System advisor model (SAM) simulation modelling of a concentrating solar thermal power plant with comparison to actual performance data

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Abstract: This paper is focused on the modelling and simulation of a 50 kW concentrated solar power (CSP) plant located in Crowley, Louisiana. The model was developed using system advisor model (SAM). The objective is to develop a predictive model (using SAM) to characterize the performance of the power plant and, thus, aid the analysis and evaluation of the plant’s performance. The power plant is a research facility of the Solar Thermal Applied Research and Testing (START) Lab. The model was validated by comparing its predictions with the actual plant data. The comparison showed a good correlation between the predicted results and the actual plant data. The validated model was then used to perform parametric analyses across different locations. The analyses showed that by operating the power plant at the optimal combination of solar multiple and hours of storage, we can achieve about 70% reduction in the cost of electrical energy.

Subjects: Environment & Resources; Simulation & Modeling; Mechanical Engineering Design; Renewable Energy; Energy &Fuels; Clean Technologies; Renewable Energy

Keywords: concentrated solar power (CSP); LCOE; renewable energy systems; system advisor model (SAM); solar multiple; thermal energy storage; parametric analyses

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Emeka K. Ezeanya is a graduate student of Mechanical Engineering at the University of Louisiana at Lafayette. He worked on this project as a member of the START Lab team under the supervision of Dr Terrence Chambers, who is also the team leader. The START Lab is aimed at developing and fostering cost competitive solar technologies both within Louisiana and beyond. The Lab also supports economic development in different ways as well as provides education and outreach programs towards promoting the use of RETs. Consequently, this project lies within the overall objectives of the START Lab, as it helps to provide a clearer understanding of the benefits of using solar technologies both within and outside Louisiana.

PUBLIC INTEREST STATEMENT

Imagine that energy for daily use can be produced and supplied at a cost-effective rate, while the environment is also conserved. This becomes a “win–win” situation whereby individuals pay less for energy use while living in a healthy environment. This research is aimed at developing and fostering renewable energy technologies (RETs) with regard to the benefits which these technologies can offer. To achieve this aim, a 50 kW solar power plant was modelled and analysed, which helped to obtain a deeper insight into the behaviour of the power plant, as well as the potential benefits of running the plant. It was determined that by operating the power plant at its optimal capacity, about 70% reduction in the cost of electrical energy can be achieved. Thus, by employing solar power technologies, significant cost reduction can be obtained, which also ensures a healthy environment because energy production is not based on fossil fuels.
1. Introduction
Within the past decade, there has been an increasing trend among countries and individuals in adopting RETs. The imperatives for this trend relate to higher energy demand, increasing industrialization (which warrants more energy consumption), the finite nature of fossil fuel, environmental impacts of carbon emissions (with their global warming effects), and reduced costs for certain RETs, especially wind and solar. Thus, referring to the 2016 Lazard study, the installed capacity of renewable energy has increased over the years, while the median cost of producing renewable energy has dropped (Lazard Study, 2016). With the growing trend in the use of renewable energy, there are currently more renewable energy jobs than fossil fuel jobs, whereby the former is about five times the latter (Ettensohn, 2017). Wind and the solar energy resources have made the greatest contribution to renewable energy development (IRENA, 2017). The US Department of Energy in its 2017 US Energy and Employment Report (USEER) stated that solar and wind energy jobs increased by 25% and 32%, respectively, in 2016 (U. S. Department of Energy, 2017). This is partly because wind and solar are generally the most available, unlike (for example) geothermal energy resources, which can only be found in some geographical locations with active volcanic sites. Renewables are rapidly employed for both power generation and heat supply. This trend in renewables is expected to continue to grow as the economies of scale are improving and prices of renewables continue to drop. Momentum will not stop now; we are past the tipping point because the unsubsidized levelized cost of energy (LCOE) for wind and solar is now lower than for traditional fossil fuel power plants. Figure 16 illustrates the overall power plant efficiency corresponding to the Lafayette, Louisiana weather measurements.

| Table 1. Nomenclature table for important terms |
|-----------------------------------------------|
| **AEP** | Annual electricity production | **NSRDB** | National Solar Radiation Database |
| **CSP** | Concentrated solar power | **ORC** | Organic Rankine cycle |
| **DNI** | Direct normal irradiance | **R&D** | Research and development |
| **FCR** | Fixed charge rate | **RET** | Renewable energy technologies |
| **FOC** | Fixed operating cost | **SAM** | System advisor model |
| **HCE** | Heat collector elements | **SCA** | Solar collector assemblies |
| **HTF** | Heat-transfer fluid | **SM** | Solar multiple |
| **kWh** | Kilo Watt-hours | **START** | Solar Thermal Applied Research and Testing Lab |
| **LCOE** | Levelized cost of energy | **TCC** | Total capital cost |
| **MAPE** | Mean absolute percentage error | **TES** | Thermal energy storage |
| **MSE** | Mean square error | **TMY** | Typical metrological year |
| **MWh** | Mega Watt-hours | **TRNSYS** | Transient system simulation |
| **NREL** | National Renewable Energy Laboratory | **VOC** | Variable operating cost |

As part of this continued effort in the development and deployment of renewable energy systems, the University of Louisiana at Lafayette, in conjunction with CLECO Power Company, developed a small concentrated solar power (CSP) parabolic trough plant—the first of its kind—in Louisiana (Chambers, Raush, & Russo, 2014; Raush, Chambers, Russo, & Ritter, 2013). The facility is called the Solar Thermal Applied Research and Testing (START) Lab. Per Raush et al. (Raush, Chambers, Russo, & Crump, 2016), the local solar resource available in Louisiana, measured in terms of the insolation, is 4–5 kWh/m²/day. Though this is low compared with the insolation in other locations like Arizona and New Mexico, it is still sufficient for a pilot scale study, including
research and development (R&D). Therefore, the START Lab was established to explore solar power options within the state (Chambers, Raush, & Massiha, 2013), as well as to provide more insight into solar power development across different locations. The START Lab project is a parabolic trough CSP generating system. The plant design parameters were discussed by Chambers et al. (Chambers et al., 2014). It is basically a 50 kWe gross output power organic Rankine cycle plant, with an overall efficiency of about 6%, which uses R245fa (i.e. 1, 1, 1, 3, 3-pentafluoropropane) as its working fluid. A simplified layout of the power plant is shown in Figure 1.

The working principle of the CSP plant shown in Figure 1 is that solar energy (direct normal irradiance (DNI)) is collected by the parabolic troughs and concentrated on the receiver (also known as the heat collector element, HCE), which contains the heat-transfer fluid (HTF). The HTF (in this case, water) is heated up and then used to vaporize the working fluid at the heat exchanger (boiler). The working fluid is consequently expanded in the turbine to generate electricity, $W$. The expanded fluid is then cooled at the condenser which is aided by the cooling tower and is recirculated by the pump so that the process repeats.

The power plant has been running since 2012 (Chambers et al., 2014; Raush et al., 2013). One of the goals of the project is to develop predictive models to aid the analysis and evaluation of the power plant. Therefore, this research develops a predictive model that will characterize the power plant using the system advisor model (SAM). Some of the practical difficulties of developing a SAM include customizing the software to typically reflect the power plant being modelled. Although SAM comes with some predefined power cycle options, they do not always match a given power plant. In this case, a custom power plant must be modelled using the software. Modelling a custom power plant might also involve the use of a custom HTF for the solar field and thermal energy storage, which must also be modelled, as was the case in this project. Making these customized changes for the power cycle could present some difficulties as they require obtaining an accurate dataset from the power plant, which must be properly defined within the plant model to make predictions that will closely match the actual output of the power plant. Using the SAM, we perform parametric studies on the power plant, focusing on key variables like solar multiple and hours of storage, to understand how they affect the overall power output of the plant and the LCOE. A lower LCOE suggests a more profitable project. This implies lower cost, with more energy production.
Parametric studies are performed for different US cities and islands. In addition, part of the objective of this research is to find out where and when a small power plant of this given size could be usefully applied. The details of these analyses will be shown in later sections.

Part of the design constraints in coming up with a SAM predictive model is that the power plant was designed for a lower temperature range, with hot water requirements of between 88°C and 116°C (i.e. 190°F—240°F) (ElectraTherm Inc, 2013); thus, the overall power generated by the system is low. By default, SAM does not allow the choice of water as a HTF. To solve this problem, water was modelled as a custom HTF to be used as a heat transfer medium, since that is what the power plant itself is based on. Given that we are using a custom HTF, a custom power cycle must be used to develop the model. The custom power cycle was modelled using the user-defined power cycle option of SAM, which allows the flexibility to specifically define the characteristics of a given power plant that may not be obtainable in the default power cycle option. The plant characteristics and controls were also defined. The results obtained compared favourably with the actual power plant data. The development of such a predictive model is an important addition to the START Lab, as it will aid the analysis and evaluation of the power generating system, which forms part of the R&D process of developing and improving solar technologies in Louisiana.

Different renewable energy systems can be modelled using SAM. Thus, Wagner et al. presented the description and operation of the SAM’s linear Fresnel model (Wagner, 2012; Wagner & Zhu, 2012); in another research, Wagner describes the central receiver model (Wagner, 2008); SAM’s photovoltaic (PV) model was also described by Blair et al. (Blair, Gilman, & Dobos, 2013); in a milestone report for the second quarter of the year 2015, Turchi and Neises discussed the hybrid/integrated power generating systems (Turchi & Neises, 2015); in another report, Turchi and Garvin discussed the molten salt power tower (Turchi & Garvin, 2013); and Neises showed that custom power cycles (user defined) can be implemented in SAM (Neises, 2015). Other software tools used include CoSiM, ThermoFlex, IPSEPro, and greenius (by DLR, Germany) for modelling the linear Fresnel system (Wagner, 2012; Wagner & Zhu, 2012). As reported by Blair et al. (Blair et al., 2013), PV systems can be analysed using various software tools, including PVsyst, PV Design Pro, PVSol, PVSim, PV-F Chart, and Polysun. Different power plant models have been developed using SAM and other software tools. Thus, Wagner and Zhu validated the capability of their SAM by performing a case study on a 100.6 MW e power plant located in Daggett, California (Wagner & Zhu, 2012). The work presented by Barcia et al. (Barcia et al., 2015) is based on the dynamic model of the HTF for a parabolic trough solar power plant using Simulink. The system was modelled by considering that the power output of a CSP plant is a function of the HTF mass flow rate, HTF temperature, and the ambient temperature. Österholm and Pålsson (Österholm & Pålsson, 2014) developed the dynamic model of a CSP plant using Modelica (based on Dymola), and the results were compared with the output of the Andasol, which is a 50 MW power plant located in Granada, Spain. There was a good correlation between the results and the actual plant outputs. In another research project, Montañés et al. (Montañés, Windahl, Pålsson, & Them, 2015) presented the modelling of a 50 MW solar power plant, which was achieved using Modelica, with results compared to the actual measurements from a reference plant, which in this case was the Andasol power plant located in Spain. In addition, the research presented by Vergura and Di Fronzo (Vergura & Di Fronzo, 2012) is a Matlab-based model. In that article, the authors discussed the simulation of a 40 MW CSP plant in consideration of an actual plant located in Bari in the south of Italy. In the project, as discussed by Bhutka et al. (Bhutka, Gajjar, & Harinarayana, 2016), a 1 MW and a 50 MW parabolic trough collector solar thermal power plants were modelled and simulated using the TRNSYS software. The results compared favourably with those of the corresponding reference plants. Ibarra et al. (Ibarra et al., 2016) developed a CSP plant model, which was used in assessing three 50 MW solar power plants found in three different locations in Saudi Arabia. In assessing the performance evaluation of a 10 MW CSP plant in Puerto Rico, Ortiz-Rivera and Feliciano-Cruz developed a Matlab/Simulink model for this purpose (Ortiz-Rivera & Feliciano-Cruz, 2009). It was determined that with clear and sunny skies, the system performance becomes better. This result is consistent with the fact that the amount of DNI depends on the clear conditions of the sky. In a case study and validation reported by NREL (NREL System Advisor Model (SAM) Case Studies and Validation, 2013a, 2013b), a SAM for Andasol-1—a 50 MW CSP plant (with thermal storage and fossil backup)
located in Aldeire, Spain—was presented. Even with the limited publicly available performance data, the results showed a very satisfactory agreement with the actual plant output. This shows the power of SAM in analysing CSP systems. Similarly, in another case study and validation (NREL System Advisor Model (SAM) Case Studies and Validation, 2013b), a SAM for the Gemasolar CSP solar tower receiver power plant was presented. The Gemasolar is a 19.9 MW power plant located in Fuentes de Andalucía, Spain. This is the first plant with the central receiver system incorporated with thermal storage and fossil fuel backup. Though there was also limited publicly available information on the plant performance, simulations performed using the SAM gave a very satisfactory agreement with the plant output. This also confirms the capability of SAM in CSP simulations, analyses, and performance predictions. Furthermore, Guzman et al. (Guzman, Henao, & Vasquez, 2014), using SAM, modelled and presented the analysis of a 50 MWe CSP plant with thermal storage and fossil backup. Desai et al. (Desai, Bandyopadhyay, Nayak, Banerjee, & Kedare, 2014) discussed the modelling and simulation of a 1 MWe CSP plant. This is a hybrid plant which intends to take advantage of combining parabolic trough collector and linear Fresnel reflector (LFR) technologies. The analysis was done to help make plans for the plant’s control operation and strategies. In addition, Schenk et al. (Schenk, Dersch, Hirsch, & Polklas, 2015) presented the modelling and simulation of a 50 MW parabolic CSP plant. The model was developed using the DLR solar library and ThermoPower library. The focus was on optimizing the start-up time for the CSP plant.

From the review given above, we see that different software tools, including SAM, have been employed in the modelling and simulation of different power plants. However, it is important to note that most of these projects are based on large-scale commercial power plants. Very little, or no attention, has been given to small-scale plants. These small plants could potentially be very useful in terms of distributed power generation and hot water/heat supply, especially in small-scale industries. They can also be very useful for remote power generation, e.g. on small islands, military bases, or some other remote locations, where the cost of fuel can be very expensive. These applications (usefulness) will be discussed in a subsequent section.

2. Methodology
This section presents the details of the method employed in developing the SAM for the 50 kW CSP plant located in Crowley, Louisiana. SAM was used because it is free software, and it can analyse different renewable energy systems. It also includes financial analyses models, which help to determine the profitability of a given renewable energy project. The approach used to develop the SAM generally follows the guidelines as suggested by Wagner (Wagner, 2014). Because there are various fields that need to be specified, Wagner recommended the following approach:

- Configure receiver and collector components
- Specify HTF and operating temperatures
- Determine transport operation limits
- Configure the loop
- Specify power cycle design point
- Specify thermal storage parameters
- Update costs and financials
- Optimize uncertain parameters
- Optimize solar multiple and TES capacity

2.1. Receivers (HCEs)
The HCE (also known as the receiver tube) used for the power plant is a Schott PTR 70 2008 (Chambers et al., 2014). This model was selected from the SAM Library for HCEs.

The receiver has an inner diameter of 0.066 m, with a glass envelope outer diameter of 0.12 m. We assume that the receivers are new and all identical, with no broken glass. The average heat
loss of the receiver was estimated to be 8 W/m, at annulus pressure of 0.0001 Torr (i.e. 1.33e-7 Bar). The receiver is shown in Figure 2.

2.2. Solar collector assemblies (SCAs)

The power plant was designed using the Gossamer Space Frames (GSF) Large Aperture Trough (LAT) 73. The GSF LAT 73 implies that the size of the aperture width is 7.3 m. This is a large parabolic trough collector with a concentration ratio of 103, as per the specification given by the manufacturer (Gossamer Space Frames and 3M, 2012). Referring to the NREL’s SAM help documentation (NREL System Advisor Model (SAM), 2017), the average-surface-to-focus-path length was determined using Equation 1:

\[
F_{\text{avg}} = w \left( \frac{4a^2 + \left( \frac{w}{3} \right)^2}{a^2} \right) \frac{12a^2 + \left( \frac{w}{3} \right)^2}{12w(4a^2 + \left( \frac{w}{3} \right)^2)}
\]

where \(a\) = focal length (2 m, for this collector) and \(w\) = solar collector aperture width (7.3 m). This gives \(F_{\text{avg}} = 2.56\) m.

Table 1 contains some important terms that are used (discussed) in this paper. The collector was defined in SAM as shown in Table 2.

| Table 2. Collector geometry                  |         |
|---------------------------------------------|---------|
| Reflective aperture area                    | 87.6    |
| Aperture width (total structure)            | 7.3     |
| Length of collector assembly                | 12      |
| Number of modules per assembly              | 3       |
| Average surface-to-focus length             | 2.56    |
| Piping distance between assemblies          | 0.15    |

| Table 3. Optical parameters                  |         |
|---------------------------------------------|---------|
| Tracking error                              | 0.974   |
| General optical error                       | 0.957   |
| Geometry effects                            | 0.92    |
| Mirror reflectance                          | 0.945   |
| Dirt on mirror                              | 0.926   |

Using the values for the collector geometry (as specified in Table 2), the total aperture reflective surface was obtained as the product of the reflective aperture area and the length of collector, which gives 1,051.2 m². Also, the optical efficiency was obtained as the product of all the optical
parameters (as specified in Table 3), which in the case becomes 0.7504, or 75%, approximately. The configuration of the SCA/HCE assemblies was set up as shown in Figure 3, since there are 12 collectors in the single-loop configuration of the power plant.

The changing colour of the receiver tube shows how the HTF (water) is heated up as it passes through the collector. Thus, it starts out cold at the blue end (inlet) and exits hot at the red end (outlet), from which it passes through the heat exchanger (boiler), vaporizing the working fluid (R245fa) that in turn drives the turbine to generate electricity.

The numbers, DF#s, show the sequence of defocusing that could be applied in the situation whereby the assembly is collecting more sunlight than required. Thus, the assembly is defocused by adjusting collectors to be out of sync with the sun tracking to reduce the amount of solar energy that could be collected. Defocusing could be sequential or simultaneous, depending on the preferred choice. In this case, the simultaneous defocusing option was used.

2.3. HTF and operating temperatures
As stated earlier, the heat transfer fluid for the power plant is water. Since water is not, by default, included in the SAM HTF library, it must be user defined. Thus, the thermophysical properties of water were generated using the online software developed by the National Institute of Standards and Technology (NIST) (National Institute of Standards and Technology, 2016). As shown in Table 4, the properties considered include temperature, specific heat, density, dynamic viscosity, kinematic viscosity, conductivity, and enthalpy. SAM performs some linear interpolations using these values to determine the behaviour of the fluid at any given temperature (NREL System Advisor Model (SAM), 2017).

For the SAM, the design loop inlet temperature was set at 93 °C, while the design loop outlet temperature was set at 118 °C which is the maximum loop outlet temperature.

2.4. Transport operation limits
The mass flow rate is given by Equation 2:

\[
\dot{m} = \rho AV
\]  

(2)

where \( \dot{m} \) = mass flow rate of water (HTF), \( \rho \) = density of water,

\( A \) is the cross-sectional area of the receiver tube, given as: \( A = \frac{\pi D^2}{4} \), \( D \) = the inner diameter of the receiver tube (0.066 m), and \( V \) = flow velocity.

The minimum flow rate (\( \dot{m}_{\text{min}} \)) was set at 16 gal/min (i.e. 1 kg/s), while the maximum flow rate (\( \dot{m}_{\text{max}} \)) measured from actual plant data was 98 gal/min (i.e. 6.183 kg/s).

The header design min flow velocity is given as:

\[
V_{\text{min}} = \frac{4 \dot{m}_{\text{min}}}{\rho_{\text{min}} \pi D^2}
\]  

(3)

where \( \rho_{\text{min}} \) is the density at 93 °C (i.e. 963.26 kg/m³). This gives 0.303444 m/s.
| Temperature (°C) | Specific heat (kJ/kg-K) | Density (kg/m$^3$) | Viscosity (Pa-s) | Kinematic viscosity (m$^2$-s) | Conductivity (W/m—K) | Enthalpy (J/kg) |
|------------------|-------------------------|-------------------|-----------------|-------------------------------|----------------------|----------------|
| 50               | 4.1815                  | 988               | 5.47E-04        | 5.53E-07                      | 0.64355              | 2.09E+05       |
| 55               | 4.1831                  | 985.66            | 5.04E-04        | 5.11E-07                      | 0.64922              | 2.30E+05       |
| 60               | 4.1851                  | 983.16            | 4.66E-04        | 4.74E-07                      | 0.65435              | 2.51E+05       |
| 65               | 4.1875                  | 980.52            | 4.33E-04        | 4.42E-07                      | 0.65896              | 2.72E+05       |
| 70               | 4.1902                  | 977.73            | 4.04E-04        | 4.13E-07                      | 0.66309              | 2.93E+05       |
| 75               | 4.1933                  | 974.81            | 3.78E-04        | 3.87E-07                      | 0.66676              | 3.14E+05       |
| 80               | 4.1969                  | 971.77            | 3.54E-04        | 3.65E-07                      | 0.66999              | 3.35E+05       |
| 83               | 4.1992                  | 969.88            | 3.41E-04        | 3.52E-07                      | 0.67173              | 3.48E+05       |
| 85               | 4.2008                  | 968.59            | 3.33E-04        | 3.44E-07                      | 0.67281              | 3.56E+05       |
| 90               | 4.2053                  | 965.3             | 3.14E-04        | 3.26E-07                      | 0.67525              | 3.77E+05       |
| 95               | 4.2102                  | 961.88            | 3.09E-04        | 3.09E-07                      | 0.67734              | 3.98E+05       |
| 100              | 4.2157                  | 958.35            | 2.82E-04        | 2.94E-07                      | 0.67909              | 4.19E+05       |
| 105              | 4.2217                  | 954.7             | 2.68E-04        | 2.80E-07                      | 0.68054              | 4.40E+05       |
| 110              | 4.2283                  | 950.95            | 2.55E-04        | 2.68E-07                      | 0.68169              | 4.61E+05       |
| 115              | 4.2356                  | 947.08            | 2.43E-04        | 2.56E-07                      | 0.68257              | 4.83E+05       |
| 120              | 4.2435                  | 943.11            | 2.32E-04        | 2.46E-07                      | 0.68319              | 5.04E+05       |
| 121              | 4.2452                  | 942.3             | 2.30E-04        | 2.44E-07                      | 0.68328              | 5.08E+05       |
| 125              | 4.2521                  | 939.02            | 2.22E-04        | 2.37E-07                      | 0.68356              | 5.25E+05       |
Similarly, the header design maximum flow velocity is given as shown below:

\[
V_{\text{max}} = \frac{4.\dot{m}_{\text{max}}}{\rho_{\text{max}}\pi D^2}
\]

where \(\rho_{\text{max}}\) is the density at 118 °C (i.e. 944.71 kg/m\(^3\)). This gives 1.913035 m/s. Thus, the header design velocity becomes equal to 0.303444 m/s and 1.913035 m/s for the \(V_{\text{min}}\) and \(V_{\text{max}}\), respectively.

Note that the loop configuration used was the setup shown in Figure 3.

2.5. Power cycle specification
The power cycle specification for this model was developed based on the user-defined power cycle option as described by Neises (Neises, 2015). This option requires that there is available data describing the power cycle performance model (Neises, 2015; NREL System Advisor Model (SAM), 2017). The user-defined option was used since the regular Rankine Cycle power option could not support the low range of temperature values at which the power plant operates. Thus, a custom power cycle must be defined. In this case, the power block model calculates the power output as a function of three independent inputs which must interact to generate the output. These inputs are the HTF temperature, mass flow rate, and the ambient temperature (Neises, 2015). Thus, the output can be expressed as:

\[
Y = f(\dot{m}, T_{\text{HTF}}, T_{\text{amb}})
\]

where \(\dot{m}\) = mass flow rate, \(T_{\text{HTF}}\) = HTF temperature, and \(T_{\text{amb}}\) = ambient temperature (Neises, 2015).

Note that although the output might appear simple as expressed by Equation (6), several other parameters are involved. Thus, determining the overall output, \(Y\), is a complex process.

Each of these inputs is specified with low-, design-, and high-level values to minimize computational requirements, as shown in the Table 5.

| Input  | Low value | Design value | High value |
|--------|-----------|--------------|------------|
| \(T_{\text{HTF}}\) | 74 °C | 118 °C | 118 °C |
| \(T_{\text{amb}}\) | 25.5 °C | 27.4 °C | 28.8 °C |
| \(\dot{m}\) (normalized) | 0.16495 | 1.0 | 1.01031 |

Note the normalized values for the HTF mass flow rate were obtained by dividing the low (16 gal/min), design (97 gal/min), and high (98 gal/min) values by the design value.

The next step is to specify performance as a function of each input, considering the input’s range of values. The idea is to create a performance model for the plant with respect to each of the inputs, together with the interactions among the inputs to generate the output. This performance model is specified in a table containing values that are meant to represent the typical behaviour of the power plant. SAM uses these values to perform parametric analyses, solving a regression model that ultimately yields the outputs (Neises, 2015).

2.6. Performance as function of HTF temperature (at HTF mass flow rates)
Considering the range of values for the HTF temperature, 20 equally spaced values were created between 74 °C and 118 °C. These values were put in a tabular form. The format requires that values be normalized at the design point.

As a starting point, temperature measurements, alongside the corresponding power generated at each temperature point, were obtained from the actual plant data. The power generated at
each temperature value was normalized with that at the design point, which is 50 kW. The heat supplied at each temperature (i.e. heat in design) was calculated using:

$$Q = \dot{m}C_p\Delta T = \frac{W}{\eta}$$  \hspace{1cm} (6)

where $Q$ = heat supplied (cycle thermal input), $\dot{m}$ = mass flow rate, $C_p$ = specific heat at constant pressure, $\Delta T$ = temperature difference, $W$ = power output, and $\eta$ = overall cycle efficiency (approximately equal to 6%). Dividing the power output (at each temperature) by the cycle efficiency, the design heat values were obtained. The heat values were also normalized at the design point by dividing through with 650 kWth, which is the thermal power input required to produce 50 kW electric power output (Raush et al., 2013).

The next step is to specify the low and high levels for the power output and the thermal input. The cycle design thermal input values were multiplied by the normalized low (0.16495) and high (1.01031) values of the flow rates (see Table 5) to obtain the low and high levels of the thermal input values, respectively. The low and high levels of the power output were obtained by considering empirical (power) ratios that could provide enough data to cover the likely off-design space of the turbine. This was achieved through a “trial-and-error” method, by evaluating different power ratios, with the aim of ensuring that the design solution space—that is, the turbine envelope for the power plant—is properly covered. At each point of this procedure, the result is compared with the actual plant measurements to see if it matches; if it does not match, the ratios are either increased or decreased until the result matches better with the measurements. Thus, a manual tuning (curve fitting) method was used in determining the power ratios. A good starting point is to consider the minimum and maximum turbine operations (which in this case were set to 0.19 and 1.17, respectively), and then go from there. The value of 0.19 was chosen since it yields minimum power losses, resulting in an annual energy value that compares favourably with the energy value calculated from the plant’s measurements. At the maximum turbine ratio of 1.0 and above, the LCOE remains constant. The power ratios, henceforth, will be designated as the ratio $L/D$ (low-to-design values) for the low-level values or $H/D$ (high-to-design) for the high-level values. The table describing the performance as function of HTF temperature is shown in Table 6.

Referring to the SAM documentation (NREL System Advisor Model (SAM), 2017), the column notations as shown in Table 6 are such that column 1 contains the range of values of the HTF (hot); columns 2, 3, and 4 contain the normalized electric power output at the low, design, and high HTF mass flow rates, respectively; columns 5, 6, and 7 are the normalized thermal power input at the low, design, and high HTF mass flow rates, respectively; columns 8, 9, and 10 are the normalized electrical consumption for cooling at the low, design, and high HTF mass flow rates, respectively; also columns 11, 12, and 13 contain the water mass flow rates at the low, design, and high HTF mass flow rates, respectively. The values from columns 8 through 13 (all 1s) are given on the assumption that the electrical consumption for cooling and water mass flow rates are kept the same at low, design, and high HTF mass flow rates. In other words, since the table is based on normalized values, there is no difference in the consumption for the cooling and the water mass flow rates across the low, design, and high levels.

### 2.7. Performance as function of HTF mass flow rate (at ambient temperatures)

In this case, we create a table of performance considering the HTF mass flow rates. The assumption is that as the HTF mass flow rate increases from minimum to maximum, the power output increases. Referring to Table 5, the minimum and maximum normalized flow rates were given as 0.16495 and 1.01031, respectively. Thus, we generate 20 equally spaced values from the minimum to the maximum normalized flow rates. The heat supply values for the low, design, and high levels are kept the same across the board and are expressed as a function of HTF flow rates. These values were set to be the same as the normalized flow rates. The values of the power cycle (design) in this case were chosen as an interaction with the low- and high-power ratios of the previous
Table 6. Performance as function of HTF temperature (at HTF mass flow rates)

| HTF temperature (°C) | \( W \) cycle low | \( W \) cycle design | \( W \) cycle high | Heat in low | Heat in design | Heat in high | \( W \) cool low | \( W \) cool design | \( W \) cool high | \( m \) water Low | \( m \) water design | \( m \) water high |
|----------------------|-------------------|---------------------|------------------|-------------|---------------|--------------|----------------|-----------------|----------------|----------------|-----------------|----------------|
| 74                   | 0.107879          | 0.2042              | 0.227317         | 0.043318    | 0.261795      | 0.264494     | 1              | 1               | 1              | 1              | 1               | 1               |
| 76.358               | 0.118973          | 0.2252              | 0.250695         | 0.047624    | 0.288718      | 0.291695     | 1              | 1               | 1              | 1              | 1               | 1               |
| 78.6316              | 0.129539          | 0.2452              | 0.272939         | 0.051854    | 0.313459      | 0.3176       | 1              | 1               | 1              | 1              | 1               | 1               |
| 80.9474              | 0.168316          | 0.3186              | 0.354669         | 0.067576    | 0.408462      | 0.412673     | 1              | 1               | 1              | 1              | 1               | 1               |
| 83.2632              | 0.195365          | 0.3698              | 0.411665         | 0.078203    | 0.474103      | 0.478991     | 1              | 1               | 1              | 1              | 1               | 1               |
| 85.5789              | 0.221569          | 0.4194              | 0.46688          | 0.08892     | 0.537692      | 0.543236     | 1              | 1               | 1              | 1              | 1               | 1               |
| 87.8947              | 0.222414          | 0.421               | 0.468661         | 0.09031     | 0.539744      | 0.545308     | 1              | 1               | 1              | 1              | 1               | 1               |
| 90.2105              | 0.230783          | 0.49684             | 0.481915         | 0.09238     | 0.563051      | 0.565825     | 1              | 1               | 1              | 1              | 1               | 1               |
| 92.5263              | 0.249579          | 0.57242             | 0.525903         | 0.099905    | 0.605667      | 0.611911     | 1              | 1               | 1              | 1              | 1               | 1               |
| 94.8421              | 0.268376          | 0.508               | 0.56511          | 0.107429    | 0.651822      | 0.657997     | 1              | 1               | 1              | 1              | 1               | 1               |
| 97.1579              | 0.283063          | 0.5358              | 0.59658          | 0.113308    | 0.686923      | 0.694005     | 1              | 1               | 1              | 1              | 1               | 1               |
| 99.4737              | 0.28972           | 0.5648              | 0.61048          | 0.115973    | 0.703077      | 0.710326     | 1              | 1               | 1              | 1              | 1               | 1               |
| 101.789              | 0.314972          | 0.5962              | 0.663896         | 0.126081    | 0.764559      | 0.772724     | 1              | 1               | 1              | 1              | 1               | 1               |
| 104.105              | 0.357342          | 0.6764              | 0.752975         | 0.143041    | 0.867179      | 0.87612      | 1              | 1               | 1              | 1              | 1               | 1               |
| 106.421              | 0.396753          | 0.751               | 0.836023         | 0.158817    | 0.962821      | 0.972747     | 1              | 1               | 1              | 1              | 1               | 1               |
| 108.737              | 0.412708          | 0.7812              | 0.86946          | 0.165204    | 1.005328      | 1.011864     | 1              | 1               | 1              | 1              | 1               | 1               |
| 111.053              | 0.438912          | 0.8308              | 0.924855         | 0.175693    | 1.065128      | 1.07611      | 1              | 1               | 1              | 1              | 1               | 1               |
| 113.368              | 0.464587          | 0.8794              | 0.978957         | 0.185791    | 1.127436      | 1.13906      | 1              | 1               | 1              | 1              | 1               | 1               |
| 115.684              | 0.4967            | 0.8834              | 0.98341          | 0.186816    | 1.132564      | 1.144241     | 1              | 1               | 1              | 1              | 1               | 1               |
| 118                  | 0.474308          | 0.8978              | 0.9944           | 0.189862    | 1.151026      | 1.162893     | 1              | 1               | 1              | 1              | 1               | 1               |

Note for Table 6, the power ratios used are as follows: \( L/D = 0.5283; H/D = 1.11321 \).
performance table. Specifically, 20 equally spaced values were generated from the $L/D$ (0.5283) to $H/D$ (1.11321) of the previous performance table (see Table 6).

The table of performance as function of HTF mass flow rate (at ambient temperature) is given in Table 7.

For the new table describing performance as function of HTF mass flow rate, the power ratios were set as follows: $L/D = 1.001$; $H/D = 0.96$. Note that in this case, $L/D$ is greater than $H/D$ since the power output is lower at higher ambient temperature, but higher at lower ambient temperature. This is because at higher ambient temperature, heat rejection by the cooling system (the condenser) is lower, while at lower ambient temperature, the heat rejection is higher. The expanded vapour exiting the turbine needs to be condensed (that means excess heat is removed) as it cycles back to the heat exchanger, and then to the turbine. Recall that the Carnot efficiency, which specifies the maximum efficiency of a heat engine (power plant), depends on the difference in the temperatures of the working fluid both at the heat exchanger (boiler) and at the cooling tower (condenser). Thus, the lower the temperature of the fluid at the cooling tower (with more heat rejection due to lower ambient temperature), the bigger the temperature difference and, consequently, greater the power output.

Referring to the SAM documentation (NREL System Advisor Model (SAM), 2017), the column notations as shown in Table 7 are such that column 1 contains the HTF mass flow rates; columns 2, 3, and 4 are the normalized electric power output at the low, design, and high ambient temperatures, respectively; columns 5, 6, and 7 are the normalized thermal power input at the low, design, and high ambient temperatures, respectively; columns 8, 9, and 10 contain the normalized electrical consumption for cooling at the low, design, and high ambient temperatures, respectively; and columns 11, 12, and 13 contain the water mass flow rates at low, design, and high ambient temperatures, respectively. The thermal input values are kept the same at the low, design, and high ambient temperatures. A similar explanation for the values in columns 8 through 13, as given previously, is also applicable in this case.

2.8. Performance as function of ambient temperature (at HTF temperatures)
The performance as function of ambient temperature (at HTF temperature) is specified in Table 8. The normalized thermal input at the design (hot) HTF temperature is kept at 1.0, while the normalized thermal input at the low and high hot HTF temperatures corresponds to the minimum and maximum normalized thermal input values at HTF mass flow rate, respectively (see Table 6). The normalized electrical power output values at the design HTF temperature are generated by creating 20 equally spaced values from the ratio $L/D$ (1.001) to $H/D$ (0.96) of Table 7. The normalized power output values at the low and high hot HTF temperatures were generated using the following power ratios: $L/D = 0.33392$; $H/D = 1.01695$.

Similar explanations for the column notations as given for Tables 6 and 7 are also applicable in this case, except that column 1 contains the values for the range of the ambient temperatures, while the low, design, and high values occur at the low, design, and high HTF temperatures, respectively.

Besides the performance tables, the power block start-up time was set to 0.5 h (30 min). This is because the power block starts up about 30 min after the power plant has been turned on. During this time, water is circulated through the solar field until it gets sufficiently hot to vaporize the working fluid (R245fa) at the heat exchanger. The minimum start-up temperature for the power block was set to 70 °C, since this is the temperature around which power generation starts. Referring to the power block specifications (ElectraTherm Inc, 2013), the thermodynamic system efficiency is up to 8%. Thus, for the power block design point, the rated cycle conversion efficiency was based on this value.
| HTF mass flow rate | $\dot{W}$ cycle low | $\dot{W}$ cycle design | $\dot{W}$ cycle high | Heat in low | Heat in design | Heat in high | $\dot{W}$ cool low | $\dot{W}$ cool design | $\dot{W}$ cool high | $\dot{m}$ water low | $\dot{m}$ water design | $\dot{m}$ water high |
|-------------------|---------------------|------------------------|---------------------|------------|----------------|------------|----------------|---------------------|----------------|----------------|----------------|----------------|
| 0.16495           | 0.5288283           | 0.507168               | 0.16495             | 0.16495    | 1              | 1          | 1              | 1                   | 1              | 1              | 1              | 1              |
| 0.20943           | 0.5596441           | 0.5367216              | 0.20943             | 0.20943    | 1              | 1          | 1              | 1                   | 1              | 1              | 1              | 1              |
| 0.25393           | 0.5904589           | 0.5662742              | 0.25393             | 0.25393    | 1              | 1          | 1              | 1                   | 1              | 1              | 1              | 1              |
| 0.29842           | 0.6212747           | 0.5958278              | 0.29842             | 0.29842    | 1              | 1          | 1              | 1                   | 1              | 1              | 1              | 1              |
| 0.34292           | 0.6520904           | 0.6253814              | 0.342921            | 0.342921   | 1              | 1          | 1              | 1                   | 1              | 1              | 1              | 1              |
| 0.38743           | 0.6829062           | 0.654935               | 0.387413            | 0.387413   | 1              | 1          | 1              | 1                   | 1              | 1              | 1              | 1              |
| 0.43190           | 0.713721           | 0.713008               | 0.431906            | 0.431906   | 1              | 1          | 1              | 1                   | 1              | 1              | 1              | 1              |
| 0.47639           | 0.7445368           | 0.743793               | 0.476398            | 0.476398   | 1              | 1          | 1              | 1                   | 1              | 1              | 1              | 1              |
| 0.52089           | 0.7753526           | 0.774578               | 0.520891            | 0.520891   | 1              | 1          | 1              | 1                   | 1              | 1              | 1              | 1              |
| 0.56538           | 0.8061684           | 0.805363               | 0.565384            | 0.565384   | 1              | 1          | 1              | 1                   | 1              | 1              | 1              | 1              |
| 0.60987           | 0.8369831           | 0.836147               | 0.609876            | 0.609876   | 1              | 1          | 1              | 1                   | 1              | 1              | 1              | 1              |
| 0.65436           | 0.8677989           | 0.866932               | 0.654369            | 0.654369   | 1              | 1          | 1              | 1                   | 1              | 1              | 1              | 1              |
| 0.69862           | 0.8986147           | 0.897717               | 0.698662            | 0.698662   | 1              | 1          | 1              | 1                   | 1              | 1              | 1              | 1              |
| 0.743354          | 0.9294305           | 0.928502               | 0.743354            | 0.743354   | 1              | 1          | 1              | 1                   | 1              | 1              | 1              | 1              |
| 0.787847          | 0.9602453           | 0.959286               | 0.787847            | 0.787847   | 1              | 1          | 1              | 1                   | 1              | 1              | 1              | 1              |
| 0.83239           | 0.9901611           | 0.990071               | 0.832339            | 0.832339   | 1              | 1          | 1              | 1                   | 1              | 1              | 1              | 1              |
| 0.87683           | 1.0218809           | 1.02086                | 0.876832            | 0.876832   | 1              | 1          | 1              | 1                   | 1              | 1              | 1              | 1              |
| 0.921325          | 1.0526916           | 1.05164                | 0.921325            | 0.921325   | 1              | 1          | 1              | 1                   | 1              | 1              | 1              | 1              |
| 0.965817          | 1.0835124           | 1.08243                | 0.965817            | 0.965817   | 1              | 1          | 1              | 1                   | 1              | 1              | 1              | 1              |
| 1.01031           | 1.1143232           | 1.11321                | 1.01031             | 1.01031    | 1              | 1          | 1              | 1                   | 1              | 1              | 1              | 1              |
## Table 8. Performance as function of ambient temperature (at HTF temperatures)

| Ambient temperature (°C) | W cycle low | W cycle design | W cycle high | Heat in low | Heat in design | Heat in high | W cool low | W cool design | W cool high | m water low | m water design | m water high |
|--------------------------|-------------|----------------|--------------|-------------|---------------|--------------|-------------|---------------|-------------|-------------|---------------|---------------|
| 25.5                     | 0.3342539   | 1.001          | 1.017949     | 0.2617949   | 1             | 1.1510256   | 1           | 1             | 1           | 1           | 1             | 1             |
| 25.6737                  | 0.335333    | 0.998842       | 1.0157724    | 0.2617949   | 1             | 1.1510256   | 1           | 1             | 1           | 1           | 1             | 1             |
| 25.8474                  | 0.328127    | 0.996884       | 1.0135778    | 0.2617949   | 1             | 1.1510256   | 1           | 1             | 1           | 1           | 1             | 1             |
| 26.0211                  | 0.320921    | 0.994526       | 1.0113832    | 0.2617949   | 1             | 1.1510256   | 1           | 1             | 1           | 1           | 1             | 1             |
| 26.1947                  | 0.3313715   | 0.992368       | 1.0091886    | 0.2617949   | 1             | 1.1510256   | 1           | 1             | 1           | 1           | 1             | 1             |
| 26.3684                  | 0.3306513   | 0.990211       | 1.007951     | 0.2617949   | 1             | 1.1510256   | 1           | 1             | 1           | 1           | 1             | 1             |
| 26.5421                  | 0.329307    | 0.988053       | 1.0058005    | 0.2617949   | 1             | 1.1510256   | 1           | 1             | 1           | 1           | 1             | 1             |
| 26.7158                  | 0.3292101   | 0.985895       | 1.0036059    | 0.2617949   | 1             | 1.1510256   | 1           | 1             | 1           | 1           | 1             | 1             |
| 26.8895                  | 0.328495    | 0.983737       | 1.0014113    | 0.2617949   | 1             | 1.1510256   | 1           | 1             | 1           | 1           | 1             | 1             |
| 27.0632                  | 0.3277689   | 0.981579       | 0.9994168    | 0.2617949   | 1             | 1.1510256   | 1           | 1             | 1           | 1           | 1             | 1             |
| 27.2368                  | 0.3270483   | 0.979421       | 0.9973012    | 0.2617949   | 1             | 1.1510256   | 1           | 1             | 1           | 1           | 1             | 1             |
| 27.4105                  | 0.3263277   | 0.977263       | 0.9951728    | 0.2617949   | 1             | 1.1510256   | 1           | 1             | 1           | 1           | 1             | 1             |
| 27.5842                  | 0.3256071   | 0.975105       | 0.9930433    | 0.2617949   | 1             | 1.1510256   | 1           | 1             | 1           | 1           | 1             | 1             |
| 27.7579                  | 0.3248865   | 0.972964       | 0.9909385    | 0.2617949   | 1             | 1.1510256   | 1           | 1             | 1           | 1           | 1             | 1             |
| 27.9316                  | 0.3241659   | 0.970789       | 0.9882439    | 0.2617949   | 1             | 1.1510256   | 1           | 1             | 1           | 1           | 1             | 1             |
| 28.1053                  | 0.3234456   | 0.968632       | 0.9859033    | 0.2617949   | 1             | 1.1510256   | 1           | 1             | 1           | 1           | 1             | 1             |
| 28.2789                  | 0.322725    | 0.966474       | 0.9838357    | 0.2617949   | 1             | 1.1510256   | 1           | 1             | 1           | 1           | 1             | 1             |
| 28.4526                  | 0.3220044   | 0.963136       | 0.9806612    | 0.2617949   | 1             | 1.1510256   | 1           | 1             | 1           | 1           | 1             | 1             |
| 28.6263                  | 0.3212838   | 0.960158       | 0.9774666    | 0.2617949   | 1             | 1.1510256   | 1           | 1             | 1           | 1           | 1             | 1             |
| 28.8                     | 0.3205632   | 0.957627       | 0.9747949    | 1           | 1.1510256   | 1           | 1             | 1           | 1           | 1             | 1             |
2.9. Thermal energy storage (TES) specification

The thermal storage HTF fluid used in this case is hot water. Because water does not come by default in the SAM library, it must be modelled. This was done by specifying the various properties of water. Essentially, hot water was used as the HTF for both the solar field and thermal storage. Water was used because the power plant being modelled operates at a low temperature range (88 °C—116 °C); therefore, we do not anticipate any phase change in the storage medium within this range. Besides, water is cheaper and more easily obtainable than most other storage media, which can undergo phase change, e.g. Hitec, Hitec XL, Hitec Solar Salt, etc. However, the power plant being studied has no thermal storage system, currently (although plans are underway to incorporate a storage system), so the default setting for storage (full load hours of TES), was set at 0 h for the initial simulation. One of the many benefits of using SAM is that we can simulate scenarios that have a storage system, whereby we vary the hours of storage to understand how they affect the amount of energy produced by the plant towards minimizing the cost of energy. Thus, a later section of this report will show details of the parametric analysis considering various locations.

2.10. Financial parameters

There are different financial models that could be used in SAM. However, the financial model used in this case is the simple LCOE calculator (based on the FCR method). In this case, the LCOE is calculated using the fixed charge rate (FCR) method. This method is useful for basic, preliminary, or feasibility project analysis, which exempts the use of complicated financial details (NREL System Advisor Model (SAM), 2017).

Referring to NREL System Advisor Model (SAM) (2017), the formula for calculating the LCOE considering the FCR is given as:

\[
LCOE = \frac{FCR \times TCC + FOC}{AEP} + VOC
\]  

where \( FCR \) = fixed charge rate, \( TCC \) = total capital cost, \( FOC \) = fixed (annual) operating cost, \( AEP \) = annual electricity production (kWh), and \( VOC \) = variable operating cost.

3. Model validation

The SAM was validated by comparing its predictions with the actual power plant output on certain days. This was done to determine the accuracy of the model in making predictions when compared with the actual plant output. However, to validate the model, some of the measurements from the power plant must be converted to the format required by the SAM input file. To this end, Equations 9, 10, 11, and 12 were used.

Wind Speed \( \left( \frac{m}{s} \right) = 0.44704 \times \text{Wind Speed (mph)} \)  

(ConvertUnits, 2018)

\[
T(°C) = \frac{T(°F) - 32}{1.8}
\]  

(RapidTables, 2017)

\[
P \text{ (mbar)} = P \text{ (inHg)} \times 33.8638
\]  

(UnitConverters, 2018)

Dew point (°C) = \[
\frac{\text{LN} \left( \frac{RH}{100} \right) + \left( \frac{17.625 - T}{243.047} \right)}{7.625 - \text{LN} \left( \frac{RH}{100} \right) - \left( \frac{17.625 - T}{243.047} \right)}
\]  

(McNoldy n. d.)

where \( RH \) = relative humidity (%); \( T \) = temperature °C
The following days were compared, and the results are hereby presented. In this case, MSE is the mean square error, while MAPE is the mean absolute percentage error. Figures 4, 5, 6, 7, 8, 9, 10, 11, 12, and 13 show the comparison between the predicted and actual power output of the plant on their respective days.

Figure 4. Predicted Vs Actual (March 21, 2016) MSE: 17.31; MAPE: 9.51%.

Figure 5. Predicted Vs Actual (March 25, 2016) MSE: 11.86; MAPE: 10.21%.

Figure 6. Predicted Vs Actual (April 29, 2016) MSE: 8.76; MAPE: 9.21%.

Figure 7. Predicted Vs Actual (May 6, 2016) MSE: 9.81; MAPE: 6.41%.
Analysis of the predictions shows that, on hourly basis, the coefficient of determination ($R^2$) is 0.81860, while the adjusted $R^2$ is 0.81848, resulting in a correlation coefficient ($R$ value) of 0.9048, with an error of about 10%, which is approximately equal to the MAPE values of several individual days analysed. In addition, the SAM was also validated by comparing the total amount of electrical energy generated during the year by the power plant with the amount predicted by the model. From measurements of plant data, the total amount was determined to be 22,301 kWh, while the model prediction was 22,913 kWh. This gives a percentage error of about 3%, which is lower than...
the MAPE for the individual days, since over the course of the year the errors in the estimates for 
individual days tended to cancel themselves out. Thus, overall, we can say that on an annual basis, 
the model predictions are correct approximately 97% of the time. Uncertainties in the model 
predictions can be improved by obtaining more measurements from the power plant and ensuring 
that the measuring instruments are always accurate and properly calibrated. This would enable 
refinements to the model towards obtaining more accurate model predictions.

3.1. Initial simulation of the 50 kw CSP plant

The validated model is next used to simulate the performance of the power plant for the Lafayette, 
Louisiana location. This is done to determine the amount of energy that could be generated by the 
power plant within its first year of operation in that location. To achieve this, the Lafayette weather 
measurements for a typical metrological year (TMY) were first downloaded from the National Solar 
Radiation Database (NSRDB) website (NREL Data Viewer n.d.). The TMY represents the measure-
ments of weather data that would typically characterize the weather pattern of a given location 
during the year. Using the TMY file as input to the SAM, at a solar multiple of 1.0 and 0 h of thermal 
storage, we ran an initial simulation of the model to obtain the result as shown in Figure 14. The 
figure shows the resource beam normal irradiance, also known as the DNI, as the top chart, and 
the corresponding system power generated as the bottom chart.

Looking at the profiles of the two charts, we see that the amount of power generated is closely 
correlated to the DNI input.

The relationship between the input DNI and the output power is such that the higher the DNI input, the 
greater the power output. The maximum power output occurred around the months of February.
through April (which is about 50 kW), while the lower level of power output occurred around the months of June through September when the DNI level is lower. The electrical energy (kWh) generated by the system is a function of the power output from the system over a given period. The amount of electrical energy generated per month corresponding to the power output of Figure 14 is shown in Figure 15.

The energy profile shows two humps. One occurred in the months of April and May, while the other (though lower) occurred in October. The humps represent the points where energy production is significantly higher. The cost of electricity is expected to be lower at these points. As reported by the SAM, the total energy produced by the power plant during the first year (for the given input) is 60,271 kWh, i.e. about 60 MWh. The power cycle efficiency yields an annual average of 6.16% (i.e. about 6%), which is the overall power plant efficiency; that is a solar-to-thermal efficiency of 75% and thermal-to-electrical efficiency of 8%.
4. Parametric analyses and results

Having validated the model, the next step is to use the model to study the relationships among solar multiple, hours of thermal energy storage, and LCOE. As stated earlier, solar multiple and hours of storage have a significant impact on the LCOE. As always, the goal is to obtain the best combinations of solar multiple and hours of storage that minimize the cost of energy, which is expressed in terms of the LCOE.

To carry out this study, three different locations across the United States were selected. The selection was based on the amount of solar radiation occurring across different regions in the United States, which may be categorized as high, medium, and low solar resource. For the high solar resource region, Albuquerque, New Mexico, was selected; for the medium resource, Lafayette, Louisiana, was selected; and for the low resource region, Williston, Vermont.

Equally, it was also decided to consider where the power plant analysed in this study (50 kW CSP plant) might be most applicable outside of the United States. The applicability or usefulness of a given power plant is considered in terms of its minimum LCOE. In this regard, two islands outside of the United States were selected; these are the US Virgin Islands (USVI) and Montserrat. Parametric analyses of solar multiple, hours of storage, and LCOE were also conducted for these two locations.

Thus, this section will present the results of the parametric analyses of the relationships among solar multiple, hours of storage, and LCOE, conducted across five different locations: New Mexico, Louisiana, Vermont, USVI, and Montserrat.

Note that the weather files used for analyses of these locations were obtained from the NSRDB website (NREL Data Viewer n. d.).

Here are the results of the parametric analyses of solar multiple, hours of storage, and LCOE conducted across five different locations. Note that for these analyses, hot water was used as the thermal storage medium. Figures 17, 18, 19, 20, and 21 show the parametric analyses of hours of thermal storage, solar multiple, and LCOE for their respective locations.

5. Discussion of results

From the parametric analyses presented in the previous chapter, it becomes clearer how thermal storage can significantly lower the cost of electrical energy. The minimum LCOE occurring at the solar multiple of 4.2 and 18 h of storage suggests that the larger the solar multiple and the more thermal energy we can store (when there is sufficient solar resource), the more electrical energy we can generate for a small increase in cost; hence, the lower the LCOE we can get. In a 24-h cycle, good sunlight that is strong enough to power the plant occurs for about 6 h per day on average; therefore, we want to have enough thermal storage that can power the plant through the remaining 18 h. This explains why we set 18 h as the maximum hours of thermal storage in our analyses. By doing so, we minimize (if not eliminate)
Figure 17. Parametric analysis (New Mexico) Min. LCOE (4.2 SM and 18 Hours of Storage): 10.33 cents/kWh (Vs 32.09 cents/kWh), i.e. 67.81% electric cost reduction.

Figure 18. Parametric analysis (Louisiana) Min. LCOE (4.2 SM and 18 Hours of Storage): 14.35 cents/kWh (Vs 69.48 cents/kWh), i.e. 71% electric cost reduction.

Figure 19. Parametric analysis (Vermont) Min. LCOE (4.2 SM and 18 Hours of Storage): 22.0 cents/kWh (Vs 72.26 cents/kWh), i.e. 69.55% electric cost reduction.
intermittency, which is one of the major drawbacks of solar power plants that occurs when the sun is not shining. In other words, by operating at the maximum hours of thermal storage, the power plant is fully dispatchable, with little or no interruption in power supply. At the optimal combination of solar multiple and hours of storage which yields the minimum LCOE, our analyses showed that we can achieve about 70% reduction in the cost of electricity (from the base case with no thermal storage), which is a significant cost reduction. This is because storage ensures that our downtime is minimized, meaning that our capacity factor is improved. In other words, with thermal storage, we have the capacity to still generate electricity even when the sun is down, for example, in the night-time, or on cloudy days. Thus, the LCOE goes down since more energy will be generated in comparison with the cost of building and operating the power plant. It becomes important to note (as shown by the results of the parametric analyses) that the higher the solar resource in a location, the lower the cost of electrical energy, and thus, the higher the viability of a solar power project within the location. For the locations examined, the viability trend (high to low) of a solar power project across the locations goes from New Mexico, to the USVI, Montserrat, Louisiana, and then to Vermont. This explains why there are up to 102 solar companies in New Mexico (Solar Energy Industries Association (SEIA), 2018).

Renewable energy, apart from being “green,” becomes very beneficial when it is considered cost-effective in comparison with the traditional fossil fuel-based energy systems. This is especially the case in remote locations, where the cost of transportation of fossil fuel is very high such that...
electricity costs in those locations become quite expensive. Usually, this is the case in remote islands, desert locations, and military camps.

Considering remote islands, we studied the viability of small commercial sized solar power projects in the Caribbean islands. In this regard, using the 50-kW power plant model, we examined the USVI and Montserrat. The average cost of electricity in the Caribbean islands is $0.33/kWh (Energy Transition Initiative, 2015a).

The report from the Energy Transition Initiative (Energy Transition Initiative, 2015a) stated that the USVI wants to achieve a 60% reduction in the use of fossil fuel by 2025; however, they are still highly dependent on fossil fuel as their major source of electrical energy supply. In 2015, the cost of electricity in this location was $0.47/kWh, while the residential and commercial electricity tariffs were $0.487/kWh and $0.517/kWh, respectively. Going by the costs of electricity within this island, we observed that operating our power plant within this region can be very cost-effective, since our analyses showed that we can generate electric power for as low as 12.32 cents/kWh. This is a significant reduction in the cost of electricity within this island, which is also in line with the island’s clean energy goals.

Montserrat is also a Caribbean island of interest. Referring to another report by the Energy Transition Initiative (Energy Transition Initiative, 2015b), Montserrat has no clean energy goals, and they are highly (if not totally) dependent on fossil fuels. Thus, residential electricity rate costs at least $0.53/kWh; it is quite expensive. Analysis of this location using our plant model showed that our power plant can be quite useful in this location. We can generate power for as low a rate as 12.43 cents/kWh. This will be a significant reduction in the cost of electricity in this location. It will equally initiate a clean energy project for this island, providing the benefits of renewable energy systems.

We also considered hot desert locations. One main feature of these locations is that they are usually far away from the main towns. Thus, the cost of transportation of fossil fuel to these locations can be quite high; therefore, it becomes economical to generate power locally. Within this scenario, we could potentially use our power plant to generate electricity at a cost-effective rate, depending on the specific situation. We can utilize the available high solar resource within these locations to generate power locally at a much lower rate.

In addition, if we consider a remote military base somewhere in the jungle, in which case it will cost a lot to transport fuel to the location, a solar power plant can be a good option for a cheaper, cleaner energy supply. From an economic point of view, it will be cheaper to generate power locally, rather than having to transport fuels from helicopters or trucks to the location. Our power plant could potentially be very useful in this regard.

Furthermore, when there is a need for not only electricity but also for hot water supply, a CSP plant (such as ours) becomes quite useful. Our power plant can be utilized for the purposes of hot water supply, as may be required by some small industries. Thus, the power plant can serve a dual purpose of electricity generation and hot water supply. This is one of the main advantages of CSP plants over PV solar plants. It would be more economical to use a CSP plant to generate hot water directly than to use a PV plant to first generate electricity, and then use the electricity to generate hot water. Thus, for the purposes of hot water supply, a CSP plant (like ours) becomes a favourable option.

6. Conclusion and recommendation
There has been a significant increase in the use of renewable energy systems over the past decade. Companies and individuals have increasingly transitioned to the use of renewable energy systems not only for the purposes of ensuring a clean environment but also as a way of providing a sufficient energy supply in a cost-effective manner. Thus, there has been an increase in renewable energy jobs when compared to non-renewable energy jobs (Ettenson, 2017).
As part of the effort in advancing renewable energy systems in Louisiana, the University of Louisiana at Lafayette in conjunction with CLECO Power Company established the START Lab. This is based on a 50 kW CSP plant, which can be used for a pilot scale study to understand and advance solar power development in Louisiana and beyond. Therefore, this research was based on developing a predictive model that aids in the analyses and understanding of the behaviour of the power plant. The model was developed using software called SAM, which is a free software created by NREL to aid the modelling and analyses of renewable energy systems. The fact that SAM is free and has the capability to more accurately model and analyse different types (combinations) of renewable energy systems makes it preferable over other renewable energy system modelling software packages.

The SAM predictive model was developed (as shown in the “Methodology” section) and validated. Using this model, we conducted some parametric analyses for various locations to determine the best combinations of solar multiple, hours of thermal storage, and LCOE. Parametrics are like “What–IF” analyses and can be done for different parameters of the power plant to determine the combinations that optimize the value of an output. We noted that by operating the power plant at the optimum combination of solar multiple and hours of thermal storage, we can achieve about 70% reduction in the cost of electrical energy, which is a significant cost reduction.

We also discussed the usefulness of the power plant, especially in such areas as remote islands, hot desert locations, and remote military camps. We equally noted that the power plant can also be utilized for the purposes of hot water supply, which is one of the main advantages of CSP over PV plants.

Currently, efforts are being made to incorporate thermal storage into our power plant. The parametric analyses performed using the SAM developed in this research can be quite useful in this regard. Obtaining more measurements of the actual plant data is considered essential, since these measurements can be used to fine-tune the model and improve the accuracy of the model’s predicted results. The more accurate the model’s predictions become, the better we understand the behaviour of the power plant in different scenarios and locations where it can be operated.

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