HIGH-TEMPERATURE SOLAR ORGANIC RANKINE CYCLE – ANNUAL SIMULATION OF VARIOUS SYSTEM DESIGNS

Björn Hunstock[1]*, Sabine Strauch[2], Wilhelm Althaus, Björn Bülten, Johannes Grob, Ralf Paucker

Fraunhofer UMSICHT
Department Energy Systems Engineering
46047 Oberhausen, Germany
[1]bjoern.hunstock@umsicht.fraunhofer.de
[2]sabine.strauch@umsicht.fraunhofer.de

* Corresponding Author

ABSTRACT

This paper deals with the simulation of high-temperature solar organic Rankine cycles. In contrast to previous simulations the diurnal variations and the effect of charging and discharging the thermal energy storage are taken into account. Furthermore, the presented simulations cover one full year. The simulations use discrete time steps with a constant operation over a period of one hour. Considering a full year, 8 760 connected simulations have been carried out to describe the full and part load operation of one plant. Annual simulations allow a detailed evaluation of a solar organic Rankine cycle. The work describes the effect of varying solar field area and thermal energy storage capacity with different design points. High values of irradiance result in small solar fields. These fields often cannot provide enough thermal energy to produce the nominal electrical power at time steps with low irradiance. Design points using a low value for irradiance allow full load operations during the winter season. On the other hand, they generate a large percentage of waste heat during summer, which cannot be used due to limited storage and power capacity. The presented annual simulations show that different design points for a solar organic Rankine cycle cause various results for the plant performance over a full year. A design point in December leads to a large solar field and a thermal energy storage with a high capacity. The annual simulations show the continuous operation over a full year and are used to evaluate the plant designs.

1. INTRODUCTION

A comprehensive use of solar energy for power production is one approach for global sustainable electricity generation. Many rural areas with high potential of solar radiation (e. g. Northern Africa) are still supplied with power from stand-alone diesel generators (Szabó *et al.*, 2011). Hence, small decentralized power plants using renewable energies can reduce the consumption of fossil fuels in such areas. Concentrated solar power (CSP) is a promising technology to generate power in areas with high direct solar radiation that is non-scattered radiation. Small CSP plants are able to replace or support existing diesel generators.

The organic Rankine cycle (ORC) efficiently converts heat into power and can be used as a decentralized power plant. High-temperature ORC (evaporation temperatures of more than 200 °C) utilizing solar thermal power suits to be combined with the state-of-the-art mid- or high-temperature parabolic trough collectors. These solar driven ORC is called solar organic Rankine cycle (SORC) Providing high evaporation temperatures, parabolic trough collectors enable ORC to operate at high

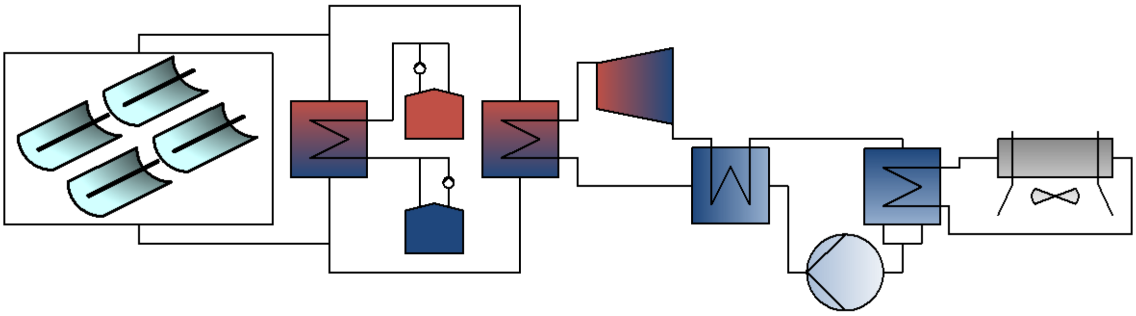

Figure 1: Scheme of a SORC plant

cycle efficiencies. Furthermore, an additional thermal energy storage (TES) increases the full load hours of the power plant. In consequence a SORC can theoretically cover a continuous load if a well-sized TES is integrated and the solar field is sufficiently large. Figure 1 shows the scheme of a SORC plant. The plant consists of two different cycles. The first one is the solar field which converts solar irradiation into thermal energy. The second one utilizes this thermal energy to generate electricity. The first cycle includes the TES which consists of two tanks (one hot and one cold tank). The indirect storage system is charged and discharged by a heat exchanger. During times with sufficient irradiance the solar field charges the TES and at the same time supplies the ORC with thermal energy. At night the stored thermal energy is used to evaporate the ORC working fluid.

Only a few high-temperature SORC plants have been built yet. Most of these SORC originate from research projects. Stine and Geyer (2001) mentioned three different SORC plants with the electrical power of 19 kW, 37 kW and 150 kW which were used to supply the pumps for wells. In 2006 a SORC with an electrical gross power of 1.35 MW started operation at Arizona Public Service in the USA (Sinai and Fisher, 2007; Canada *et al.*, 2004). A thermocline storage was planned for a future expansion of this SORC to store the thermal energy for a full load operation of six hours. Orosz *et al.* (2010a) developed a small scaled SORC with 1 kW_{el} for decentralized power generation tested in Lesotho, Africa. Kane (2003) presented operation data of a 15 kW_{el} ORC connected to linear Fresnel collectors, whereas Moustafa *et al.* (1984) showed a SORC plant that uses parabolic dishes to produce thermal energy for a 100 kW_{el} ORC.

The academic research focuses on the simulation of SORC. For different applications the cycle has been simulated and optimized to achieve a high cycle efficiency. Delgado-Torres and García-Rodríguez (2007a) and (2007b) simulated different SORC and compared different ORC working fluids. The simulations used a constant direct normal irradiance (DNI). The steady-state simulations did not consider a TES and determined the collector area taking into account different condensation temperatures for recuperative and non-recuperative ORC. Several other works dealt with the simulation of SORC systems, for example Bruno *et al.* (2008), Nafey and Sharaf (2010), Orosz *et al.* (2010b) and Quoilin (2011). A thermal energy storage is considered by Price and Hassani (2002), McMahan (2006), He *et al.* (2012) and Al-Sulaiman *et al.* (2011), but the operation for different values of irradiance was not included. Orosz *et al.* (2010b) developed a design tool for small scaled SORC on the basis of the plant design described in Orosz *et al.* (2010a). The continuing impact of the hourly varying direct irradiance during a full year on a SORC has not been focused by research yet.

Hence, this paper deals with the annual simulation of SORC plants considering the charge and discharge of an integrated TES. Different SORC configurations are analyzed. Plant parameters are varied to show the effects in operation. Technical or economic interests are not taken into account. An ORC power capacity of 500 kW_{el} serves as an example for decentralized power supply applications. SORC of this plant size are considered to be technically mature and available (Dürr Cyplan, 2015).

First of all, it is shown how the design of a SORC can differ depending on varying values of DNI. For different solar field sizes and TES capacities the daily variation of produced energy is computed to preselect design points. The parameters are varied to show the influence on the annual solar capacity factor. Considering these results annual simulations with hourly time steps for three different designs are carried out and main results of the annual simulations are analyzed.

2. EVALUATING DESIGN POINTS FOR SORC PLANTS

2.1 Basics for simulations

The simulation of the SORC including solar field, TES and power block are carried out with the commercial software THERMOFLEX. The program allows modeling several thermal systems, e. g. steam power plants, gas turbines etc. Thermodynamic properties for various fluids are included in the model. Therefore different working fluids for an ORC can be taken into account. The software allows predicting the part load behavior of an energy system with an off-design simulation mode.

At first, a design is specified and simulated. The chosen design is used to simulate the off-design behavior, for example the part load operation caused by low irradiance. Discrete time steps are used to calculate time dependent results. Each time step represents one hour. A higher time step resolution would increase the duration of calculation. The direct normal irradiance as input parameter does not cause fast load changes. Only for sunrise and sunset a higher time step resolution would increase the precision. Therefore, one steady state simulation runs for each hour of the day. The state of charge (SOC) of the TES depends on the previous SOC and on the actual charging or discharging rate. Therefore, the SOC of the TES at the end of a time step is used as input value for the following time step. Heat capacity of plant material and flow simulation are not taken into account.

To simplify, the ambient temperature for every simulation is fixed at 15 °C. This satisfies the requirements of the approach chosen in this paper, which does not consider exact efficiency losses caused by high ambient temperatures. For an economic analyze it must be kept in mind.

The size of a solar field is often specified as dimensionless factor, the solar multiple. According to the definition in Montes *et al.* (2009) the solar multiple SM equals the ratio between the thermal power of solar field at design point and the thermal power required for full load operation of the power block.

$$SM = \frac{\dot{Q}_{\text{th, SF}}}{\dot{Q}_{\text{th, ORC}}} \tag{1}$$

According to this approach for this ORC application the SM is calculated by dividing the thermal power required for full load operation of the ORC $\dot{Q}_{\text{th, ORC}}$ by the thermal power of the solar field $\dot{Q}_{\text{th, SF}}$ (compare Equation (1)). Following this definition, a solar field with a solar multiple $SM = 2$ causes a collector area twice as much as a solar field with $SM = 1$. The solar multiple mainly depends on the used irradiance and the power capacity of the power block.

A calculation shows the impact of the amount of DNI on the required solar field area. For this calculation all losses are assumed to be negligible during energy conversion to prove the direct interrelationship between solar field area and direct normal irradiance. Table 1 demonstrates the dependency of the solar field area and the normal component of the beam irradiance. Equation (2) outlines this correlation.

$$\dot{Q}_{\text{th, SF}} = \eta_{SF} \cdot G_{bn} \cdot A_{ap} \tag{2}$$

The thermal power of the solar field is calculated by multiplying the solar field efficiency η_{SF}, the

Table 1: Required solar field area to produce 2 MW_{th} for different values of irradiation

DNI	Solar field area
400 W/m²	5 000 m²
600 W/m²	3 333 m²
800 W/m²	2 500 m²

collected direct normal irradiance G_{bn}, and the aperture area of the solar field A_{ap}. Hence, assuming a high irradiance, e. g. in the summer season, the calculation results in a small solar field. A solar field at that size might not be able to provide sufficient thermal energy to operate the ORC during winter times. In Table 1 each solar field area delivers a thermal power of 2 MW. Assuming that an ORC requires the same thermal power, each solar field would have a SM of 1, although the area differs.
The annual performance of a CSP plant can be described with the annual solar capacity factor CF_{sol}. Equation (3) shows this ratio between the electrical energy yield and the product of the DNI on aperture and the aperture collector area.

$$CF_{sol} = \frac{\sum_{i=1}^{8\,760} P_i \cdot \Delta t_i}{\sum_{i=1}^{8\,760} G_{bn,i} \cdot A_{ap} \cdot \Delta t_i} \quad (3)$$

2.2 SORC without a TES

To show the influence on the plant design and operation three different dates of the year are used to design a SORC with the same process parameters.

The site location is assumed to be at a longitude of 30° north of the equator. Table 2 summarizes the main design parameters of the SORC. The design points are on March 21th (spring equinox) as well as June 21st and December 21st (summer and winter solstice). The irradiance on the spring and autumn equinox is identical, therefore only March 21st is taken into account. For every design point a solar time of 12:00 o'clock is assumed to estimate the irradiance.

The ORC uses toluene as working fluid and an internal heat exchanger to recuperate the thermal energy of the superheated steam after expansion. Previous research studies favored toluene as working fluid, which allows a high cycle efficiency compared to other fluids (Delgado-Torres and

Table 2: Relevant simulation parameters for comparison of different design points without a TES

	March 21st	**June 21st**	**December 21st**	
Site				
Longitude	30			° north
Solar time (decimal)	12.00			h
Direct normal irradiance on aperture area	719.1	869.8	429.2	W/m²
Day of the year	80	172	355	-
ORC				
ORC Gross power	500			kW_{el}
Working fluid	Toluene (C7H8)			-
Evaporation pressure	25.00			bar
Condensing pressure	0.14			bar
ORC gross efficiency	24			%
Solar field				
Heat transfer fluid	Therminol 66			-
Aperture area	4 624	3 542	9 756	m²
Solar multiple	1			-
Thermal power	2 039			kW
Outlet temperature	320			°C
Inlet temperature	250			°C
Solar field efficiency	61.3	66.2	48.7	%

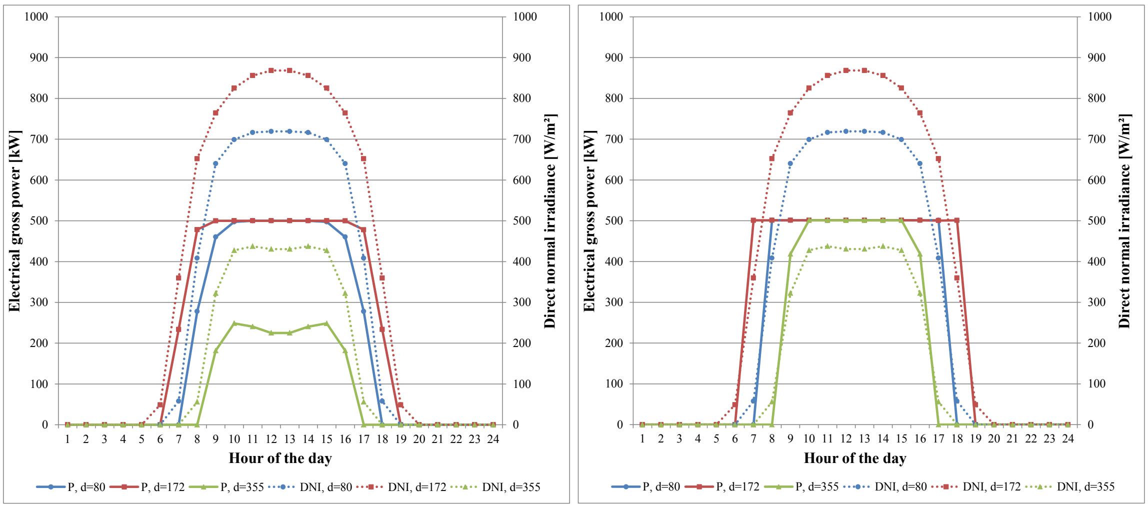

Figure 2: Electrical gross power of the SORC for the design point March 21st (left) and December 21st (right)

García-Rodríguez, 2007a). The inlet pressure of the turbine is 25 bar at about 280 °C. This prevents thermal decomposition that may occur above 300 °C. The condensing pressure of the cycle is 0.14 bar at about 53 °C. For the design point a turbine isentropic efficiency of 75 % is used and a feed pump isentropic efficiency of 75 %. With a gross power of 500 kW_{el} the ORC achieves a gross efficiency of 24 %.

Each design uses a solar field with $SM = 1$. Due to the different direct normal irradiance, the required area of the solar field varies. The used heat transfer fluid is Therminol 66 and the thermal power of each configuration is about 2 039 kW. A TES is not considered in the first run, but will be added in following simulations. The solar field efficiency depends among other parameters on the ambient temperature and solar irradiance, which is the reason for varying efficiencies presented in Table 2.
Hourly off-design simulations are carried out for each design on all design dates. The irradiance for one time step is constant. The value is determined at the middle of one hour. This means, that for the twelvth hour of a day (11:00 to 12:00) the solar time 11:30 is used to estimate the irradiance for the entire time step.

Figure 2 shows the results of the off-design simulations using March 21st ($d = 80$) and December 21st ($d = 355$) as design points (right chart). On the left ordinate the electrical gross power of the SORC in kW is plotted, while the right ordinate gives the DNI on the aperture area in W/m². The March design allows six hours of full load operation on the design day and eight hours on June 21st ($d = 172$). The higher irradiance in June and the long sunshine duration allow two more hours with full load operation for the ORC. In contrast, the available solar fiel area does not allow a full load operation on December 21st. In this case, a solar field of a larger area with $SM > 1$ is necessary to satisfy the required thermal power of a 500 kW_{el} ORC. As shown in Table 2 the solar field size nearly doubles, but it allows full load operation with a low irradiance at the design point in December. On the other side, this large solar field causes a great amount of excess thermal energy in March and June. This waste heat can only utilized when using a TES.

Chosing the optimal design point for the SORC is essential to satisfy a local power demand. Increasing the solar field size causes more full load hours during sunshine duration especially in times of low DNI. A TES or an auxiliary boiler allow operation after sunset. In conclusion, a TES is considerd in the following simulations.

2.3 SORC with a TES

For these simulations the design point is March 21st. A TES of 17.7 MWh capacity is included to enable a 500 kW_{el} ORC for six hours of full load operation. The solar multiple takes the values 1, 2 and 4 to size the solar field. The off-design simulations are carried out for March 21st, June 21st and December 21st. Each of these days is analyzed on the SOC and electrical power. The SOC of the TES at the end of the last time step is equal to the SOC at the beginning of the first time step. This condition ensures realistic behavior of the plant for sequent days with nearly the same irradiance profile.

Figure 3 shows the trend for three different days for a SORC plant with a solar multiple of 1 and 2. The system design with $SM = 1$ leads to a small solar field and, therefore, not sufficient thermal energy is supplied to the storage on December 21st and March 21st. On June 21st there are higher irradiance and more sunshine hours available to increase the SOC. The peak of the storage level is at the 17th hour with a value of approximately 30 %. A solar field with $SM = 1$ does not allow charging the TES. The solar field is too small to use a TES appropriately. A solar field twice as big ($SM = 2$) enables a more effective use of the TES in March and June, and it allows full load operation in December. The TES is charged between morning and afternoon while the ORC is supplied directly. When the irradiance decreases, the TES is discharged and the ORC operates nearly at 90 % load. The reason for this is the lower temperature of the heat transfer fluid after discharging due to the temperature difference at the pinch point. The TES is integrated as an indirect system and uses a heat exchanger to store the thermal power of the solar field. In storage mode the heat exchanger reduces the temperature twice for the reason of charging and discharging. The bigger solar field allows a full load operation during sunshine in December, whereas operation during that time is not possible at $SM = 1$.

In Figure 4 the performance of two storage capacities, namely six and twelve hours, are compared with each other. The design point is March 21st and the SM is 4. The off-design simulations are carried out for the same days as in Figure 2 and under the same cycle conditions for each day. Compared to the results of the simulations for $SM = 2$ the full load operation on December 21st is increased by using a large solar field. This even allows operation of 90 % load in the evening.

In March and June the TES is already fully charged in the morning, but at the beginning of the day the storage is totally discharged. This shows that the storage capacity is too small for 24 hours of operation and an increased solar field does not result in more full load hours. The TES with a capacity of 12 hours in chart of Figure 4 allows this operation in March and June. The solar field size does not

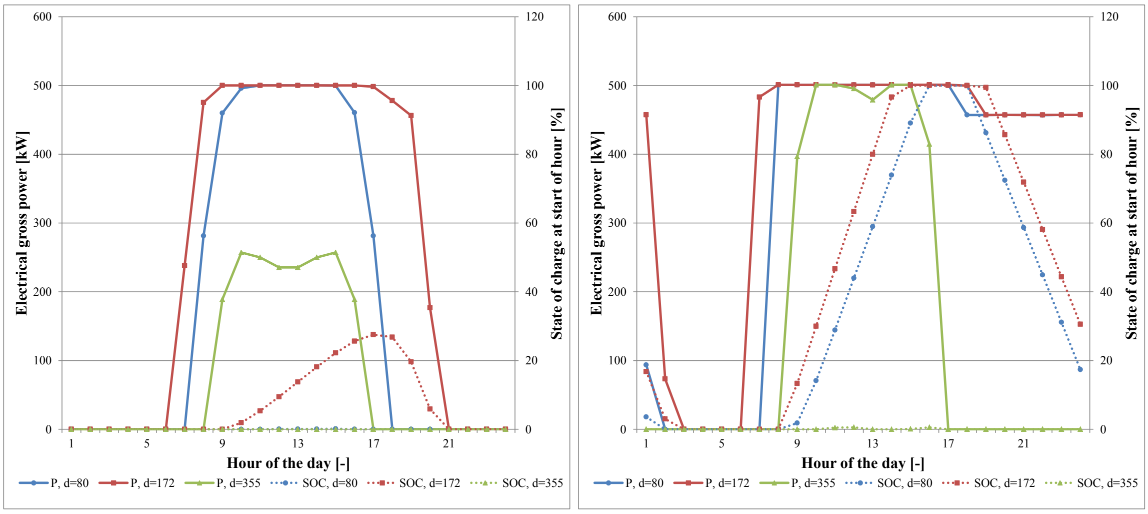

Figure 3: Electrical gross power (left ordinate) and state of charge at start of hour (right ordinate) for off-design simulations with $SM = 1$ (left chart) and $SM = 2$ (right chart).

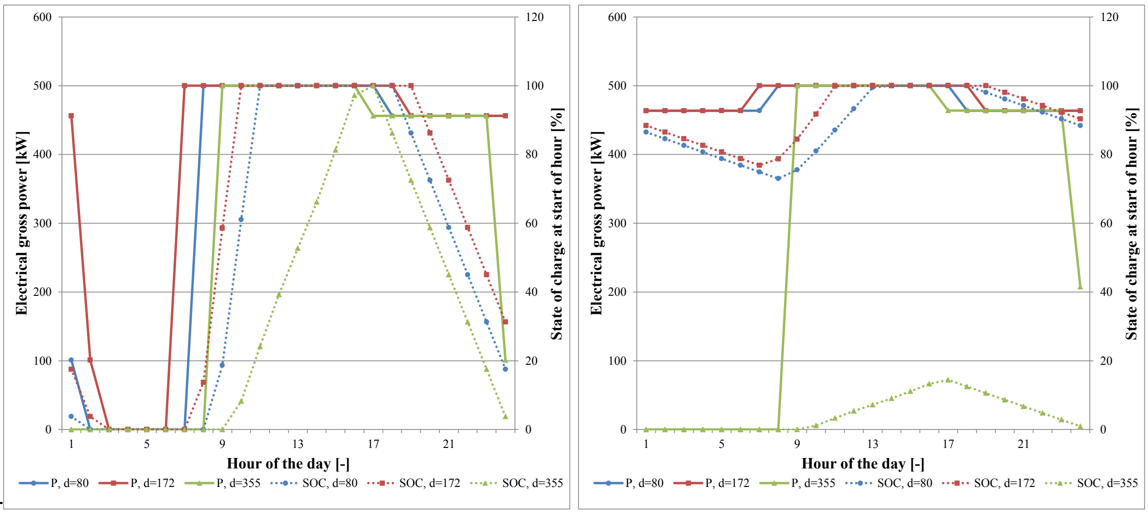

Figure 4: Electrical gross power (left ordinate) and state of charge at start of hour (right ordinate) for off-design simulations with a storage capacity of 6 hours (left chart) and 12 hours (right chart).

change and the excessive thermal energy is stored in the TES. On December 21st the collected thermal energy does not suffice to operate the ORC from the beginning of the day. For this amount of irradiance the solar field is too small and the storage cannot be charged sufficiently. At the charge peak only 15 % of the capacity is used. On March 21st and June 21st the TES is not discharged totally. The minimum SOC reaches only 72 % (March 21st) and 75 % (June 21st). Hence, in these cases the designed storage is oversized and does not suit the solar field size. Furthermore, this design does not suffice for continuous operation on December 21st.

The previous simulations made it possible to evaluate different designs on independent days. However, these daily simulations are not suitable to predict the real behavior of a SORC on successional days, but they are essential to specify characteristic design points. This approach is beneficial regarding aspects of time required for computing and simulating. The preselection using the characteristic design points helps to avoid surplus annual simulations.

Hence, annual simulations for three different design points are carried out in a case study to evaluate the annual performance of a SORC plant.

3. CASE STUDY – ANNUAL SIMULATION OF A SORC

Considering the results of the simulations prior to this, three different annual simulations are carried out. Case 1 refers to the 21st of March (80th day of the year), case 2 to June 21st (172nd day of the year) and case 3 to December 21st (355th day of the year). As in the previous simulations, the ORC has an electrical nominal gross power of 500 kW. The TES is sized with a capacity of 12 full load hours for the ORC and the solar field has a *SM* of 4. The DNI at 12:00 o' clock solar time is used as design point. Table 3 shows the main results of the annual simulation for each design point.

The different DNI on aperture of collector influences the solar field area. In December the low irradiance results in the need of a big solar field, nearly twice as big as the solar field with design point in June. The sunshine duration of an entire year is 4 382 hours. Hence, a TES has to cover the remaining hours for continuous operation. As shown in Figure 4, the design points in March and June lead to the fact that the solar field is too small to charge the TES in winter times when the irradiance is low. The bigger solar field in case 1 allows more operation hours compared to case 2. Whereas, the solar field in case 3 allows 8 760 operation hours for the SORC. The amount of hours out of operation is a theoretical value since e. g. no maintenance stops are taken into account for these simulations. For case 3 the annual electrical energy yield is 4 202 MWh. The solar field and thermal energy storage

Table 3: Case study: results of annual simulation

	Case 1	**Case 2**	**Case 3**	**Unit**
Design point	March 21st	June 21st	December 21st	-
Aperture direct normal irradiance	719.1	869.8	429.2	W/m²
Solar field aperture area	18 596	14 418	39 286	m²
Sunshine duration	4 382			h
Hours out of operation	485	1 022	0	h
Annual aperture direct normal irradiation	2.306			MWh/m²
Annual collected normal irradiation	42 885	33 248	90 597	MWh
Annual collected thermal energy	18 596	14 882	16 580	MWh
Annual electrical energy yield	3 955	3 690	4 202	MWh
Annual solar capacity factor	9.2	11.1	4.6	%

allow SORC operation in every simulated time step. However, the huge solar field causes a low annual solar capacity factor of 4.6 %. The annual solar capacity factor of case 1 is about 9.2 % and for case 2 11.1 %.

To evaluate one SORC design in detail an in-depth view has to be carried out. An annual simulation can be reviewed by looking closely at single days. Hence, in Figure 5 the course of various parameters for March 21st and June 21st of the annual simulation of case 3 is presented. For both entire days the electrical gross power, the direct normal irradiance and the SOC of the TES at the beginning of every time step are plotted. The solar field and the TES ensure the continuous power production of the SORC plant. The TES is charged within a few hours. This is caused by the fact that the simulation allows a higher heat flux than the nominal thermal heat flux for the ORC. If this heat flux is limited, charging times will become longer. The trend of the SOC shows that only about 30 % of the TES load are used on December 21st. Therefore, the storage capacity and the solar field size are not regarded to be well designed for this plant since in this case a huge percentage of the storage fluid is not needed during most of the year. Finding a more suitable design will need several more simulations of further designs which on their part again have to evaluated by annual simulations.

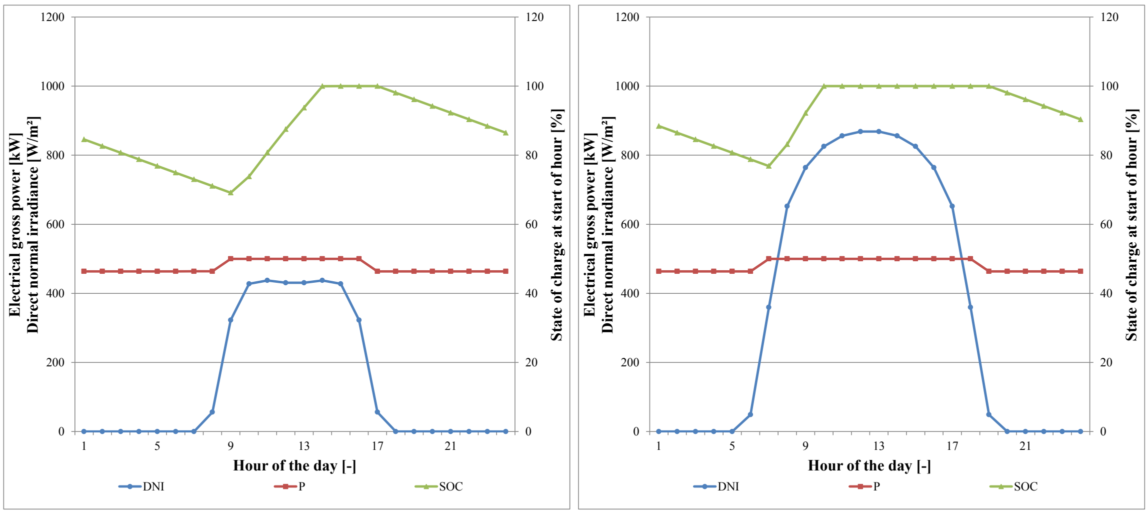

Figure 5: Gross power P, DNI (both left ordinate) and SOC (right ordinate) for December 21st (left chart) and June 21st (right chart), all charts are created with the results of case 3 plant design

4. CONCLUSIONS

Many options exist to design and engineer a SORC. The size of TES and of solar field are directly linked to plant availability and the number of annual operation hours at full and part load. The solar field size and the TES size influence the capacity factor of the SORC. For sizing the solar field and the TES an appropeiate design point has to be chosen. Annual simulations describe accurately the full and port load behavior of a SORC plant. With these simulations the chosen design can be evaluated.

In detail, the simulations carried out in this paper conclude in the following:
- A time step approach is used to describe the full and part load behavior of a SORC. A steady-state simulation is not considered to be a suitable approach.
- Choosing an appropriate design point is essential when designing and evaluating a SORC plant with annual simulations.
- The available irradiance and the required thermal power for the ORC influence the solar field size significantly.
- When sizing the TES, the following parameters have to be taken into account at least: the solar field size, full load hours, demand profile and direct normal irradiance over a period of one year.
- Specifying the most suitable design for solar field and TES with simulations results in an optimization problem characterized by a large number of degrees of freedom.
- To determine the best SORC plant design (including economic parameters) an optimization is required.

The simulations described in this paper do not consider economic constraint, auxiliary equipment such as boilers or load profile for power demand. In these cases the simulation needs to be extended by the relevant parameters to optimize a design and to compare it to a diesel generator.

Further works focus on the design of an optimization model. This model will aim at finding the most suitable basic engineering parameters, e. g. capacity of ORC and TES and size of solar field, for a SORC design as adecentralized power plant. The optimization model will contain an economic objective function and uses, among others things, a power demand and an irradiance profile as constraints. The modell will include part load behavior for the SORC to satisfy a load dynamic.

NOMENCLATURE

A_{ap}	aperture area	(m^2)
d	day of year	(-)
G_{bn}	beam (direct) normal irradiance	(W/m^2)
P	electrical power	(kW)
$\dot{Q}$	thermal power	(kW)
SM	solar multiple	(-)
Δt	duration of time step	(h)
η	efficiency	(-)
CF	capacity factor	(-)

Subscripts

el	electrical
i	time step ‘i’
sol	solar
th	thermal

Abbreviations

DNI	direct normal irradiance
ORC	organic Rankine cycle
SF	solar field
SORC	solar organic Rankine cycle
SOC	state of charge
TES	thermal energy storage

REFERENCES

Al-Sulaiman, F. A., Dincer, I., Hamdullahpur, F., 2011, Exergy modeling of a new solar driven trigeneration system, *Solar Energy*, vol. 85, no. 9: p. 2228-2243.

Bruno, J. C., López-Villada, J., Letelier, E., Romera, S., Coronas, A., 2008, Modelling and optimisation of solar organic rankine cycle engines for reverse osmosis desalination, *Applied Thermal Engineering*, vol. 28, 17-18: p. 2212-2226.

Canada, S., Cohen, G., Cable, R., Brosseau, D., Price, H., 2004, Parabolic Trough Organic Rankine Cycle Solar Power Plant, *Proceedings of the 2004 DOE Solar Energy Technologies Program Review Meeting*, National Renewable Energy Laboratory:

Delgado-Torres, A. M., García-Rodríguez, L., 2007a, Comparison of solar technologies for driving a desalination system by means of an organic Rankine cycle, *Desalination*, vol. 216, 1-3: p. 276-291.

Delgado-Torres, A. M., García-Rodríguez, L., 2007b, Preliminary assessment of solar organic Rankine cycles for driving a desalination system, *Desalination*, vol. 216, 1-3: p. 252-275.

Dürr Cyplan, 2015, Hochtemperaturanlagen ohne Wärmenutzung, http://www.durr-cyplan.com/de/energietechnik-produkte/ht-anlagen-ohne-waermenutzung/, last access: 18 May 2015.

He, Y.-L., Mei, D.-H., Tao, W.-Q., Yang, W.-W., Liu, H.-L., 2012, Simulation of the parabolic trough solar energy generation system with Organic Rankine Cycle, *Applied Energy*, vol. 97: p. 630-641.

Kane, M., 2003, Small hybrid solar power system, *Energy*, vol. 28, no. 14: p. 1427-1443.

McMahan, A. C., 2006, *Design & Optimization of Organic Rankine Cycle Solar-Thermal Powerplants*, Masterthesis, Madison (Wisconsin).

Montes, M. J., Abánades, A., Martínez-Val, J. M., Valdés, M., 2009, Solar multiple optimization for a solar-only thermal power plant, using oil as heat transfer fluid in the parabolic trough collectors, *Solar Energy*, vol. 83, no. 12: p. 2165-2176.

Moustafa, S., Hoefler, W., El-Mansy, H., Kamal, A., Jarrar, D., Hoppman, H., Zewen, H., 1984, Design specifications and application of a100 kW_{el}(700 kW_{th}) cogeneration solar power plant, *Solar Energy*, vol. 32, no. 2: p. 263-269.

Nafey, A. S., Sharaf, M. A., 2010, Combined solar organic Rankine cycle with reverse osmosis desalination process: Energy, exergy, and cost evaluations, *Renewable Energy*, vol. 35, no. 11: p. 2571-2580.

Orosz, M. S., Mueller, A., Quoilin, S., Hemond, H., 2010a, Small Scale Solar ORC System for Distributed Power, *Eurosun 2010: 2nd International Congress on Heating, Cooling and Buildings*.

Orosz, M. S., Quoilin, S., Hemond, H., 2010b, SORCE: A design tool for solar organic Rankine cycle systems in distributed generation applications, *Eurosun 2010: 2nd International Congress on Heating, Cooling and Buildings*.

Price, H., Hassani, V., 2002, *Modular Trough Power Plant Cycle and Systems Analysis,* National Renewable Energy Laboratory, 118 p.

Quoilin, S., 2011, *Sustainable Energy Conversion Through the Use of Organic Rankine Cycles for Waste Heat Recovery and Solar Applications*, Dissertation, Liège, 138 p.

Sinai, J., Fisher, U., 2007, 1 MW Solar Power Plant using Ormat® Energy Converter, *Proceedings of the 14th Sede Boqer Symposium on Solar Electricity Production*, Ben-Gurion University of the Negev:p. 53-56.

Stine, W. B. and Geyer, M., 2001, Power From The Sun, Online book, http://powerfromthesun.net/book.html, last access: 27 January 2014.

Szabó, S., Bódis, K., Huld, T., Moner-Girona, M., 2011, Energy solutions in rural Africa: mapping electrification costs of distributed solar and diesel generation versus grid extension, *Environ. Res. Lett.*, vol. 6, no. 3: p. 1-9.