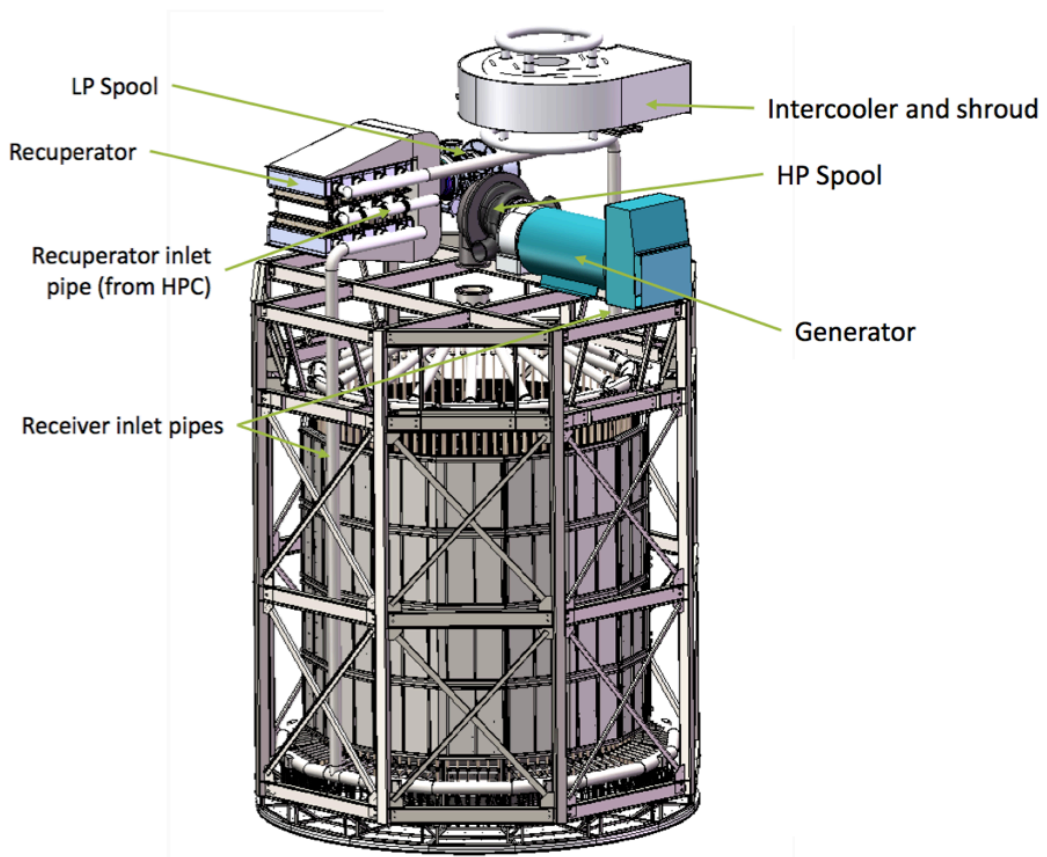
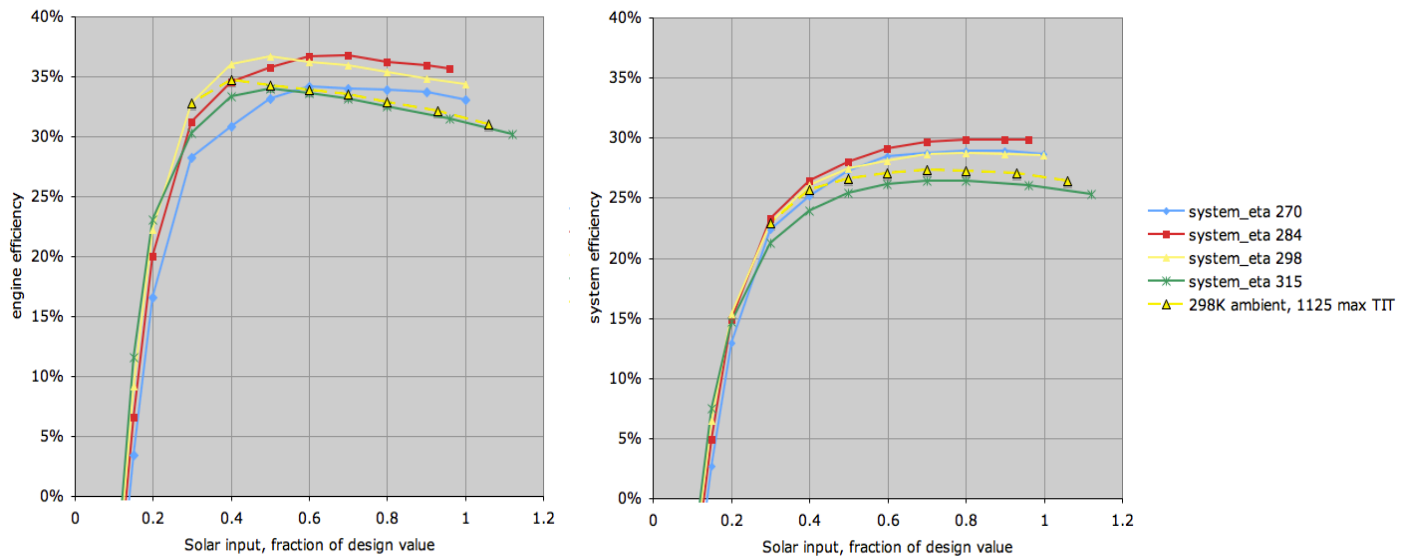


Diagram of assembled engine and receiver

A more in depth description of our brayton engine configuration can be found in: [RE<C: Brayton System Hardware](#).

Engine and System Efficiency

In the figure below, we show how the engine efficiency and overall system efficiency (engine and receiver combined) vary with the input of solar power. Results are shown for four different ambient temperatures that cover the full range of expected ambient temperatures for the heliostat field. The maximum efficiency of the brayton engine by itself is 37%, but with combined with the receiver it is 30% due to heat being lost out of the receiver's opening. Engine and system efficiency are relatively flat once total solar input passes 40% of the design (i.e. full) power level.



Engine-only and full system efficiency as a function solar input power. The different cases correspond to different ambient temperatures given in Kelvin. In degrees Celsius the values are: - 3, 11, 25, and 42.

More of our performance modeling can be found in [RE<C: Brayton System Performance](#).

Conclusions

Although we did not ultimately carry out our design through to a prototype, we still came away with a number of important results and useful perspectives on both the engine components and operation, and on the levelized cost of energy.

Engine components and operation

- The turbomachinery design is well within current industry experience levels. The low pressure spool can be an off-the-shelf large turbocharger, such as what's used in large marine diesel engines.
- The solar receiver design proved to be much more difficult than originally expected. Temperature gradients were a challenge and metal creep and fatigue were big issues. A viable design may be possible with ceramic materials, but much more development is required.

The future of Brayton CSP

- Photovoltaic power generation is coming down in cost faster than expected. Our Brayton cycle solar power solution has essentially no energy storage component, placing it in direct competition with PV. A key differentiator would be to incorporate storage into a solar Brayton system, which would allow its power to be dispatchable. For such applications, more advanced Brayton cycles (such as supercritical closed-cycle CO₂) that can operate efficiently at lower temperature look promising.
- High temperature CSP steam-based systems are still viable at large scale, especially those that incorporate storage to allow operation for several hours after the sun goes down.

We would like to acknowledge the efforts of the engineering team: Tim Allen, Alec Brooks, Kevin Chen, Mikhail Dikovsky, John Fitch, David Fork, Philip Gleckman, Zvi Gershony, Ross Koningstein, Selver Corhodzic, and Bill Weihl, and finally our partner, Brayton Energy LLC.

We dedicate this work to the memory of Tim Allen.