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Solar Augmentation for Process Heat with Central Receiver Technology

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Abstract. Coal fired boilers are currently one of the most widespread ways to deliver process heat to industry. John Thompson Boilers (JTB) offer industrial steam supply solutions for industry and utility scale applications in Southern Africa. Transport cost add significant cost to the coal price in locations far from the coal fields in Mpumalanga, Gauteng and Limpopo. The Helio100 project developed a low cost, self-learning, wireless heliostat technology that requires no ground preparation. This is attractive as an augmentation alternative, as it can easily be installed on any open land that a client may have available. This paper explores the techno economic feasibility of solar augmentation for JTB coal fired steam boilers by comparing the fuel savings of a generic 2MW heliostat field at various locations throughout South Africa.

INTRODUCTION

The TIA Helio100 (1) project is a central receiver collector technology development project intended for commercialization. The project aims to deliver South Africa's first commercially viable heliostat technology which is both low cost and offers high local content potential. The project is demonstrated on a small central receiver collector pilot and research facility at Mariendahl in Stellenbosch. The Helio100 teams' design philosophy was:

- High localization
- Simple in-field assembly by teams of two unskilled laborers
- Smart calibration
  - Low cost smart electronic control systems that relaxes the tolerances on the physical heliostat
  - Intelligent self-calibration
- Wireless
  - Wireless communication
  - Powered by photovoltaic cells (batteries to give backup power)
- No ground preparation required
  - Small heliostat sizes to minimize wind force and to leverage the economies of scale
  - No foundations required
- Big or small installations

This resulted in a heliostat that is low cost, has high localization and is flexible enough to be installed on nearly any piece of land with minimal site preparation. The wireless nature of the heliostat also adds to this flexibility as this minimizes field wiring. This easy and flexible implementation makes the Helio100 heliostats attractive for process heat augmentation (or delivery), as clients may have irregularly shaped, uneven pieces of land available.

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John Thompson Boilers (JTB) (2) offer industrial steam supply solutions for industry and utility scale applications. One of their largest business sectors are package boilers that deliver process steam to clients. This may include hospitals, food processing factories, distilleries, paper processing, wood drying and many other industries scattered throughout Southern Africa. These boilers typically use coal as fuel. Coal prices in South Africa are highly dependent on location, as the transport cost of coal is a large cost contributing factor. Some of the highest coal prices can be found in locations where the yearly sum of direct normal irradiation (DNI) is high; this makes the prospect of solar augmentation an attractive option for fuel saving augmentation.

This paper will focus on the techno-economic feasibility of solar augmentation on JTB's small package boilers using the low cost Helio100 heliostats. The analysis will consider the economics of a 2MW field using Helio100 technology installed at various sites in South Africa with different coal prices and different DNI values. Furthermore, three different implementations will be considered.

THE HELIO100 SYSTEM

The Helio100 system is demonstrated in the Helio100 Pilot on the Mariendahl experimental farm just outside of Stellenbosch, presented in FIGURE 1. The field contains 102 heliostats, each with a $2.23m^2$ mirror facet. The heliostat's two rotational axes are arranged in a fixed horizontal configuration, driven by two linear actuators. The control board and batteries are attached to the back of the single faceted mirror module, and a single strip of PV panels are attached along the top of each mirror module. The heliostats are clustered in pods, each pod holds 6 mirror modules connected to a common triangular pedestal.

FIGURE 1. Helio100 pilot

The cost of the heliostat is highly dependent on the quantity of heliostats built. The current heliostat design is well suited for low volume manufacturing techniques. The cost of the current heliostat design, for production volumes of 1500 and 20 000 heliostats per annum, is listed in TABLE 1. At high volume production, the heliostats can be produced using manufacturing techniques that are better suited for high volume manufacturing, which further reduces the cost. The industrialized cost of the Helio100 heliostats at production volumes of 20 000 heliostats per annum is also shown in TABLE 1. Industrialized costs assume further innovation and design alterations for low cost manufacturing. The cost presented in TABLE 1 is the total installed cost. The cost of the field will be calculated using these values.

TABLE 1. Helio100 heliostat cost at volume (3)

Design:	Cost	Production volumes
Current design	US$ 275/m^2	1 500 p.a
Current design	US$ 155/m^2	20 000 p.a
Industrialized design	US$ 126/m^2	20 000 p.a

SOLAR RESOURCE IN SOUTH AFRICA

South Africa has some of the best solar resources in the world. FIGURE 2 shows a map of the annual sum of direct normal irradiation (DNI) in South Africa with the locations considered in this study marked with red stars. These locations were chosen because they are the industrial hubs within South Africa. The yearly sum of DNI for these locations and the average peak DNI of these locations is presented in TABLE 2. The yearly sum of DNI is used to calculate the expected sum of the annual thermal energy that the field will be able to deliver, where the average peak DNI is used to size the field.

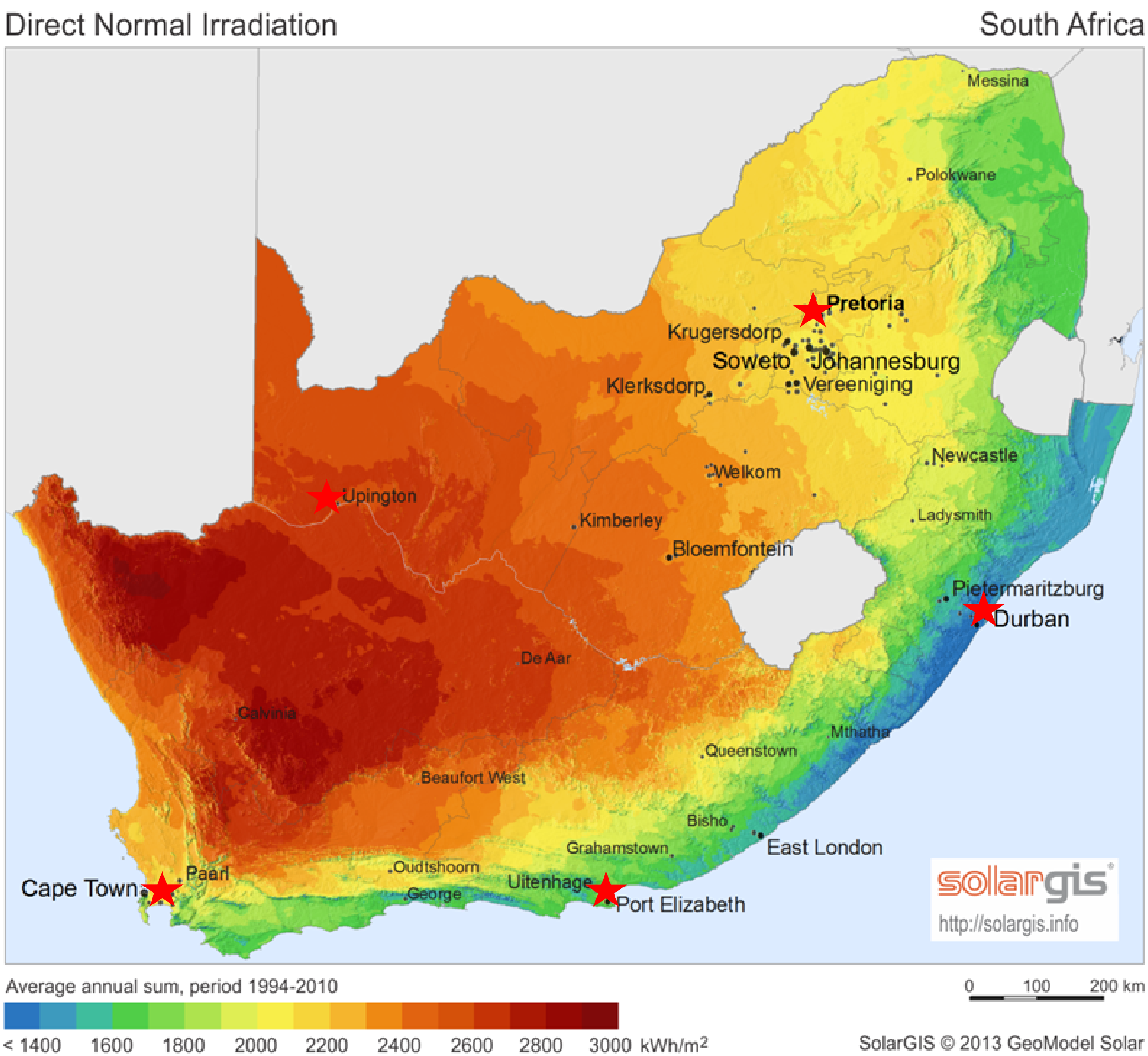

FIGURE 2. DNI map of South Africa (4)

TABLE 2. Approximate total yearly sum of direct normal irradiation and average peak direct normal irradiation

	Yearly sum of DNI (4)		Average peak DNI (5)	
Cape Town	2150	kWh/m^2	0.981	kW/m^2
Port Elizabeth	1800	kWh/m^2	0.970	kW/m^2
Durban	1650	kWh/m^2	0.950	kW/m^2
Pretoria	2100	kWh/m^2	0.995	kW/m^2
Upington	2816	kWh/m^2	0.995	W/m^2

FIELD SIZING, COST AND ANNUAL YIELDS

The optical characteristics of the field that will be required to do a preliminary field costing are:

- The solar multiple: This will be taken as 1, as all the heat produced by the field will be used to augment the thermal process.
- Peak collector efficiency: This is used to determine the size of the field aperture based on the required maximum thermal input and the typical peak DNI values that occur at the specific location.
- Yearly average collector efficiency: This is used to determine how much solar energy the collector system can collect per annum based on the field aperture and the yearly sum of DNI that can be expected at the location.
- Average land use ratio: This is used to determine the size of the land required based on the field aperture.

The optical characteristics of the field should ideally be calculated using a ray-tracer that takes the site, location, and field layout into consideration. Furthermore, the receiver efficiency is dependent on its operating temperature. Designing a field for every scenario is outside the scope of this paper, so generalized field optical characteristics had to be taken. In general large fields have been quoted to have peak efficiencies between 57.8% and 88%, and yearly average efficiencies of about 41% to 62% (6) (7). This includes the receiver efficiency which is taken as 90%. Because of the difficulty to assign these numbers to arbitrary fields, these figures will have to be assumed, and are presented in TABLE 3.

The average land usage and facet size is taken to be the same as that of the Helio100 pilot.

TABLE 3. H100 field optical properties

Solar multiple:	1	
Peak collector efficiency:	0.63	
Yearly averaged collector efficiency:	0.54	
Average land usage ratio	0.37	
Facet size	2.23	m^2

Looking at the solar resource data in TABLE 2, the peak average DNI of all the locations averages 0.972 kW/m^2, which was used to size the 2 MW field using the optical properties listed in TABLE 3. The field size and cost of a generic 2MW field is presented in TABLE 4 using an exchange rate of R12/US$.

TABLE 4. Field cost

Field aperture (m^2)	Land use (m^2)	Number of heliostats	Field cost: Current design at 1500 p.a	Field cost: Current design at 20 000 p.a.	Field cost: Industrialized design at 20 000 p.a.
3236	8827	1452	R10 803 682	R 6 089 348	R 4 950 051

Using the field aperture presented in TABLE 4, the optics presented in TABLE 3, and the solar resource data in TABLE 2, the annual thermal input of the collector system could be calculated for every location marked on the map in FIGURE 2. This is shown in TABLE 5.

TABLE 5. Annual thermal energy collected

Location	Year sum of DNI (kWh/m^2)	Annual thermal input into the system (kWh)	(GJ)
Cape Town	2150	3 791 887	13 650
Port Elizabeth	1800	3 174 603	11 428
Durban	1650	2 910 052	10 476
Pretoria	2100	3 703 703	13 333
Upington	2816	4 966 490	17 879

INTEGRATION OPTIONS

To augment a coal fired boiler, there are three approaches that may be implemented:

- Make-up water heating
- Feedwater heating
- Parallel steam production

In make-up water heating (FIGURE 3), the water that comes from the storage reservoir is heated up before it is fed into the boiler along with the return condensate that comes from the client's plant. It is well suited for clients that do not collect all of the condensate from their process. The inlet water will be at atmospheric conditions, and will be placed in a hot well. The hot well will act as a buffer between the solar input and the boiler demand. The hot well will be unpressurized, and therefore the feedwater can only be heated to 100^{o}C. The receiver will be heating subcooled water, making it more robust against burnout, and allowing greater flux distributions. (6).

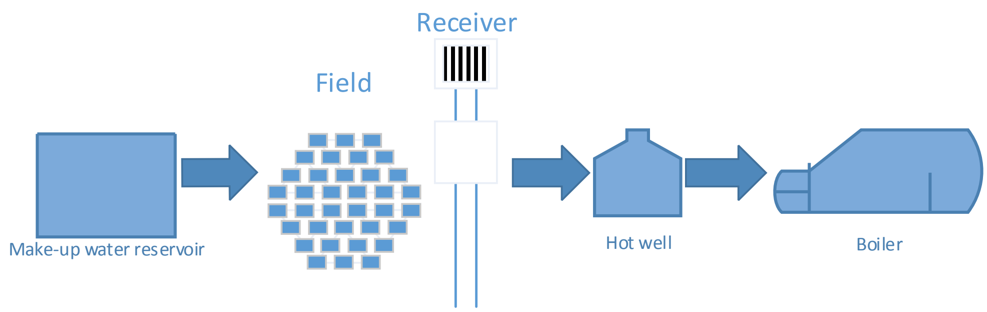

FIGURE 3. Make-up water heating

With feedwater heating (FIGURE 4), some of the feedwater from the high pressure pump is passed through the receiver and into the boiler. As with the make-up water heating application, the coolant in the receiver is subcooled water, as the water in the receiver will be around 10bar, and below the saturation temperature of 180^{o}C. This makes the feedwater heating application very similar to the make-up water heating application.

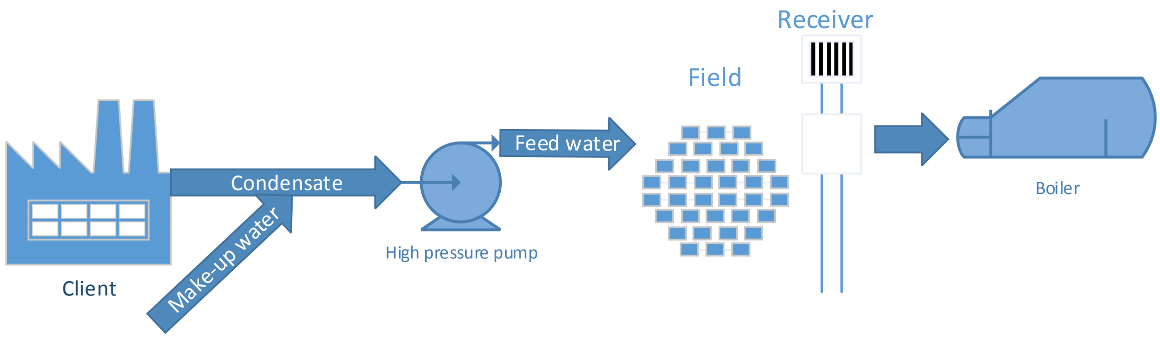

FIGURE 4. Feedwater heating

The parallel steam delivery application (FIGURE 5) is significantly different from the other two integration options, as it has to deliver saturated steam at 10 bar. The boiler construction will have a tangent tube wall for the receiver, with a steam drum with steam separation equipment. This is much more complicated and much heavier than the receivers in the other two applications, since the receiver will be operating at saturation, and boiler circulation is essential to prevent receiver burnout.

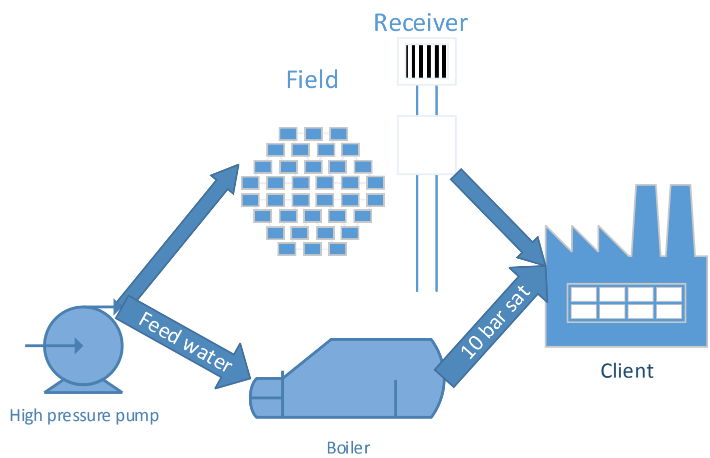

FIGURE 5. Parallel steam delivery

To estimate the total installation cost of a solar augmentation system, the Helio100 team and the JTB team had to draw on experience with similar projects. Apart from the field costs, the integration cost is divided into site improvements, balance of plant, tower cost, and receiver cost. The three integration options were considered in a holistic fashion. A Systems Advisor Model (SAM) simulation showed that a 2MW field with the Helio100 heliostats would require a 22m tower. Using an average flux of 0.233MW/m^2 (6), the receiver has been sized to be a 2.9 m x 2.9 m panel in all three applications. The make-up water and the feedwater heating receivers are very similar in construction apart from material grade to compensate for the pressure. The cost data for both the feedwater and the make-up water integrations were based on the Helio100 experience, as the Helio100 pilot has a receiver cooled with subcooled water. As for the parallel steam delivery, the cost estimations were made based on JTB experience with steam delivery.

The estimated cost of the three integration options is presented in TABLE 6. The large price discrepancy between the parallel steam delivery scheme and the other two is due to the complexity of the steam production system and the large increase in mass between a subcooled water heater and a steam boiler. The cost of a 2MW collector field for the current design at 1500 heliostats per annum, at 20 000 per annum and the industrialized design at 20 000 heliostats per annum is also presented in TABLE 6. The totals between various integration options and heliostat fields are also presented in TABLE 6. It is clear that the installation cost depends on the application, but if the Helio100 heliostat technology is industrialized and produced at volume, a 2MW solar augmentation can be done for a capital outlay of between R 6 390 051.00 and R 8 950 951.00.

TABLE 6. Estimated installed cost of the integration options for a 2MW heliostat field for solar augmentation

		Make-up water heating	Feed water heating	Parallel steam delivery
		R 1 440 000.00	R 1 500 000.00	R 4 000 000.00
Current design at 1500 p.a	R 10 803 682.00	R 12 243 682.00	R 12 303 682.00	R 14 803 682.00
Current design at 20 000 p.a.	R 6 089 348.00	R 7 529 348.00	R 7 589 348.00	R 10 089 348.00
Industrialized design at 20 000 p.a.	R 4 950 051.00	**R 6 390 051.00**	R 6 450 051.00	R 8 950 051.00

THE VALUE OF PROCESS HEAT AUGMENTATION

The cost of the process heat sold by JTB consists of:

- Fixed cost:
    - Capital
    - Labor
    - Fixed maintenance
- Variable cost
    - Fuel
    - Chemicals
    - Variable maintenance
    - Ash removal

Of all these costs, only the fuel cost will be offset by the CSP augmentation. The fuel price is largely affected by the transport cost of the coal from the coal fields, which are mainly located in Gauteng, Mpumalanga and Limpopo. Coal in Pretoria costs R900/ton, whereas it costs R1600/ton in Cape Town because of the transport cost. Converting the coal price into the fuel component involves taking boiler efficiency and the heating value of the coal into account. The fuel component of the steam cost is presented in TABLE 7. The estimated annual fuel savings (in Rand) for a 2MW solar augmentation of a coal boiler is the product of the estimated annual thermal input into the system (kWh) and the fuel component of the steam (R/kWh), which is presented in TABLE 7.

TABLE 7. Estimated annual fuel savings on a $2MW_{peak,th}$ CSP augmentation system

Location	Annual thermal input into the system (kWh)	Fuel component of steam cost (R/kWh)	Annual fuel savings
Cape Town	3 791 887	0.275	**R 1 023 809**
Port Elizabeth	3 174 603	0.249	R 790 390
Durban	2 910 052	0.251	R 733 057
Pretoria	3 703 703	0.151	R 517 578
Upington	4 966 490	0.196	**R 971 184**

From TABLE 7, it is clear that locations where the coal cost is high, the augmentation is of more value. An interesting observation is that Upington, with a significantly higher yearly sum of DNI than Cape Town, has a lower annual savings than Cape Town. This emphasizes that the value of augmentation is higher in areas where the fuel price is high. Furthermore, if the capital for a $2MW_{peak,th}$ CSP augmentation system is R 6 390 051.00 for a make-up water heating system, an annual income of R1 023 809 would ensure a reasonable payback period. It is hard to quantify the financial framework of such an augmentation scheme, as each client will differ, and therefore estimations on payback periods are purposefully avoided in this paper.

CONCLUSION

The techno-economic feasibility of the solar augmentation of a coal fired steam boiler is dependent on the local coal price, the year averaged DNI and the installation cost. It has been shown that a 2MW solar augmentation of a coal fired steam boiler can cost between R 6 390 051.00 and R 8 950 051.00 if the Helio100 technology is industrialized. The value of the process heat is directly linked to the price of coal at the specific site, and the annual savings are dictated by the yearly sum of DNI on the site. In South Africa, the coal price at a specific site is greatly affected by the distance of the site form the coal fields, which are located mainly in Mpumalanga. Therefore, whilst the Western Cape does not have the highest yearly sum of DNI, solar augmentation will be more profitable than in Upington, which has a significantly higher yearly sum of DNI but a lower coal price.

It was found that the industrialized Helio100 heliostats can yield financially viable solar augmentation schemes, given that the fuel price and the yearly sum of DNI are high enough.

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