# SAM PROCESS HEAT MODEL DEVELOPMENT AND VALIDATION: LIQUID-HTF TROUGH AND DIRECT STEAM GENERATION LINEAR FOCUS SYSTEMS

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## Abstract

Two new solar industrial process heat (SIPH) models have been added to the System Advisor Model (SAM) energy simulation tool. The two process heat models were: i) liquid-heat transfer fluid (HTF) parabolic troughs; and ii) direct steam generation (DSG) linear-focus collectors. The DSG model can simulate either DSG parabolic troughs (PT) or DSG Linear Fresnel (LF) fields, based on the optical characteristics supplied. These models help to meet the need for independent, validated tools that reliably simulate the effects of adding a solar field to provide heat for potential IPH applications. During the pre-validation of the liquid-HTF model, operational data was provided and preprocessed by SPF and evaluated at ZAE Bayern. The beta liquid-HTF model provided excellent agreement between the simulations and the operational data for the solar thermal yield generation on a yearly and monthly basis (4.4% difference). The final liquid-HTF process heat model has been further optimized with test users such as ZAE Bayern and SPF. Key improvements in the SIPH models to better model SIPH fields include the use of smaller piping systems and heat capacities, a single collector field, and a higher time-step resolution than for electricity generation (down to 10 minutes). Both the final liquid-HTF and DSG models were successfully validated against operational data for respective solar fields, and showed less than 5% deviation to actual results. A brief application where the liquid-HTF process heat model is used for a brewery in California and the value of reliably simulating a potential SIPH solar field are highlighted.

*Keywords: Solar Industrial Process Heat (SIPH), Concentrating Solar Power (CSP), Parabolic Trough (PT), Linear Fresnel (LF), Direct Steam Generation (DSG),), System Advisor Model (SAM), Energy Modelling*

## 1. Introduction

After significant interest during the 1970s, but relatively few deployments, the use of concentrating solar technologies for thermal and industrial applications, including solar enhanced oil recovery (solar EOR), thermally-driven desalination, and industrial process heat (IPH), are again receiving global interest (Kurup and Turchi 2015; IEA 2017; Frank et al. 2014). For larger scale adoption of both non-concentrating and concentrating solar power (CSP) technologies for SIPH, trusted, validated, and readily available thermal energy generation and simulation tools are needed. Free tools that can simulate the use of CSP technologies for SIPH now include the newly modified System Advisor Model (SAM) and the German Aerospace Center's Greenius software packages (NREL 2017b; Deutsches Zentrum für Luft und Raumfahrt (DLR) 2017).

This paper highlights the overall developments and validations to SAM's new process heat models for using concentrated solar thermal energy, made available from the 2017 release of SAM. The paper describes: the need for developing SIPH modules using CSP technologies; detailed model developments for both SIPH models; the differences between the thermal models and SAM's existing electricity generation models; and importantly, the validations of both models to real operational sites where the solar field provides heat. It is worth noting that the SIPH models have focused only on concentrating technologies, but non-concentrating technologies are also very suitable for lower-temperature hot water heating applications, as seen in the Solar Water Heating models in SAM (NREL 2017b). Two models have been developed for SIPH application, the first that utilizes a selectable liquid-HTF with parabolic troughs (e.g., pressurized water, glycol or a synthetic mineral oil), and the second, DSG systems using water in linear-focus collectors. It is important to highlight that the DSG SIPH model can model the parabolic trough (PT) and linear Fresnel (LF) systems, based on changing the optical characteristics, pumping power, and heat loss of the collector. The paper also highlights a utilization of the liquid-HTF model for a brewery in California that could potentially install a new parabolic trough solar field to provide heat.

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### *1.1 Motivation for the developing the SAM SIPH models due to the increasing global interest*

Energy-generation and simulation tools such as Greenius and SAM provide a reputable, validated and “consistent framework for analyzing and comparing power system costs and performance across the range of solar technologies and markets” (Wagner and Gilman 2011). SAM’s original solar-thermal models were specifically developed for the electricity sector. With growing interest in SIPH, it is important to develop energy-generation modelling tools also able to undertake thermal energy yield analysis. It is straightforward to provide IPH temperatures (e.g., >150°C) using the same CSP technologies as for electricity (e.g., liquid-HTF troughs or DSG collectors). However, there are differences in the solar field modelling used for electricity generation, and a SIPH field used for heat generation. In CSP electricity modelling, the solar field typically is coupled to an integrated steam-Rankine power block used for electricity generation (Wagner and Gilman 2011). It has been shown that when the SAM inputs and the SAM code were changed to minimize the power-cycle impacts (e.g., a constant solar field inlet temperature), the “power cycle caused a 6% underestimation of performance from what should have transpired had the model been freed of the power cycle constraints” (Turchi et al. 2016). Since the outlet of the power block serves as an inlet to the solar field, the state of operation of the power block has a direct impact on the solar field performance. Without the constraints (e.g., a variable solar field inlet temperature) and de-coupling of the power cycle, in attempting to model solar fields used for process heat applications, it was found the performance was underestimated by about 14% (Turchi et al. 2016).

A key project known as Solar Payback was initiated in October 2016 with support from the German Federal Environment Ministry and has partners including the Fraunhofer Institute for Solar Energy and the German bank KFW (German Solar Association 2017). This three-year project funded at nearly €3 million has the purpose of promoting the use of SIPH across four partner countries (Brazil, Mexico, India, and South Africa) to: 1) raise SIPH awareness; 2) highlight the technical merits and economic potential, to then 3) help increase commercial investment in all forms of SIPH (German Solar Association 2017). The first “Solar Heat for Industry” report has highlighted that 74% of the global energy consumed by industry was for heat, with only ~9% of that being provided by renewables rather than by conventional fuels (e.g., coal and natural gas) (German Solar Association 2017). With industrial heat demands expected to increase, SIPH could play an increasingly important role globally, particularly in decarbonizing the industrial sector. Real examples of installed CSP solar fields (e.g., PT or LF) for IPH have highlighted that up to 40% of a large industrial site’s heat demand can be met with the CSP solar field. For example, at the Lechera Guadalajara plant the solar field installed in 2016 meets nearly 35% of the heat demand in the pasteurization process. In another example, at Ram Pharma’s large pharmaceutical plant, between 30% and 40% of diesel demand is being met with the new solar field (German Solar Association 2017).

Within India, CSP has great potential for SIPH use at the small and industrial scale, with the prospect of fuel displacement in industry and rural areas. The United Nations International Development Organization (UNIDO) has estimated that a market potential of approximately 6.45 $GW_{th}$ for concentrating solar thermal (CST) technologies could exist for Indian industrial applications (MNRE 2017). For example, at the SKF Technologies manufacturing plant in Mysore before solar integration, diesel was the prime fuel burnt to provide heat for the phosphating process. After the integration of the 256.4 $m^2$ parabolic trough solar field in 2013, the facility now obtains pressurized water from the solar field at 130°C for use in the phosphating processes (PWC India 2017). The solar field, which received a grant for the installation, has been found to reduce diesel consumption by approximately 14,000 liters annually, and the investment had a payback of 5.2 years (PWC India 2017).

India is also increasing investment significantly to meet the potential for SIPH using CST collectors and storage, which provide potential opportunity for technology developers. The SunFocus quarterly report highlights the use of CST (for both electricity and IPH) in India. There is significant developing interest for storage (e.g., phase-change materials [PCMs] and salts) as part of the SIPH integrated solution (MNRE 2017). The Indian Ministry of New and Renewable Energy (MNRE) and UNIDO are also working on a project to provide financial support to concentrating SIPH projects and are helping to create new business models for solar thermal heat to help adoption and deployment (MNRE 2017). With SIPH projects being developed both in the U.S. and globally, the value of independent and validated SIPH modelling tools is clear.

Without such freely available tools, the end-users/beneficiaries of such SIPH solar fields would find it difficult to gauge the value, thermal energy yield, and potential fuel savings from the new solar fields for their applications. The new SAM modules (liquid-HTF and DSG) were created to better understand thermal energy generation and the potential levelized cost of heat (LCOH) at global locations for SIPH applications.

## 2. Liquid-HTF and DSG Model Development

Various technologies such as non-concentrating collectors and concentrating systems (e.g., sensible liquid-HTF troughs and DSG systems) can be utilized for SIPH applications, depending on the temperatures required by the end-user and the industrial processes (Artic Solar Inc. 2017; IEA 2017). It is important to select the collector technology best suited to the irradiance and land conditions most suitable for the site. This paper considers only the modelling and validation for concentrating collectors, including collectors utilizing either liquid-HTF or DSG, but non-concentrating collectors for SIPH (e.g., flat plate) can also be modeled by SAM (NREL 2017b). Prior to 2017, older versions of SAM already employed robust models for CSP electricity generation systems. The steam power cycle added complexities to extract results relevant for the case where the solar field is only providing thermal energy, i.e., for SIPH. Also, many aspects of the model, such as the solar field layout and piping design, were not optimal for IPH application due to the coupled nature of the solar field and the power cycle. Hence, two new modules were developed to simplify access to SAM's solar thermal collector/receiver models and to simulate solar thermal systems for IPH. Here, we describe some of the development efforts.

### *2.1 Pre-validation of the liquid-HTF process heat model during model development*

In 2016 before the final 2017 development and validation of the liquid-HTF process heat model, a pre-validation was undertaken of a beta SAM version that sought to test the process heat model using liquid-HTF. This work was conducted to isolate the CSP solar field operation, improve the liquid-HTF process heat model, identify bugs, and enhance the user interface. As part of the pre-validation efforts, operational data was provided by the Swiss Institute for Solar Technology (SPF), which highlighted the operations of a 627-$m^2$ parabolic trough solar field used for a Swiss dairy processing plant (Frank et al. 2014). SPF delivered high-quality operational data and, together with the Bavarian Center for Applied Science (ZAE Bayern), preprocessed and evaluated the operating data; both groups were test users for a beta version of the SAM liquid-HTF model. The Swiss SIPH site is in Saignelégier (northwest of Switzerland), has a 360-kW peak power, and the heat from the solar field is utilized as part of the milk processing. A pressurized water-glycol mixture is used as the HTF, and the required outlet temperature of the solar field is 120°C (Frank et al. 2014). The beta SAM model was used to compare the simulated results of the solar field to one year of operational data from the SIPH site. The SAM weather file for Saignelégier was developed using on-site measured direct normal irradiance (DNI), and ambient temperature.

The beta SAM process heat model already showed good agreement with the operational data from the Saignelégier SIPH site when the solar field was constrained from the power-cycle effects. This was the case especially for the monthly and annual comparison of results for the thermal energy generated. The Saignelégier SIPH site has a designed yearly heat production of 220 MWh. ZAE Bayern utilized beta versions of the SAM liquid-HTF model to validate and compare the modeled thermal output from the solar field to the real yearly experimental thermal yield of 203 MWh. In 2015 NREL provided recommendations for use of the existing CSP Physical Trough model that allowed ZAE Bayern to model the SIPH plant without the specific SAM thermal-application models that are currently available in SAM 2017. Fig. 1 shows the monthly thermal outputs of the simulated SAM Saignelégier solar field compared to the measured or real case. The cumulative yearly thermal energy yield of the solar field simulated through the beta SAM model was 194 MWh, corresponding to an underestimation of only 4.4% compared to the measured thermal output of 203 MWh. On monthly comparisons, the results of the beta version were similarly encouraging, see Fig. 1.

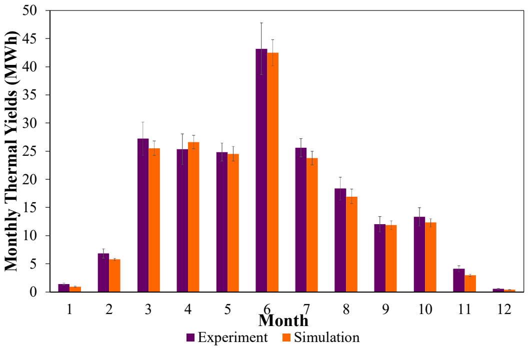

**Fig. 1: Monthly comparison between modeled and real thermal outputs at Saignelégier PT-SIPH by ZAE Bayern (Samoli 2016)**

The simulated results for the annual thermal energy generation between the real and the beta-version simulated Saignelégier case were within 5% of each other, though deviations in daily simulations could be identified compared to the real operational data. Especially for cloudy days, which do not have a large influence on the total monthly thermal energy generation, an underestimation between the simulated and experimental solar thermal energy generated on an hourly basis showed total daily deviations of up to 15% (Samoli 2016).

It is important to note that SAM typically can handle simulations in one-hour time steps, which were identified as too large for SIPH applications. A key issue in the beta SAM liquid-HTF process heat model was the restriction in using large piping diameters and pipe lengths (suited for power generation), which resulted in large thermal masses. Hence, longer heating periods for the solar field and consequently less thermal energy output was delivered from the solar field in the simulated results compared to the operational data. There were significant differences between the simulated and measured inlet and outlet temperatures, as well as for the volume flow in the main circuit of the solar field. Prior research has identified that the thermal masses play an important role for the prediction of the solar thermal energy generation, particularly for SIPH applications (Möllenkamp et al. 2016). As such, with discussions between NREL and SPF/ZAE Bayern, a more flexible field design as well as a higher time-step resolution (e.g., sub-hourly) was implemented in the beta SAM code, and it allowed a better thermal energy yield prediction than previous, SAM liquid-HTF CSP Physical Trough models.

Moreover, during the pre-validation of the beta SAM liquid-HTF model, standard SI units have been widely introduced and the sensible liquid-HTF trough model has been supplemented by a transient energy balance for the headers and runners. Also, in the pre-validation, the default SAM liquid-HTF case used for the beta version was changed and was more representative of an SIPH application (e.g., 5-$MW_{th}$ facility using pressurized water at 150°C), and some bugs have been removed, which make the beta SAM version more suitable for IPH application. For example, an overnight recirculation of hot fluid that occurred during simulations has been amended. An important real-world implication of SIPH solar fields was the alternating row distances between the rows of collectors (as in Saignelégier), which can lead to errors in the simulated shadowing losses when using fixed row distances. These findings have been incorporated and contributed to support the optimization of the SAM liquid-HTF process heat model. More details of ZAE Bayern's optimizing and pre-validation can be found in work by ZAE Bayern and SPF (Samoli 2016).

## *2.2 SAM process heat liquid-HTF and DSG model developments and changes*

NREL engaged with ZAE Bayern in 2016 and 2017 to address questions and issues found in using the older SAM code for SIPH cases. Review of the ZAE report (Beikircher et al. 2016) helped NREL identify several issues that made the new SAM models more amenable to SIPH applications. NREL has worked to address ZAE Bayern's questions and concerns and to provide feedback and support to this experienced SAM user. The engagement with ZAE Bayern helped the NREL CSP team understand design and operational methodologies for SIPH sites. The work at ZAE Bayern has highlighted key issues such as SIPH sites having smaller piping diameters than the original piping library within SAM, and SIPH solar field layouts that differ from large power plant designs. This type of future engagement will be key to continuing to build and code robust SAM modules for SIPH applications. Working with ZAE Bayern/SPF and understanding how process heat modelling could be changed, the latest version of SAM released in 2017 (NREL 2017b) has the CSP process heat models developed for liquid-HTF and DSG systems. Compared to the previous SAM CSP models for power generation, the solar field model has undergone some significant changes to accommodate the nature of SIPH systems. For example, the solar field from the CSP electricity model had a minimum of two subsections with "H" or "I" configurations common for electrical systems (Wagner and Gilman 2011). This "H" solar field layout is shown in Fig. 2 .

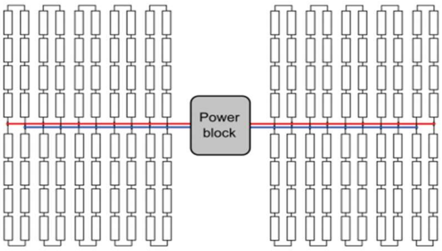

**Fig. 2: Typical "H" power block and solar field layout for CSP solar fields for electricity generation (Wagner and Gilman 2011)**

Since process heat systems can be much smaller and simpler, the solar fields in the liquid-HTF and DSG process heat models have been developed to utilize a single solar field section (effectively half or one section of the solar field in Fig. 2). In addition, the new models for both liquid-HTF and DSG systems allow for smaller pipe diameters. Also, since the heat sink or process heat exchanger between the solar field and the industrial site can be much closer to the solar field than for power generation sites, the fixed cold and hot header lengths of 50 m has been removed (Wagner and Gilman 2011). In addition, piping through the heat sink can be modeled to allow inclusion of additional thermal capacitance, thermal losses, and pressure drop across the solar-to-process heat exchanger. The DSG model has been developed to allow for modelling either a DSG PT or DSG LF system with a water/steam mixture, where the user can change the optical characteristics of the field. Both process heat models include a simple LCOH calculation and can include financial parameters such as the cost of debt.

## 3. SAM Model Validations

### *3.1. Liquid-HTF parabolic trough validation and results*

For the final validation of the new liquid-HTF model, having finished the development and optimization, a detailed simulation of an existing parabolic trough solar field was undertaken. This site in Nevada, USA, uses pressurized water in the solar field, and the solar field has a thermal power of 17-MW$_{th}$ (DiMarzio et al. 2015). The parabolic trough solar field was built to provide heat input for a hybrid process, and as such, it was considered a suitable SIPH application. Site operators supplied detailed operational data of the solar field.

The actual solar thermal energy output from the solar field was compared to the SAM simulations (which utilized the final SIPH-model) of the thermal yield generated. The operational data provided included site conditions such as DNI, wind speed, solar field thermal output, and ambient temperature for 58-days of continuous operation between March and April 2015. The validation used 58 days because this was the span of operational data provided, and it was long enough to understand the liquid-HTF model behavior in a variety of DNI conditions. To create the simulation model of the SIPH site, a site-specific weather file was developed, which included the site conditions for the approximate two-month period, and a Typical Meteorological Year (TMY) file was used for the remainder of the year to allow for an annual simulation. While an annual simulation was performed, the modelled simulation of the thermal energy yield was compared to the measured, real solar field thermal output for only the 58 days. This allowed a direct comparison between the simulated and the real thermal outputs and solar field behaviors.

Over the 58-day period, the measured solar field thermal output was recorded to be 4,832 MWh. The SAM model predicted energy output whenever adequate sunlight existed, as well as the cumulative generation that only includes time periods when the actual power plant was operating. Cumulative generation when the plant was operating was calculated by post-processing the SAM data to only sum energy values when the plant had a power output greater than 0 MW$_{th}$. In the former case, SAM overestimates generation by 1.8%, and in the latter case, SAM underestimates by 1.3%. It is not clear why the plant was idle during certain periods of acceptable sunlight, but the behavior highlights that SAM may need to provide additional user-defined constraints on plant operation. Fig. 3 shows three days of normalized operations data from the SIPH site compared to the simulation.

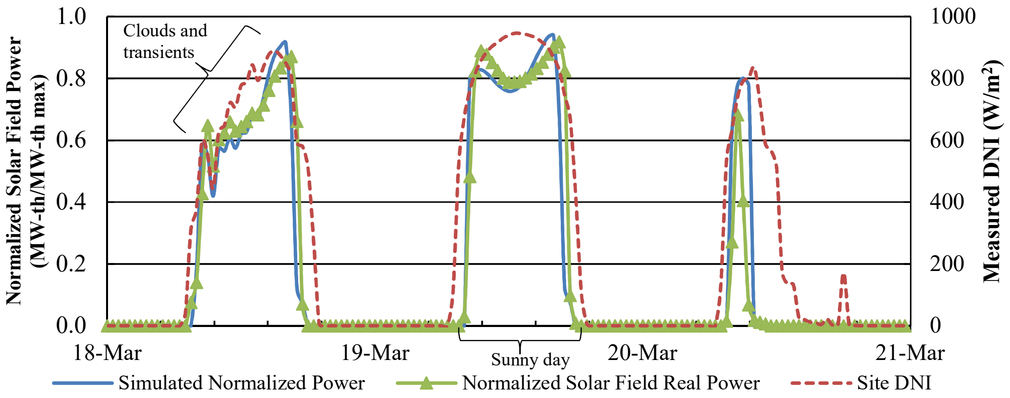

**Fig. 3: Comparison of modelled normalized solar field output vs. the normalized solar field actual output for three days**

The measured site DNI can also be seen (red dashes); for example, March 19, 2015 was a sunny day, after what was likely a cloudy day on March 18. As can be seen on March 18, the clouds and transients (e.g., the spikes in DNI) led to transient thermal output from both the simulated (green line) and actual operations (blue line). The modelled simulations using the final liquid-HTF model for that day are very similar to the actual site operations. As seen in Fig. 3, on March 20 the SIPH site suddenly stops operations near midday for an unknown reason. The simulated thermal output would normally follow the DNI shape more closely and calculate more thermal energy than the actual site produced on this date. In Fig. 3, an external constraint is applied to the simulation to limit production only to times when the actual plant is operating. Although appropriate for a validation study, such constraints need to be based on plant operation knowledge for a predictive simulation.

### 3.2. DSG linear-focus collector model validation and results

It has been possible to gain access to operational data for a DSG LF field in Calasparra, Spain. Through collaboration with Tubosol, the plant operators of the 30-$MW_e$ Tubosol Puerto Errado 2 (Tubosol PE2) electricity generation plant, NREL has received and processed operational data for the entire 150-$MW_{th}$ solar field (Novatec Solar 2011) for the month of June 2015. It was determined that the DSG process heat model (which does not include recirculation, but only once-through mode (OTM)), could be used to simulate the Tubosol PE2 solar field. This assumption seemed appropriate because there is no water/steam recirculation in the Tubosol PE2 solar field itself; also, the solar field can be considered to operate as if it were an OTM field, with the steam separation from the water/steam mix occurring after the solar field at the steam drum. The current DSG model would be unsuitable to simulate recirculating DSG fields.

These operational data allow for in-depth observation of the behavior of the solar field, both in normal and transient conditions. The data for the solar field (made up of 28 rows in total) are split into two equal segments (Tubosol PE2.1 and Tubosol PE2.2), where each segment is approximately 75-$MW_{th}$ with 14 collector rows. The reason for the solar field segments is to allow in winter to direct steam from both solar fields to one 15-$MW_e$ turbine. This arrangement ensures maximum electricity generation, rather than generating electricity from both 15-$MW_e$ turbines at part load due to a lack of solar radiation. Each independent solar field segment has the following specification seen in Tab. 1 (Novatec Solar 2011). The data in Tab. 1 has been used for the SAM DSG model validation. It was decided since each segment can be operated independently, that the validation would be done only on one solar field segment. A weather file that uses site data, e.g., the DNI and ambient temperature, has also been created for the validation; again, a TMY file was used for the rest of the year.

**Tab. 1: Data used for the SAM DSG validation of the Tubosol PE2 solar field segment**

| Parameter | Value | Unit |
|---|---|---|
| Product name | Nova-1 | NA |
| Number of rows in solar field | 14 | NA |
| Solar field length | 940 | m |
| Aperture area | 151,000 | $m^2$ |
| Operating temperature | 270 | °C |
| Operating pressure | 55 | bar |
| Peak thermal output | 75 | $MW_{th}$ |

The validation of the DSG process heat model has been done by comparing the predicted thermal energy by the SAM model with the plant data from the Tubosol PE2 segment, although an estimate of the solar thermal power has been made. It is important to note that since Tubosol PE2 has been designed for electricity generation (i.e., 30-$MW_e$), it was not possible to directly measure the solar thermal power output from the solar field, as the exit of the solar field is a two-phase fluid of steam and water. Unlike the validation of the SAM liquid-HTF process heat model, where the solar field thermal output was directly measured and compared to the SAM simulated solar field thermal output, this was not possible for the DSG validation. While SAM can undertake simulations sub-hourly, the minimum time step for the SAM DSG validation is 10 minutes. Therefore, the sub-minute data from the Tubosol PE2 solar field segment has been averaged to make 10-min time-step intervals, e.g., for the weather file for Calasparra and the estimation of the solar field power output.

Each solar field segment has measurements for pressure, temperature, and mass flow rate of the combined water/steam fluid. Thus, the enthalpy and the steam quality are unknown at each measured interval at the exit of the solar field segment. Hence, to calculate the solar field thermal output power at each 10-min time step, the steam quality is estimated in two ways (identified as Case 1 and Case 2).

Case 1—where there was a constant steam quality of 0.7485 (i.e., approximately 75% steam in the steam drum). This was determined from the design conditions obtained from the balance of plant process diagram (Novatec Biosol 2011) and thus was used to calculate the enthalpy at each 10-min step.

Case 2—where variable steam quality is estimated from the steam-drum level given in the operations data, then averaged over every 10-min time step. The steam-drum level, as confirmed with Tubosol PE2, is a measure of the steam and water mix in the steam drum, where the steam drum separates the remaining water in the fluid from the steam produced by the solar field. Using the steam-drum level is an estimate of the steam quality produced by the solar field. The calculated enthalpy is multiplied by the mass flow rate to obtain an approximate value of thermal power delivered by the solar field. This estimated thermal power is then compared with the one predicted by the SAM simulation.

However, there are differences between the way the SAM DSG model predicts the solar field operation and the way the actual Tubosol PE2 solar field operates. Therefore, to make a better (and more realistic) comparison, there are a couple of constraints added for Case 2.

Constraint 1: The solar field has hot fluid in the field during the night periods (as well as the day), and the thermal energy can theoretically be calculated during this time. However, as no thermal power from the field is delivered during the night to generate steam, the solar field thermal power output from 9 pm to 6 am is ignored.

Constraint 2: When SAM thermal output is predicted, but the plant itself is for some reason not producing solar thermal power to generate steam for the turbine, this is excluded from the SAM output in a post-processing step.

Fig. 4 shows a plot of such a situation, where the thermal power predicted by the SAM model is shown against the real estimated solar field thermal power output. It can be seen the estimated solar field thermal output was barely present during the day (e.g., the green line), even though there was sufficient DNI for SAM to predict some thermal power generation. The thin blue line represents the SAM simulated power. As seen in Fig. 4, due to the DNI variations (e.g., perhaps due to several clouds that day), the model responded to the spikes in DNI with a considerable power production, whereas the estimated actual output was nearly zero through the day. Hence, the simulated thermal power for days like this was ignored in post-processing, as specific operational decisions such as this made at the site are not accounted for in the DSG model.

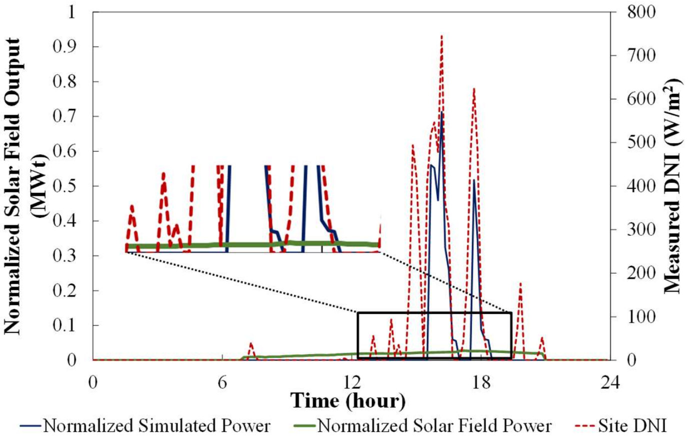

**Fig. 4: Comparison of the simulated solar field power output and the estimated actual solar field power output on a day with transients, and showing the need for a constraint to exclude the SAM output when the estimated actual output was minimal**

Tab. 2 shows the comparison between thermal energy generation predicted by the SAM DSG model and the calculated estimation using actual field data (for the constant and variable steam quality cases) for June 2015.

**Tab. 2: Comparison of the thermal energy generated (MWh) between the actual estimated solar field and the simulated solar field, for the cases of constant and variable steam quality (Case 1 and Case 2, respectively)**

| Case | Condition | Real estimated thermal energy of solar field (MWh) | SAM thermal energy of solar field (MWh) | Difference in thermal energy (MWh) | Difference (%) |
|---|---|---|---|---|---|
| Case 1 | Constant steam quality at design conditions | 141,105 | 126,534 | 14,571 | -10.32 |
| Case 2 | 2.1: Estimated variable steam quality | 130,864 | 126,534 | 4,330 | -3.3 |
| | 2:2: Estimated variable steam quality with constraints | 127,082 | 126,128 | 954 | -0.75 |

As can be seen in Tab. 2, with constant steam quality (Case 1), the actual estimated thermal energy generated for June 2015, was approximately 141.1 GWh, compared to approximately 126.5 GWh from the SAM simulated solar field. In other words, the SAM thermal output was 10.32% less than the real estimated value. Case 1 (i.e., constant steam quality from the solar field) can be considered unrealistic, as there will be a varying steam quality produced by the actual Tubosol PE2 solar field segment. Discussions with the operators at Tubosol PE2 have confirmed that the steam quality can vary from 70% to 80% depending on the DNI conditions. As seen in Case 2 from Tab. 2, when variable steam quality is calculated for the Tubosol PE2 solar field segment, the estimated solar thermal energy generated in June 2015 from the field segment was 130.8 GWh, compared to the simulated output of 126.5 GWh. This is Case 2.1, without further constraints as mentioned being applied. As can be seen, the difference in the energy generated between the simulated solar field and the estimated actual is approximately -3.3%. When the constraints are added, the difference between the actual estimated thermal energy generated and the SAM output drops to 0.75%.

Fig. 5 and Fig. 6 shows the excellent comparison between the normalized simulation (blue) and the normalized estimated actual thermal power output for Case 2. Fig. 5 shows a day that had significant DNI variations (i.e., many clouds throughout the day); Fig. 6 shows a single transient in an otherwise very sunny day.

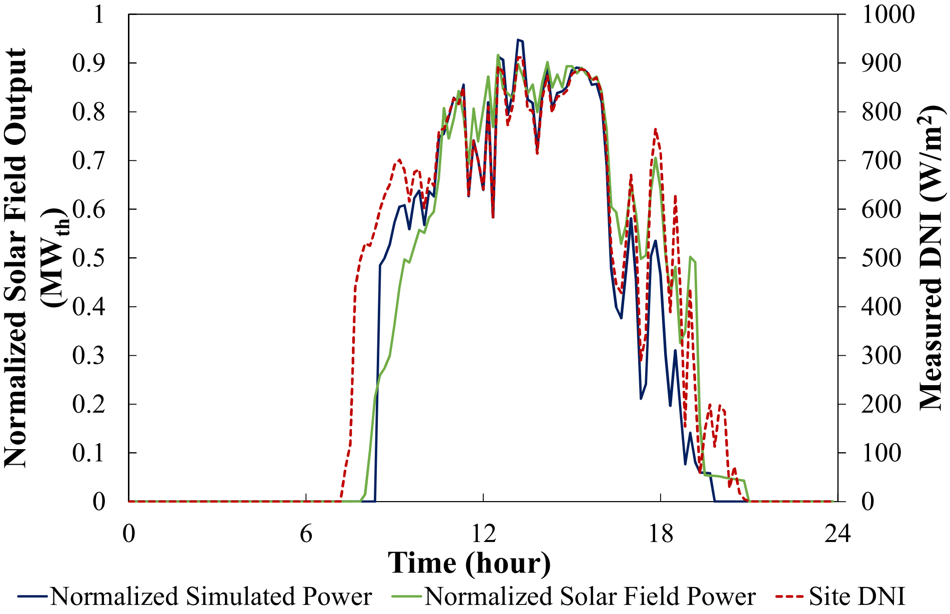

**Fig. 5: Comparison of normalized simulated solar field power output and normalized actual estimated output on a day with significant DNI variations**

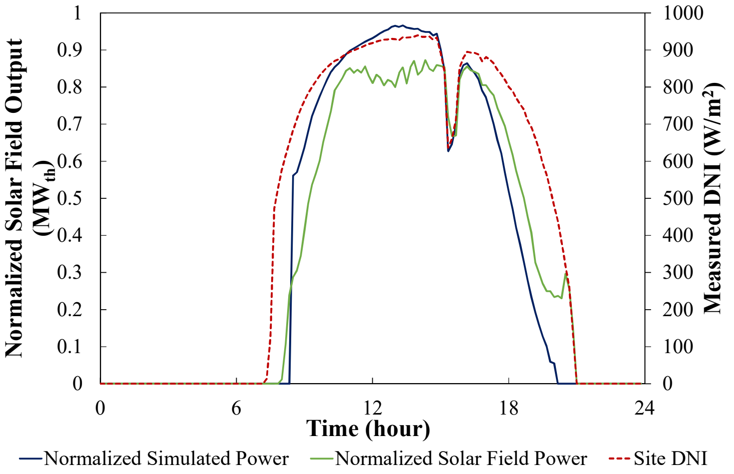

**Fig. 6: Comparison of normalized simulated solar field power output and normalized estimated output with one DNI transient**

As seen in Fig. 5 and Fig. 6, the simulated power output from the solar field tracks the DNI variations well throughout the day, although the simulated power output, in general, is smoother than the actual estimated solar field output. It is worth noting that near the start of the day, the simulated power compared to the real estimated power is generally slightly overestimating the power output, whereas the reverse is true in the evening. In Fig. 5 and Fig. 6, the simulated power is underestimated relative to the actual estimated amount in the evening. The -3.3% difference between the simulated DSG and the actual estimated energy output for the time period gives confidence that the DSG model is successfully modelling the conditions in the solar field and handling the energy flows. This shows that once the modeled solar field for DSG (at least in this DSG LF case) can be separated from the power generation aspect, the solar field can be well modelled.

## 4. Utilization of the SAM Liquid-HTF Process Heat Model

The use of both the liquid-HTF and DSG process heat models for potential actual commercial applications would have been ideal. But, it has only been possible to do an initial energy simulation and analysis with the liquid-HTF model. The DSG process heat model could be utilized in future analysis.

The concept of using SIPH for heat addition and integration into breweries is gaining strength, especially in Europe and South Africa, where several studies and operating demonstration SIPH plants for breweries exist (German Solar Association 2017; Mauthner et al. 2014). Either through concentrating or non-concentrating SIPH technologies, breweries that are located in regions having sufficient DNI for solar heat integration could significantly decrease the energy consumed from burning hydrocarbons (Lauterbach et al. 2009; Mauthner et al. 2014).

The newly developed SAM liquid-HTF process heat model has been used for an initial analysis of a brewery in California that is considering implementing a parabolic trough solar field to decrease natural gas usage. An important and potentially valuable financial incentive that currently exists in California is the maximum of up to $800,000 that a project can receive based on being able to show a metered decrease in natural gas due to the addition of a new solar thermal field (California Public Utilities Commission [CPUC] 2017).

The key parameters of the brewery's potential solar field include a design point yield of 1 $MW_{th}$ and the use of unpressurized water as the HTF. The weather file for the site has been created using the National Solar Radiation Data Base, and the brewery site has a daily average DNI of greater than 6.5 $kWh/m^2/day$ (NREL 2017a). The process heat thermal load requirement from the brewery has been highlighted as being approximately constant at 0.3 $MW_{th}$, 24 hours a day, 365 days a year. The Heat2Hydro solar field and system design also includes a mixed single-tank water storage unit of 50,000 gallons. The storage is expected to be charged fully and maintain an exit temperature to the brewery heat exchanger of 85°C. It is worth noting that SAM version 2017.9.5 has no storage built in. The potential new storage solution for the brewery cannot be directly modelled with the SAM 2017.9.5 version of the process heat model.

The SAM simulation file for the case has been created to model the annual heat input from the solar field to a brewery process heat exchanger. The parameters for the brewery's load (i.e., delivered thermal power to the heat exchanger) have been simulated using collector information provided by Heat2Hydro and Rackam Technologies. At present, since the publicly available SAM 2017.9.5 process heat module is without storage, the initial brewery case has been created whereby all the solar field output in excess of the process load can be absorbed by an ideal storage system. This is a reasonable assumption considering the large storage volume (50,000 gallons) for the Heat2Hydro storage that is charged with the excess thermal energy from the solar field. But this assumption will need to be tested in the future—particularly, how much of the excess energy from the solar field can be absorbed by the single mixed tank.

## 5. Conclusions

In on-going efforts to improve SAM, the models and use cases for SIPH will continue to be developed. Working with solar developers (e.g., SkyFuel), the SIPH process model developments, particularly for the liquid-HTF model, are likely to include thermal storage and dispatch strategies. With further investigation of the sizing of typical deployed SIPH systems, the default solar field size may be changed, e.g., to 1-$MW_{th}$ for liquid-HTF SIPH fields. The DSG process heat model improvements include developing a recirculation mode to send the remaining water exiting the solar field back to the solar field for further evaporation. This would then allow SAM to better model actual DSG systems, as few DSG systems have been developed as OTM (Feldhoff 2012). Future use of the DSG model could provide a better understanding of the thermal yield generation and steam production for solar EOR.

The highlighted brewery initial case will be important to continue to develop into a case study, to develop both the energy yields and costs of the potential solution, and the financial models to understand economic viability e.g., the net present value (NPV) and the payback period. This will develop the understanding of SIPH applications in California, where the incentive scheme currently in place (e.g., for $800,000 granted to projects that can show a metered decrease in natural gas due to a solar thermal field). As of October 4, 2017, the legislative bill (Bill AB-797 Chapter 473) supporting the CPUC incentive scheme has been extended for two years (California Legislative Information 2017). Further investigation is needed of the financial implications of the extension of Bill AB-797 Chapter 473, particularly on potential projects in California.

The NREL SAM process heat models could help to show thermal energy generation and economic value for known and future applications of SIPH. As global use for SIPH applications continue, modelling tools such as SAM and Greenius can certainly provide an independent method to gauge the potential energy yield at the site. It is possible that the newly developed SAM process heat models could help some users looking to apply for the recently released U.S. Department of Energy (DOE) solar desalination Funding Opportunity Announcement (DOE 2017). The use of the process heat models could help prospects and awardees, better understand thermal energy yield generations and the potential LCOH of CSP process heat solutions, which could then provide heat for desalination activities.

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