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The design of a model for a 1 MW parabolic trough concentrated solar power plant in Sudan using TRNSYS software

Abstract: Solar photovoltaic (PV) and concentrated solar power (CSP) systems are the present worldwide trends in utilizing solar energy for electricity generation. Solar energy produced from photovoltaic cells (PV) is considered the main common technology used due to its low capital cost; however, the relatively low efficiency of PV cells has spotlighted development and research on thermal engine applications using concentrated solar power. The efficiency of concentrated solar power is greater than that of PV and considering the solar potential for Sudan. Therefore, this study has been performed in an attempt to draw attention to the utilization of CSP in Sudan since the share of CSP is insignificant in comparison with PV, besides the suitability of CSP applications to Sudan's hot climate and the high solar energy resource, the study presents a design model of 1 MW parabolic trough collectors (PTC) using the Rankine cycle with thermal energy storage (TES) in Sudan, by adopting reference values of the Gurgaon PTC power plant in India. The design of a 1 MW Concentrated Solar thermal power plant using parabolic trough collectors (PTC) and thermal energy storage is proposed. The simulation was performed for a site receiving an annual direct normal irradiance (DNI) of 1915 kWh/m^2, near Khartoum. The results showed that the plant can produce between

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nearly 0.6 to 1 MWh during the year, and around 0.9 MWh when it encompasses thermal energy storage with an average thermal efficiency of 24%. These results of the PTC Power plant encourage further investigation and the development of CSP technologies for electricity generation in Sudan.

KEYWORDS: thermal storage, thermal solar collectors, photovoltaic solar panel, renewable source of energy, solar power plants

Introduction

The energy dilemma and global warming are considered as the most crucial challenges facing our planet as the consumption of energy is proportional to the world economic development and population growth (Mikhno et al. 2021), thus today's world needs to rely more on renewable energy sources rather than on traditional fossil fuels. Fortunately, the capabilities and efficiency of the energy sector have been boosted in the recent years due to the development of renewable energy and the utilization of new technological innovations, as a result, this has reduced negative effects on the environment, declined the demand for fossil fuel, and helped the implementation of alternative energy supplies (Cader et al. 2021). The world solar energy production increased by 15% in 2020, with more than thirty-seven countries exceeding the 1 GW of solar photovoltaic (PV) capacity (Sribna et al. 2021). Despite the supply chain challenges of 2021, the largest contributor to the total generation was solar photovoltaic with a new additional capacity of 133 GW and the global weighted average levelized cost of electricity (LCOE) decreased by 13% from USD 0.055/kWh to USD 0.048/kWh.

With regard to concentrating solar power (CSP), only 110 megawatts (MW) of capacity were added in the Atacama Desert in Chile and the global weighted average LCOE is volatile. (IRENA 2021); however, from 2010 to 2020, the CSP plants showed a 68% reduction in the LCOE from USD 0.34/kWh to USD 0.108/kWh (IRENA 2020). Mainly, CSP can be classified as two types 'line concentrating' or 'point concentrating' according to the mechanism of how collectors concentrate the incident solar irradiance. The linear Fresnel collector, parabolic trough collector (PTC), and solar tower have been utilized on a commercial scale (Nixon et al. 2010).

Solar energy intermittency and unpredicted weather raised interest in introducing storage units. Storage units would help to buffer against the uncertainties of electrical generation and fluctuating demand. Also, this would allow the energy unit to perform at the optimal efficiency points (Krawczyk et al. 2020). Energy storage systems have been used for centuries, several storage technologies have undergone continual improvements and many technologies have been innovated such as the electrochemical, battery, thermal storage, thermochemical, flywheel, compressed air, pumped, magnetic, chemical, and hydrogen energy storage. In this study, thermal energy storage (TES) has been employed because it has a proven commercial maturity and low cost. The TES system consists of a storage medium which could be natural or an artificial mater and equipment for injecting and extracting the heat (Koohi-Fayegh and Rosen 2020).

Sudan has been suffering from an energy shortage for the past twenty years. According to the World Bank report, only about 54% of Sudan has access to power, but the electricity demand is growing by an average of 11% yearly (World Bank 2019). Unfortunately, due to the political situation and the rise of revolution, the situation is getting worse day by day in Sudan, the supply is not stable and experiences regular outages and daily blackouts. Hydro-power has had the largest share of energy generation for many decades, but expanding the hydro-power capacity to meet energy needs is limited. Oil and gas production in Sudan is not significant, and as a result, it will have to turn to the importation of fossil fuels to meet energy needs. One of the promising solutions to energy problems is to move toward renewable energy, especially solar energy. PV is the most employed technology in the country with a total installed capacity of about 2 MW; approximately half of the installed capacity is associated with the telecommunication industry (e.g. remote off-grid antennas and satellites) (Rabah et al. 2016).

1. Literature review

The goal of this literature review is to examine scientific papers on the PTC in-depth. Firstly, The PTC technology has been utilized in a variety of places across the world, and it is the most commonly used CSP technology in the high-volume generation power plants (Santos and Baron 2018). With regards to CSP technology, there are few studies dealing with the simulation of such a complex system, and most of these studies were conducted by TRNSYS and based on Scott A. Jones SEGS simulation. Scott A. Jones used the solar thermal electrical section of the software library to build a detailed model of the 30 MW SEGS VI parabolic trough framework using a TRNSYS framework and its simulation environment to examine both solar and power performance. Generally, an outstanding connection has been seen between model forecasts and plant data, with errors often less than 10% as the result of errors of taking an incorrect reading, the transitory variables such as start-up and shutdown have been adequately represented. While the model might be improved, it demonstrates a capacity to perform detailed research and is useful in areas like evaluating possible storage systems. In order to accurately predict SEGS VI plant performance on short time intervals (minutes) as well as during transients, a complete model was created. As a consequence, rather than monthly or yearly assessments, the TRNSYS model estimates are contrasted here on a daily basis with observed plant data. The findings were estimated for sunny and cloudy weather in 1991 with solar-only operation (Jones et al. 2001).

Following the same strategy, a TRNSYS model for a 30 MW SEGS VI power plant was developed; simulations were then performed under the Algerian weather conditions, alongside an economic assessment to identify the optimum site for the power plant based on the average unit electricity cost. The TRNSYS model is verified and found to have an excellent agreement with just a 10% deviation from the reference data. The annual electricity generated at the Bechar site is 49,139.8 MW, with power generation of around 32 MW, with a power plant output efficiency of about 12 percent, and an annual mean solar effectiveness of 40.9 percent, in which it can convert 40% of the thermal energy received from the sun into electricity (Abdelkader et al. 2012). In addition, the research assesses and quantifies some of the most significant cost-cutting options based on research (Price and Kearney 2003), by adopting Prince H. used an integrated solar combined-cycle system (ISCCS) instead of the Rankine cycle besides using strategies such as resizing up the power production, introducing thermal storage, increasing concentrator size, and using more highly developed receiver innovation, which leads to major declines in the cost of energy (Abdelkader et al. 2012). Another piece of research assessed Makkah's potential for CSP electrical power generation by developing a TRNSYS model of a 30 MW SEGS-VI solar power plant; the generated results showed a highest temperature of 375 degrees Celsius with the maximum power output of 34 MW (Abdel-Dayem et al. 2013).

Bhutka et al. (2016), intended to design a model for a power plant using solar-energy modelling software TRNSYS to estimate the potential of CSP plants and he used two power plants in India. There are two power plants in India that were taken as references to compare his produced generated electricity, the first is Rajasthan plant (50 MW) and the second is Gurgaon plant. The represented values taken from that comparison survey explain that there were nearly similar results with a small deviation of 3.1% for the Gurgaon power plant and 3.6% for the Rajasthan power plant. One of the main benefits of this model is that the values and parameters used in this model have been tested in different plants in the world (18 sites). By adapting the values of the model we can use these parameters without making any essential changes to the power-plant design values. The accepted range has been estimated between the real output results and the expected electricity generated in which it falls between this interval (0.4–13.7%), and the mean divergence is estimated to be 6.8%. If we compare present electricity production, we get a percentage smaller than 10%, so some research work and development should take place to estimate the overall performance of the country. The old model output results were used to compare the current output which shows that the annual capacity potential of a 1 MW solar thermal power plant range in value between 900 and 2700 MWh (Bhutka et al. 2016).

Remlaoui et al. (2019) used solar thermal power from a PTC to create a TRNSYS simulation for a thermodynamic plant firstly by using the sun as the main source for the power plant and secondly by using a conventional Rankine cycle using a combustion chamber as a heat source. In addition to the mechanical components, the system contains the weather data from Ain Témouchent in the city (Algeria) which was used as the power plant's meteorological data reference data for the power plant. The results showed a comparison between the first and second scenarios. In the first scenario, the work of the steam turbine increases from 9 hr to its maximum value of 856 kJ/kg at 13 hr while the PTC fluid exit temperature peaks at 330°C, whereas in the second scenario, from the start of the simulation until 1 hr, the highest value of the power stays unchanged because the flow of fuel (natural gas) does not fluctuate over the operation duration (Remlaoui et.al 2019). Achour et al. (2018), integrated two power plants, a parabolic trough solar field and a conventional merged cycle in order to analyse the efficiency of an integrated solar power plant combined cycle in southern Algeria. Up to the present, the integrated power merged cycle (ISCC) is undoubtedly the best framework for transforming solar energy to electricity among all possible hybrid solar thermal systems. Since solar radiation data is not readily available for many Algerian locations, a linear regression model that focuses on the sunshine period was first created to predict the direct solar irradiance at the targeted address. Then, by taking the optical and thermal characteristics of the collector taken into consideration, the solar field was modelled. The mass and energy flows of every element of the power plant were then used to generate the ISCC thermodynamic system. In this system, the power plant's thermal efficiency was modelled. The efficiency of the solar field was investigated at different times of the year. Modifications in numerous operational parameters, such as flow rate and sun incidence angle, were studied. On four typical days, the ISCC's overall outcome was analyzed and the solar -power performance was reviewed, in addition, the southern Algerian environment was used as a reference value to evaluate the performance of an ISCC plant, in addition to the total efficiency of the hybrid solar power plant, the intensity of solar radiation was assessed by created thermodynamic system. Summer has the greatest solar power performance, which may reach 14.4%, while winter has the lowest solar radiation output, which is also influenced by the angle of solar events, at around 8%. The model has shown that the ISCC can reach a total thermal efficiency of greater than 60%. In other words, the more the energy produced by solar radiation, the higher the thermal performance. In 2011, a sustainable energy goal was established in Algeria, so these result outcomes are the instructions and suggestions for the development of appropriate solar combined cycle technology in Algeria (Achour et al. 2018).

García et al. (2011), simulated a PTC power plant incorporating thermal energy storage by developing a comprehensive design model; these results were compared with actual data from ACS Industrial Group 50 MW facility in Spain, they showed an excellent agreement with a very low deviation. This model was built mainly to calculate the generated power at several phases of construction, design, operation, and planning. Furthermore, this model can be utilized in strategic planning and procedure improvement strategies for the real power station.

Much research has been performed to analyse and optimize some major components of the PTC power plants, Ari Rabl, compared various solar concentrators in terms of concentration, mirror error sensitivity, acceptance angle, the average number of reflectors and reflector area size (Rabl 1976). A wind flow analysis on a parabolic trough collector at various wind velocities (2.5, 5, 10 and 15 m/s) reveals that the pressure fields surrounding the collector are 15 to 20 times smaller than the pressure in the collecting area when the consequent force acting on the collector framework is normal (Naeeni and Yaghoub 2007). In terms of improving thermal performance, the tracking system is 46.5 percent more efficient after the creation of a two-axis tracking system for a parabolic trough collector, and it being contrasted with a fixed surface system (Bakos 2006). Improvement research conducted to optimize the absorber tube heat transfer rate with length, diameter, incoming radiation intensity, and heat transfer fluid flow parameters (Bakos et al. 2001).

1.1. Novelty of this research article

The primary goal of this study is to develop a parabolic trough solar collector power plant in Sudan based on a TRNSYS model from Gurgaon PTC power plant in India and to evaluate its efficiency and performance to perform and operate in Sudan based on specific meteorological data zones. Despite the fact that many researchers have simulated utilizing a parabolic trough solar collector, only few researchers have reported employing this type of power plant in Sudan. This model encompasses the utilization of thermal energy storage and studies their impact on the power plant.

One of the main goals of this research is to promote and encourage the use of small-scale power generation in off-grid locations, particularly rural societies in Sudan, where diesel generators are the primary source of electricity (Rabah et al. 2016). As a consequence of the acceptable outcomes of this study, these results will pave the way for the development and construction of parabolic trough solar power plants in Sudan, thus enhancing the production of renewable energy in Sudan.

The primary uniqueness points for this research article as well as the novelty of a significant research paper linked to it are highlighted in Table 1 below.

Table 1. Novelty of different studies

Tabela 1. Nowe rozwiązania w różnych badaniach

Study	Novelty	Novelty in this research article
TRNSYS modeling of the SEGS VI parabolic trough solar electric generating system (Jones et al. 2001)	The first model of the 30 MW SEGS VI parabolic trough system utilizes the solar thermal electrical component of the software library employing a TRNSYS framework, with a 10% deviation from the actual plant measurements.	This research is the first of its kind in modeling and simulating a PTC power system in Sudan using TRNSYS software.
A TRNSYS dynamic simulation model for a parabolic trough solar thermal power plant (Remlaoui et al. 2019)	Developed a TRNSYS model to compare the 1-hour performance of a thermodynamic plant that uses the solar field as the heat source and a traditional combustion chamber as a source of heat.	Develop A TRNSYS model that compares the performance of a power plant generating power that uses the solar field as the heat source and a thermal storage tank as a source of heat.
Modelling of Solar Thermal Power Plant Using Parabolic Trough Collector (Bhutka et al. 2016)	Their TRNSYS model for PTC power plant achieved an average of 6.8% deviation in power generated compared to actual power plants across the world.	The development of a TRNSYS model for a PTC power plant resulted in a 5% deviation in power output when compared to actual power plants throughout the world.

1.2. A parabolic trough solar power plant

It is considered as the main component of the power plant; the solar energy absorber is made of reflecting material by bending it into a parabolic shape. A black metal pipe with thermal fluid is placed alongside the focal point of heating by the concentrated solar radiation, transforming it into beneficial heat. The fluid could be water, oil or molten salt, or any other organic solvents. Morimoto and Maruyama (2005) stated that the performance of the solar collector is essentially determined by the ratio of the effective aperture area to the absorber surface area (concentration ratio) and he found that the temperature of the working fluid in a parabolic trough collector could approach 400°C.

A parabolic trough collector has U-shaped mirrors that focus most of the thermal energy absorbed from the sun onto a receiver, which is primarily based on linear concentrator systems and is also known as a heat absorber or heat collector. Near the parabolic curved reflectors' focal line, the latter is a long pipe positioned particularly in the center. Synthetic oil or molten salt is used as a heat transfer fluid to fill the pipe because of its efficiency in maintaining heat and the required temperature. The fluid heats up and becomes very hot until its temperature reaches over 390°C as a result of the sun's reflected wave; the water transforms into steam after being pumped and passing through the heat exchanger which is used to heat all the water passed through it. In order to generate electricity, the steam expands into a standard steam turbine, which runs a generator. For completing the cycle and acquiring continuous power generation, the steam is recovered and condensed before being used again in the turbine stages. The same procedure takes place for the working fluid, which is recycled first and then reused after converting its heat to water.

1.3. TRNSYS

This is a versatile and complete modelling tool for dynamic system simulation. TRNSYS provides an opportunity to test and model different engineering concepts and projects from basic household domestic hot water systems to modeling and designing building and associated components including control approaches and alternative energy sources (wind, solar, photovoltaic, hydrogen systems). This creates the chance for engineers and researchers throughout the world to test all innovative energy concepts. TRNSYS models contain STEC packages that are used specifically for simulating solar thermal power generation. The STEC packages include gas turbine steam cycles, thermal collectors, and superior temperature storage systems. The STEC packages built using TRNSYS incorporate solar thermal power plant characteristics (Schwarzboezl 2006). SolarPACES users established SolarPACES activity and they regularly updated. The solar thermal electric component (STEC) library was built in 2002 by Peter Schwarzbozl (DLR, Germany) and Scott Jones (SNL, New Mexico). This is used to generate electricity by modeling thermal processes (both solar and conventional). Most recent solar thermal power technologies frequently use STEC simulation models in terms of feasibility studies for solar thermal power projects and research programs.

2. Methodology and simulation configuration

2.1. Power plant sites and location

The availability of annual relatively high direct normal irradiation (DNI) is critical for CSP plant power output and economic viability. As a result, CSP plants can only be built in areas with high sun direct normal irradiation (DNI). Direct solar radiation is the only way to keep operating temperatures high enough for CSP facilities to generate energy. The selection of a site for a CSP power plant is the first step. When it comes to meeting the standards of a CSP site, there are a lot of variables to consider. These requirements are essential for the plant to efficiently and effectively generate power. The power plant is located in Sudan, which is one of the largest countries in Africa and is located in the north-eastern part of the continent, with abundant solar radiation. The average sunlight hours in the capital (Khartoum) range from 8.7 hours per day in July to 10.5 hours per day in February, for a yearly average of 9.92 hours per day and around 3600 hours per year according to the National Weather Service; this results in an average DNI of 5.68 kWh/m^2/Day and an average GHI of 6.2 kWh/m^2/Day (The World Bank, Solargis 2020).

2.2. Weather data

All transient thermal simulations need meteorological data to some extent. The Solar Energy Lab has gathered meteorological data in several formats and made it available and accessible to the modelling community. The Solar Energy Lab's TRNSYS simulation tool can handle a variety of meteorological data types, including mean monthly readings, TMY basic (typical meteorological year), TMY2 readings, and hourly weather files.

The TMY2 type data is derived from the 1961–1990 National Solar Radiation Database, the dataset is very accurate and recommended by the National Renewable Energy Laboratory

Table 2. Shambat station weather data

Tabela 2. Dane pogodowe stacji Szambat

Location	Latitude {N}	Longitude {E}	Elevation {m}
Shambat, Khartoum	15.67	32.53	376

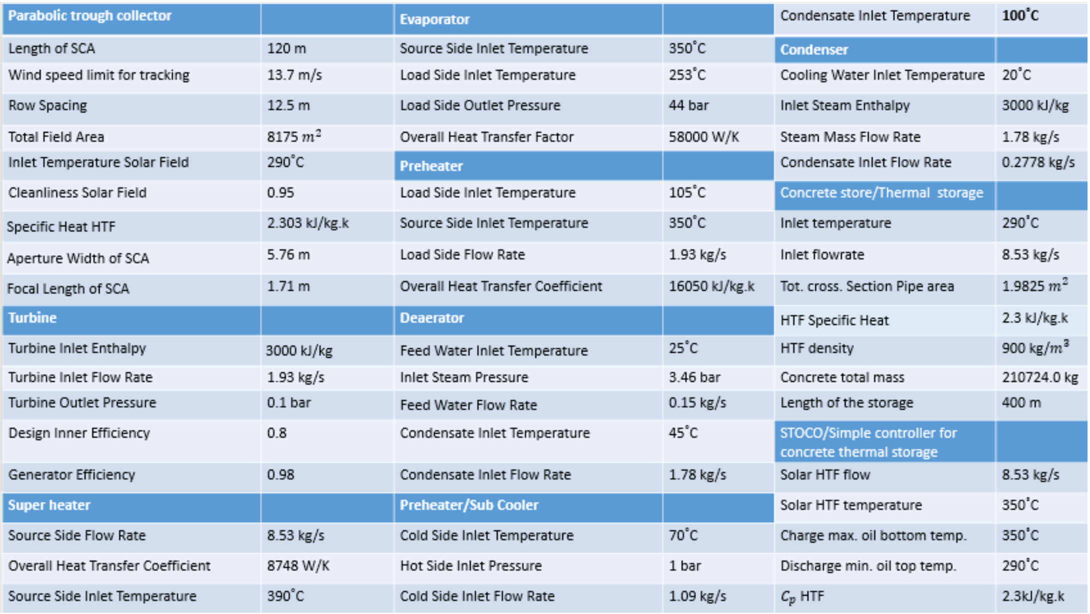
(NREL) (TMY2). In this paper, the meteorological data in the TMY2 format for the 1 MW PTC power plant located in Khartoum, Sudan was obtained from Meteonorm software (distributed under license from Meteotest).

2.3. PTC model inputs and configuration

Essentially, before starting the power plant modelling process, a set of input data and several settings needs to be configured, including operating conditions for components such as the deaerator, parabolic trough, super heater, turbine, and condenser. The power plant model is developed in the TRNSYS environment utilizing all of the parameters and inputs listed in Table 3.

Table 3. Inputs data parameters used in TRNSYS simulation

Tabela 3. Parametry danych wejściowych używane w symulacji TRNSYS



Parabolic trough collector		**Evaporator**		Condensate Inlet Temperature	**100°C**
Length of SCA	120 m	Source Side Inlet Temperature	350°C	**Condenser**	
Wind speed limit for tracking	13.7 m/s	Load Side Inlet Temperature	253°C	Cooling Water Inlet Temperature	20°C
Row Spacing	12.5 m	Load Side Outlet Pressure	44 bar	Inlet Steam Enthalpy	3000 kJ/kg
Total Field Area	8175 m^2	Overall Heat Transfer Factor	58000 W/K	Steam Mass Flow Rate	1.78 kg/s
Inlet Temperature Solar Field	290°C	**Preheater**		Condensate Inlet Flow Rate	0.2778 kg/s
Cleanliness Solar Field	0.95	Load Side Inlet Temperature	105°C	**Concrete store/Thermal storage**	
Specific Heat HTF	2.303 kJ/kg.k	Source Side Inlet Temperature	350°C	Inlet temperature	290°C
Aperture Width of SCA	5.76 m	Load Side Flow Rate	1.93 kg/s	Inlet flowrate	8.53 kg/s
Focal Length of SCA	1.71 m	Overall Heat Transfer Coefficient	16050 kJ/kg.k	Tot. cross. Section Pipe area	1.9825 m^2
Turbine		**Deaerator**		HTF Specific Heat	2.3 kJ/kg.k
Turbine Inlet Enthalpy	3000 kJ/kg	Feed Water Inlet Temperature	25°C	HTF density	900 kg/m^3
Turbine Inlet Flow Rate	1.93 kg/s	Inlet Steam Pressure	3.46 bar	Concrete total mass	210724.0 kg
Turbine Outlet Pressure	0.1 bar	Feed Water Flow Rate	0.15 kg/s	Length of the storage	400 m
Design Inner Efficiency	0.8	Condensate Inlet Temperature	45°C	**STOCO/Simple controller for concrete thermal storage**	
Generator Efficiency	0.98	Condensate Inlet Flow Rate	1.78 kg/s	Solar HTF flow	8.53 kg/s
Super heater		**Preheater/Sub Cooler**		Solar HTF temperature	350°C
Source Side Flow Rate	8.53 kg/s	Cold Side Inlet Temperature	70°C	Charge max. oil bottom temp.	350°C
Overall Heat Transfer Coefficient	8748 W/K	Hot Side Inlet Pressure	1 bar	Discharge min. oil top temp.	290°C
Source Side Inlet Temperature	390°C	Cold Side Inlet Flow Rate	1.09 kg/s	C_p HTF	2.3kJ/kg.k

Source: Bhutka et al. 2016.

The flow chart in Figure 1 (below) depicts the idea of operating the thermal storage system to match the electric demand when there is insufficient solar energy in the solar parabolic trough section. If there is insufficient thermal energy in the solar field to cover the demand, the Rankine cycle will begin using the heat source from the thermal storage tank. The working fluid in the tanks (both cold and hot tanks) is essential in the control of the system since the HTF flow rates to the power block, solar field, and HRS are all interrelated in this subsystem.

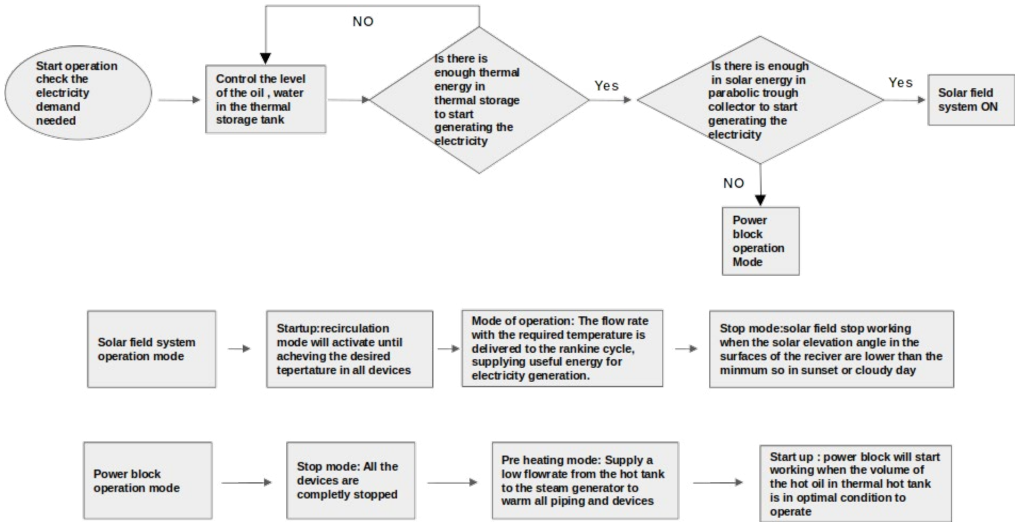


Fig. 1. Flow chart describing the operating of the power plant

Rys. 1. Schemat blokowy pracy elektrowni

In this article, the PTC power plant will be modelled and simulated in two scenarios. In the first scenario, the PTC power plant relies solely on the thermal energy from the parabolic trough collectors and thus it operates during the daylight hours only. The plant layout and TRNSYS power plant layout are described in Figures 2 and 3, respectively. In the second scenario, a TES will be introduced to the power plant to compensate for the thermal energy shortfall at night. The model and its layout in the TRNSYS environment for the second scenario are illustrated in Figures 4 and 5. From the TRNSYS STEC library, the parabolic trough collector (type 196) is selected, Type 196 is built on Lippke's model, it employs an integrated efficiency equation to compensate for the variable fluid temperatures at the collector field's entrance and exit. It estimates the required mass flow rate of the heat transfer fluid to attain a user-defined output temperature T out. The parabolic trough collector is used in this design, which is based on Lippke's method by Dudley et al. (1994) calculated the correct variable fluid temperatures at the collector field's input and exit by using an incorporated efficiency equation. In order to achieve a user-specified exit temperature, they calculate the required mass flow rate of the HTF. Essential input data and parameters such as field area and SCA length of the field, the inlet temperature of heat transfer fluid, ambient air temperature wind speed, the specific heat of HTF, DNI, the mass flow rate of the HTF, in addition to many coefficients like pump power coefficient and losses coefficients are required by the solar field model. Once the heat transfer fluid reaches the necessary temperature, the thermal energy provided by the parabolic trough collector must be utilised to generate superheated steam via heat exchangers. A heat exchangers model is used for transferring the thermal energy power that is made and generated inside the solar field collector (parabolic trough). This model contains three main components: the first is A type 115 which is used to generate the sensible heat with zero capacitance and then transferred in counter flow mode, in this case, both devices (economizer and super heater) are used. For the latent heat exchange, an evaporator (type 116) is used. The hot (source) and cold (load) side intake temperatures and flow rates are used to estimate the efficacy of heat exchangers. The total heat transfer coefficient is assigned a set value as a heat exchanger design parameter. The super heater is connected with evaporator and economizer, in which the heat transfer pass through the superheated and is then directed to the evaporator and economizer to complete the heat exchanging cycle, after that the heat transfer fluid leaves the economizer and is then directed to the heat storage tank, which is used to support the heat to the power plant during the night. The heat transfer fluid feeding into and leaving the evaporator has temperatures of 350 and 253°C, respectively, while the economizer has temperatures of 220 and 105°C, respectively (Bhutka et al 2016). After the steam is formed and generated in the super heater, the steam is sent through the pipe towards the turbines stage in which (type 118) components have been used for this purpose. This turbine stage component calculates the input pressure of the turbine stage using the output pressure and it uses the isentropic efficiency of the Rankine cycle to compute the outlet enthalpy from the intake enthalpy and the inlet and outlet pressure. Controlled splitters (type 189) are coupled with the stage turbine at high pressure and used to extract the steam then send it to the feed-water heaters. The enthalpy and pressure of the steam are divided into two flow paths, with outlet enthalpy 1 and 2 equivalent to the intake enthalpy. The first exit is used to supply steam to the Low-Pressure turbine at the necessary steam pressure and use this steam to produce a portion of the power coming from the low-pressure turbine and then the steam moves through the condenser (type 183) to obtain the heat and transformed to water once more to complete the cycle, the second outlet is linked to a deaerator (type 184), which uses mechanical and chemical methods to remove gasses from the steam. In order to extract the electrical power from turbines, an electric generator is linked to stage turbines, and a type 175 is used for this purpose. The cooling water temperature rises as a consequence of the temperature difference between the cooling-water departure temperature and the condensing temperature; thus, the condensing pressure is purely influenced by the constant intake water temperature. The component (type 117) describes as a steady-state mix of water preheater; it operates as a pre-heater to preheat feed water under saturated conditions, the condensate water flow comes from the condenser, and the low-pressure steam flow comes from a splitter. Because all gases are liberated in the deaerator using mechanical and chemical means, all steam that flows through the Low-Pressure and High-Pressure turbines will mix again in the deaerator; the steam is then transported through the feed water pump to the feed water heater and lastly to the economizer to finish the cycle. JWT’s Rockbed Thermal Storage (type 10) which features concrete thermal storage for single-phase fluid (HTF oil, water) was employed as a thermal storage medium to feed the power plant. According to the standards, the storage unit is made up of a series of parallel, evenly spaced concrete tubes through which HTF can flow in one of two directions: up flow (normally discharge flow entering cold) or down flow (usually charge flow entering hot). A simple controller for concrete thermal storage (type 230) has been used to manage the charge and the discharge of storage in order to monitor and control the operation of the thermal storage tank. Storage is deemed ‘full’ when the HTF exit temperature (at the bottom) exceeds a particular upper limit when charging. When the HTF exit temperature (on top) goes below a particular lower limit during discharging, the storage is regarded as empty. Basic case checking is used to synchronize the HTF flowrate supply and demand with particular dead bands to reduce variations.

Figure 2: This figure shows the layout of the parabolic trough solar collector that operates directly from the parabolic trough solar collector without using any external source of energy, such as a thermal storage tank. This plant consists of a solar energy field represented by the parabolic trough system (parabolic trough, economizer, evaporator, and pre-heater), and a second main part that includes the Rankine cycle-based electricity generation side (turbine stages, condenser, deaerator, and electrical generators). The orange line shows the flow of heat transfer fluid from the solar field to the heat exchanger, while the blue line indicates the steam/water cycle through the heat exchanger, steam turbine, and condenser.

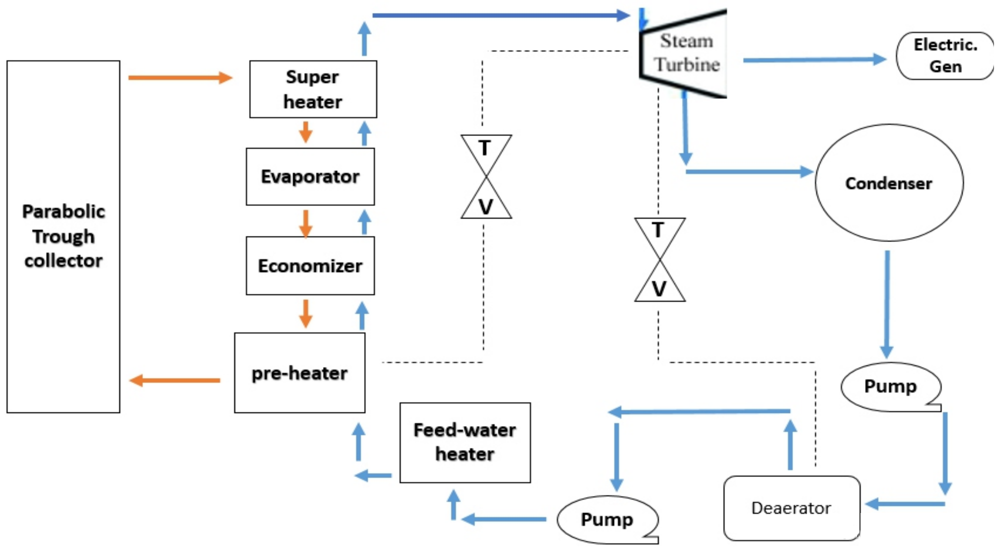


Fig. 2. Power plant layout operates only parabolic trough collector

Rys. 2. Układ elektrowni obsługującej tylko paraboliczny kolektor rynnowy

Figure 3: TRNSYS parabolic trough solar power plant. TRNSYS is software that is used to simulate and model energy systems. Using TRNSYS, a parabolic trough solar power plant is simulated in this layout. It consists of a solar energy field represented by the parabolic trough system (parabolic trough, economizer, evaporator, and pre-heater), and a second main part that includes the Rankine cycle-based electricity generation side (turbine stages, condenser, deaerator, and electrical generators). The blue line represents the steam/water cycle from heat exchanger to steam turbine to condenser, while the orange line illustrates the heat transfer fluid cycle from the storage tank and the solar field to the heat exchanger.

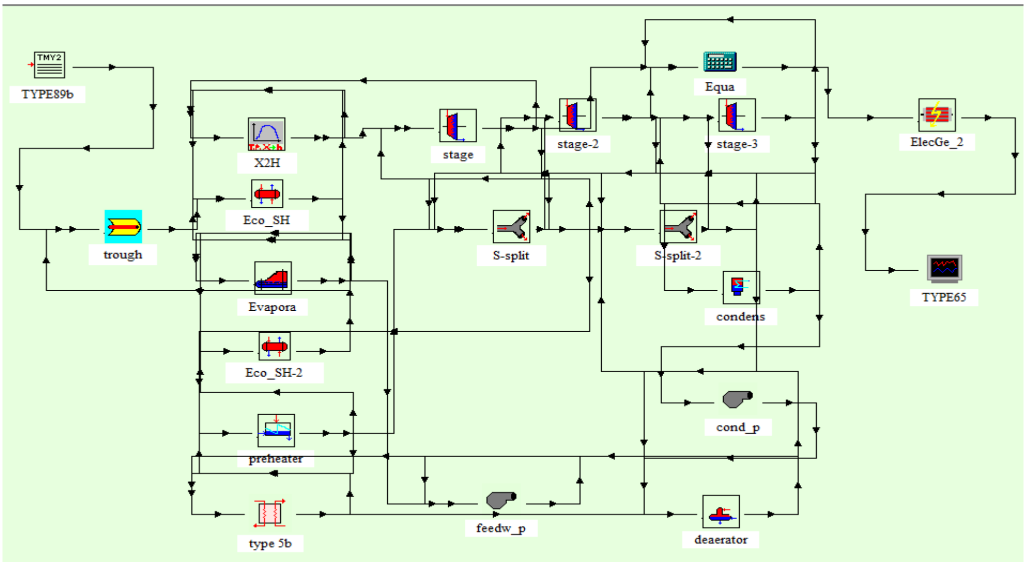


Fig. 3. TRNSYS power plant layout operates only parabolic trough collector

Rys. 3. Układ elektrowni TRNSYS obsługującej tylko paraboliczny kolektor rynnowy

Figure 4: A solar power plant with a parabolic trough and a storage system. This power plant involves a thermal storage system and a solar energy field represented by the parabolic trough system (parabolic trough, economizer, evaporator, and pre-heater), as well as a second main section that includes the Rankine cycle-based electricity producing side (turbine stages, condenser, deaerator, and electrical generators). The thermal storage tank is specifically installed in this power plant construction to cover the thermal energy absence that occurs during the night hours and on cloudy days.

Figure 5: TRNSYS parabolic trough solar power plant with storage system. TRNSYS is software that is used to simulate and model energy systems. Using the TRNSYS, a parabolic trough solar power plant is simulated in this layout. It consists of a thermal storage system in addition to a solar energy field represented by the parabolic trough system (parabolic trough, economizer, evaporator, and pre-heater), and a second main part that includes the Rankine cycle-based electricity generation side (turbine stages, condenser, deaerator, and electrical generators).

2.4. Model validation

Before starting the simulation of the PTC power plant model in Sudan, the accuracy and reliability of the model were tested and validated against actual operating PTC power plants in India and in Spain. This has been accomplished by applying the parameters of power plants in the

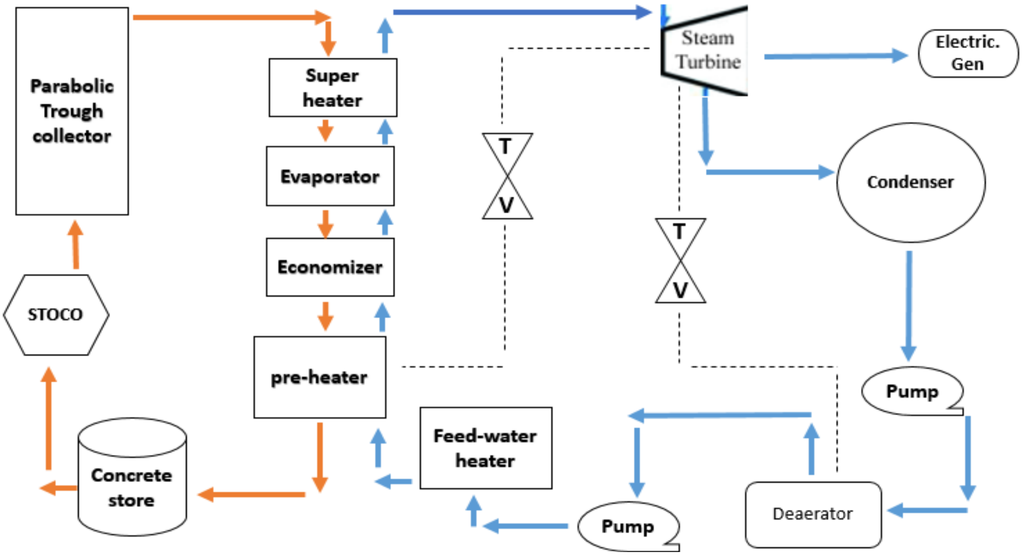


Fig. 4. Power plant layout using the thermal storage system

Rys. 4. Układ elektrowni z wykorzystaniem systemu akumulacji ciepła

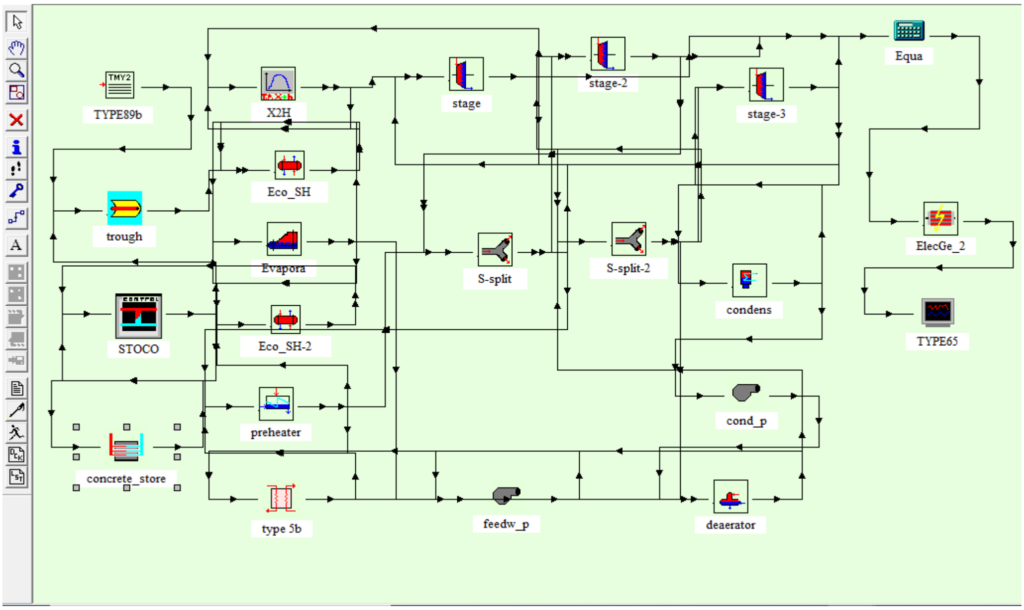


Fig. 5. TRNSYS power plant layout using the thermal storage system

Rys. 5. Układ elektrowni TRNSYS z wykorzystaniem systemu magazynowania ciepła proposed model and running the simulation. The energy output of the simulation of National Solar Thermal Power Facility and Andasol-1 power plants are 1430 MWh/yr and 183,254 MWh/yr, respectively, the actual energy output is 1365 MWh/yr for Gurgaon (National Solar Thermal Power Facility 2021) and 174,511 MWh/yr for Andasol-1 (Andasol-1 2021), which shows a 5% deviation in comparison to the actual energy output of the Gurgaon and Andasol-1 power plants as shown in Table 4.

Table 4. Validation of the PTC power plant model with the actual power plant at Gurgaon

Tabela 4. Walidacja modelu elektrowni PTC z rzeczywistą elektrownią w Gurgaon

Plant Name, Location	Aperture area [m^2]	Plant capacity [MW]	Actual energy output [MWh/yr]	Simulation energy output [MWh/yr]	Deviation [%]
National Solar Thermal Power Facility, Gurgaon, India	8175	1	1,365	1,430	4.76
Andasol-1 Spain	510120	50	174,511	183,254	5.01

3. Results

The simulation was performed for a period of one-year (8,760 hours) with a time interval of 0.125 hours. Meteonorm program meteorological data weather data TMY2 has been utilized for the selected location which is Shambat, Khartoum, the meteorological characteristics of the chosen location have shown good potential for utilizing solar power and it has been found that:

1. The power plant will receive an annual average of (1,915 kW/m^2) DNI, the greatest DNI of (250 W/m^2/mo) is recorded during April , and the lowest of (136 kW/m^2/mo) is observed in August. The direct net irradiance has a tangible effect on the power plant; at the start of the year, direct normal irradiance is almost near the maximum value, then it begins to fluctuate until it reaches the minimum value in August, and it will then gradually rise until it hits the peak value in April (see Fig. 6).

2. From the meteorological data, the average yearly ambient temperature, also called the dry -bulb temperature, at the beginning of the year is 27°C, then declining during the first month to the minimum value of 18°C, then gradually rising until it reaches the maximum value of 42°C in April, then falling until below 20°C in December (see Fig. 7). These are good values that emphasize the potential of the operation of the power plant as the dry bulb temperature is an indicator of the heat content of the location.

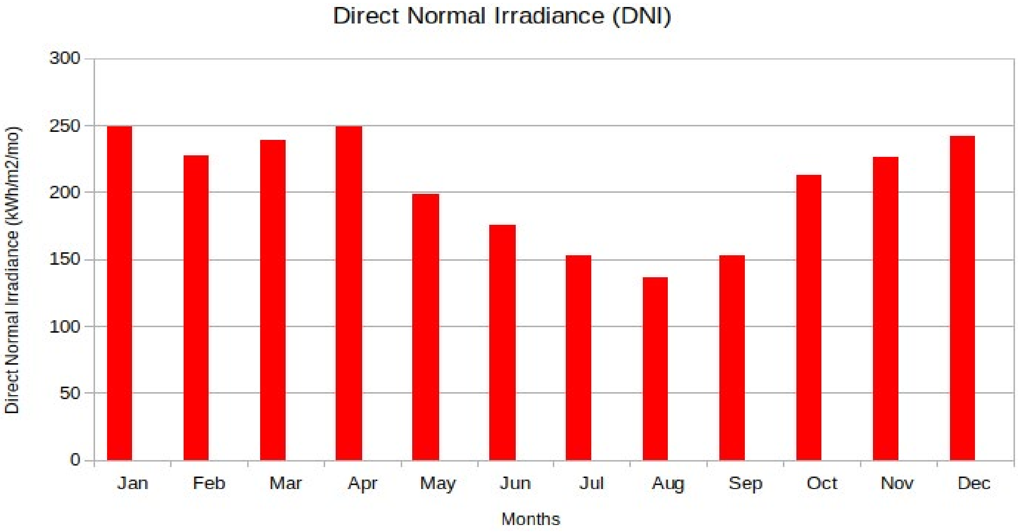


Fig. 6. Direct normal irradiance generated during the months [kW/m^2/mo]

Rys. 6. Bezpośrednia normalna irradiancja generowana w ciągu miesięcy [kW/m^2/mc]

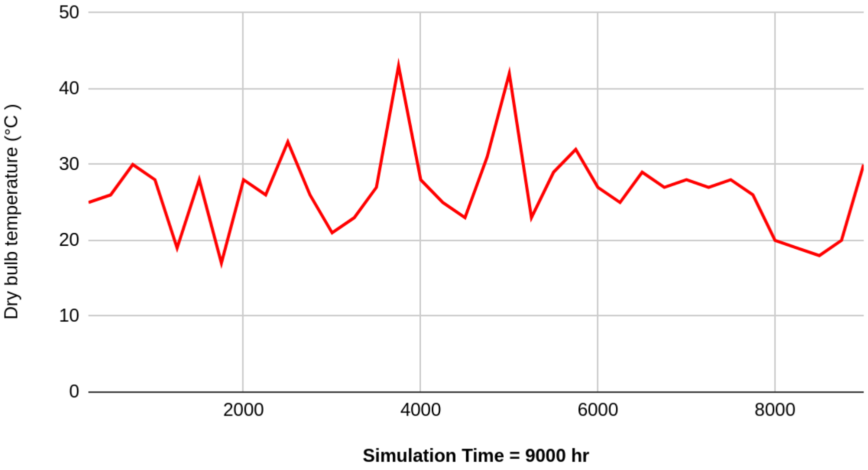


Fig. 7. Dry bulb temperature generated during the year [°C]

Rys. 7. Temperatura termometru suchego w ciągu roku [°C]

3. The power plant has been evaluated in two scenarios for the power generated, and the modeling of the power plant is done throughout the year from (0–8,760 hr), which in this instance will cover the generated electricity that was produced in each hour during the year. Since it is assumed that there is no thermal storage to sustain and operate the power plant during the night

hours, the power plant only functions for day hours in the first scenario. It has been found that in the first quarter of the year, the power plant produces approximately 1.2 MWh which is the greatest overall output of the year, however, during the second quarter, energy production increases steadily from 0.9 MWh to a maximum of 1.4 MWh. Finally, the energy production fluctuated until a maximum value at the end of the year of around 1.8 MWh.

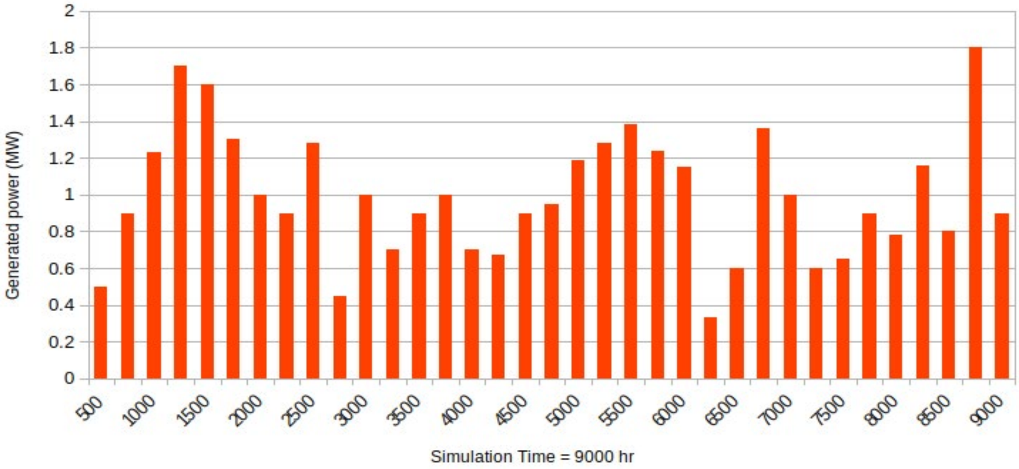


Fig. 8. Electrical power generated during the year using parabolic trough without TES [MW]

Rys. 8. Moc elektryczna generowana w ciągu roku z wykorzystaniem rynny parabolicznej bez TES [MW]

4. In the second scenario, the power plant is modeled throughout the year from (0–8,760 hr), and a thermal storage tank is included, which in this case covers the generated electricity that was produced in every single hour of the year. The thermal storage will power and sustain the power station during the night, allowing it to operate continuously for 24 hours per day. In accordance with the above, a consistent level of energy generation is attained throughout the year, which will be close to 0.9 MWh.

5. The electricity production was compared in both scenarios using the graph below (Fig. 10); when using solar energy alone, the electricity produced indicated a fluctuation due to the lack of solar energy during the night, whereas when using a thermal storage tank, the electricity production demonstrated stable production with a small variation over the required power 1 MW.

6. The average annual thermal efficiency was calculated to be roughly twenty-four percent. As seen in the graph, the average thermal efficiency began the year at 15% and reached its peak of 40% in February, before oscillating between 30% and 13% in the following months and ultimately remaining steady at 25% at the end of the year in December (Fig. 11).

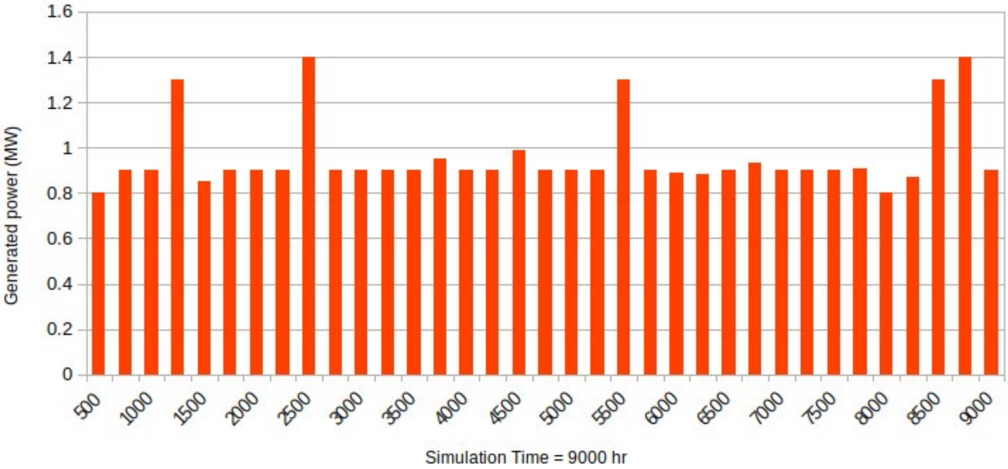


Fig. 9. Electrical power generated during the year using parabolic trough with TES [MW]

Rys. 9. Energia elektryczna generowana w ciągu roku z wykorzystaniem rynny parabolicznej z TES [MW]

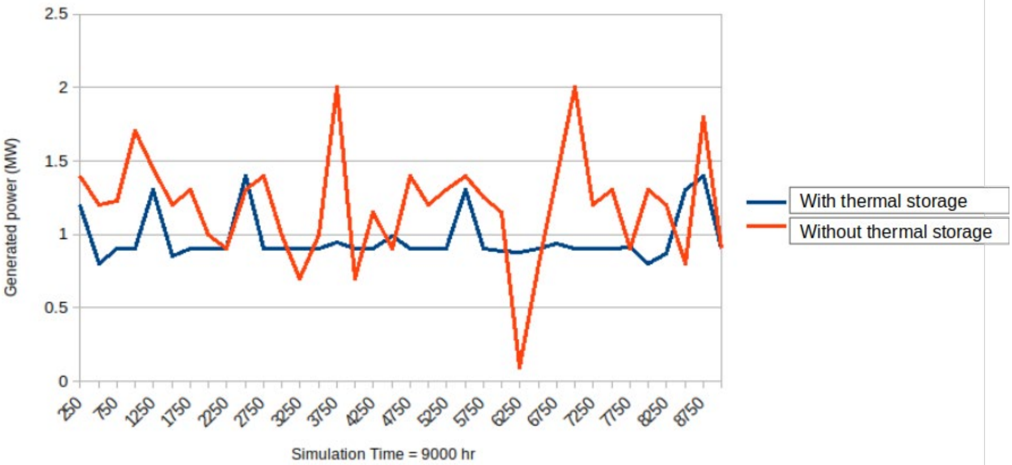


Fig. 10. A comparison of power generation with and without the use of a thermal storage system [MW]

Rys. 10. Porównanie wytwarzania energii z i bez systemu magazynowania ciepła [MW]

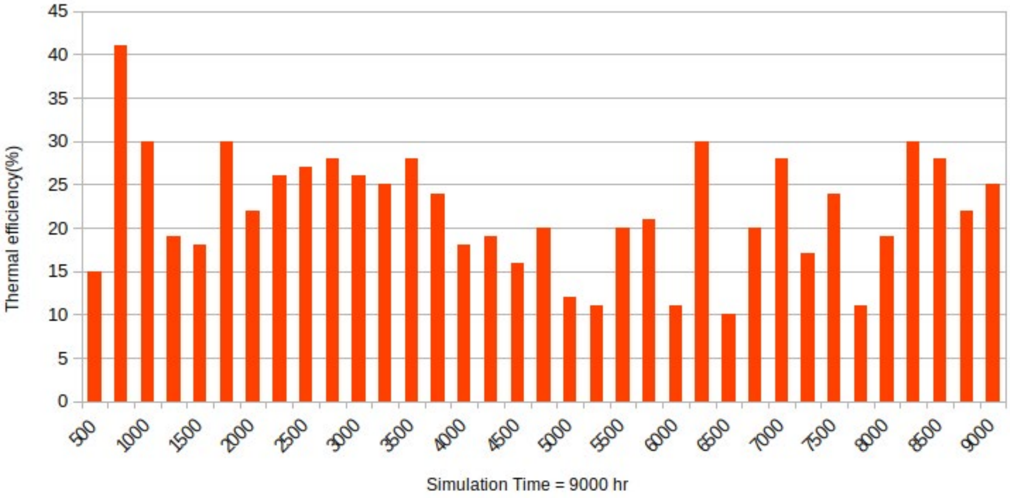


Fig. 11. Thermal efficiency during 1 year

Rys. 11. Sprawność cieplna w ciągu 1 roku

Conclusion

This research study covered the design and simulation of a model of a 1 MW parabolic trough concentrated solar power plant with thermal energy storage operating in Sudan using TRNSYS software. The use of renewable energy is necessary to alleviate the problem of a lack of electricity, particularly in remote regions where there is no connection to the national electricity grid. The model provided energy estimation with 5% deviation when it was validated against two commercial power plants, which enabled us to test and assess the performance of the hypothetically 1 MW PTC power plant in Sudan.

The study has shown that the direct normal irradiance varied from (250 kW/m^2/mo) the peak point in April to the lowest one (136 kW/m^2/mo) recorded in August, and the dry bulb temperature ranges between 21°C in December and 42°C in April as a maximum value throughout the year. Two scenarios of power generation were evaluated: the first assumes that the plant only functions during day hours without a storage system, this scenario results in fluctuation of the power generated between 0.6 to 1 MW during the year. The other scenario encompasses a thermal energy storage that will provide around 0.9 MW during the year. To conclude, this model has potential as a tool for analyzing the performance of PTC power plant components as well as estimating the generated power in different scenarios and cases.

Abbreviation table

PV	photovoltaic
CSP	concentrated solar power
PTC	parabolic trough collectors
TES	thermal energy storage
LCOE	levelised cost of electricity
SEGS	solar energy generating systems
ISCCS	integrated solar combined-cycle system
CFD	computational fluid dynamic
ISCC	integrated solar combined cycle
GHI	global horizontal irradiance
DNI	direct normal irradiance
STEC	solar thermal electric component

Nomenclature

A: Area [m^2]
P: Power [W]
T: Temperature [ºC]
h: Enthalpy
P: Pressure [bar]
m: mass [kg]
mo: month

DNI: Direct normal irradiance [W/m^2]
V: Velocity [m/s]
c: specific heat [kJ/kg.k]
$\dot{m}$: Flow rate [kg/s]
Q: Overall heat transfer factor W/K
L: Length [m]

References

Abdel-Dayem et al. 2013 – Abdel-Dayem, A.M., Nabil Metwally, M., Alghamdi, A.S. and Marzouk, E.M. 2013. Potential of solar thermal energy utilization in electrical generation. *2^nd^ International Conference on Energy Systems and Technologies*, Cairo, Egypt.

Achour et al. 2018 – Achour, L., Bouharkat, M. and Behar, O. 2018. Performance assessment of an integrated solar combined cycle in the southern of Algeria. *Energy Reports* 4, pp. 207–217, DOI: 10.1016/j.egyr.2017.09.003.

"Andasol-1" SolarPACES. National Renewable Energy Laboratory. [Online] http://www.nrel.gov/csp/solarpaces/project_detail.cfm/projectID=3 [Accessed: 2022-02-10].

Bakos, G.C. 2006. Design and construction of a two-axis Sun tracking system for parabolic trough collector (PTC) efficiency improvement. *Renewable Energy* 31(15), pp. 2411–2421, DOI: 10.1016/j.renene.2005.11.008.

Bakos et al. 2001 – Bakos, G.C., Ioannidis, I., Tsagas, N.F. and Seftelis, I. 2001. Design, optimisation and conversion-efficiency determination of a line-focus parabolic-trough solar-collector (PTC). *Applied Energy* 68(1), pp. 43–50, DOI: 10.1016/S0306-2619(00)00034-9.

Bhutka et al. 2016 – Bhutka, J., Gajjar, J. and Tirumalachetty, H. 2016. Modelling of Solar Thermal Power Plant Using Parabolic Trough Collector. *Journal of Power and Energy Engineering* 4, pp. 9–25, DOI: 10.4236/jpee.2016.48002.

Cader et al. 2021 – Cader, J., Olczak, P. and Koneczna, R. 2021. Regional dependencies of interest in the "My Electricity" photovoltaic subsidy program in Poland. *Polityka Energetyczna – Energy Policy Journal* 24(2), pp. 97–116, DOI: 10.33223/epj/133473.

Dudley et al. 1994 – Dudley, V.E., Kolb, G. J., Mahoney, A.R., Mancini, T.R., Matthews, C.W., Sloan, M. and Kearney, D. 1994. Test results: SEGS LS-2 solar collector. Albuquerque, NM (United States): Sandia National Laboratories (SNL-NM).

García et al. 2011 – García, I.L., Álvarez., J.L. and Blanco, D. 2011. Performance model for parabolic trough solar thermal power plants with thermal storage: Comparison to operating plant data. *Solar Energy* 85(10), pp. 2443–2460, DOI: 10.1016/j.solener.2011.07.002.

International Renewable Energy Agency (IRENA) 2020. Renewable Power Generation Cost.

International Renewable Energy Agency (IRENA) 2021. Renewable Power Generation Cost.

Jones et al. 2001 – Jones, S., Robert, P.-P., Schwarzbözl, P. and Blair, N. 2001. TRNSYS Modeling of the SEGS VI Parabolic Trough Solar Electric Generating System. *Conference: Solar Forum 2001, Solar Energy: The Power to Choose*. April 21–25, Washington, DOI: 10.1115/SED2001-152.

Kays, W.M. and London, A.L. 1958. *Compact heat exchangers*. McGraw-Hill.

Koohi-Fayegh, S. and Rosen, M.A. 2020. A review of energy storage types, applications and recent developments. *Journal of Energy Storage* 27, DOI: 10.1016/j.est.2019.101047.

Krawczyk et al. 2020 – Krawczyk, P., Śliwińska, A. and Ćwięczek, M. 2020. Evaluation of the economic efficiency of storage technology for electricity from coal power plants in large-scale chemical batteries. *Polityka Energetyczna – Energy Policy Journal* 23(2), pp. 67–90, DOI: 10.33223/epj/120033.

Lippke, F. 1994. Simulation of the part-load Behaviour of a 30 MWe SEGS plant. Albuquerque, NM (United States): Sandia National Laboratories (SNL-NM).

Lobón et al. 2014 – Lobón, D.H., Baglietto, E., Valenzuela, L. and Zarza, E. 2014. Modeling direct steam generation in solar collectors with multiphase CFD. *Applied Energy* 113(C), pp. 1338–1348, DOI: 10.1016/j.apenergy.2013.08.046.

Mikhno et al. 2021 – Mikhno, I., Koval, V., Shvets, G., Garmatiuk, O. and Tamošiūnienė, R. 2021. Green Economy in Sustainable Development and Improvement of Resource Efficiency. *Central European Business Review* 10(1), pp. 99–113, DOI: 10.18267/j.cebr.252.

Morimoto, M. and Maruyama T. 2005. Static solar concentrator with vertical flat plate photovoltaic cells and switchable white/transparent bottom plate. *Solar Energy Materials and Solar Cells* 87(1–4), pp. 299–309, DOI: 10.1016/j.solmat.2004.08.013.

Naeeni, N. and Yaghoubi, M. 2007. Analysis of wind flow around a parabolic collector (1) fluid flow. *Renewable Energy* 32(11), pp. 1898–1916, DOI: 10.1016/j.renene.2006.10.004.

"National Solar Thermal Power Facility" SolarPACES. National Renewable Energy Laboratory. [Online] https://solarpaces.nrel.gov/project/national-solar-thermal-power-facility [Accessed: 2022-02-10].

Nixon et al. 2010 – Nixon, J., Dey., P. and Davies, P. 2010. Which is the best solar thermal collection technology for electricity generation in north-west India? Evaluation of options using the analytical hierarchy process. *Energy* 35(12), pp. 5230–5240, DOI: 10.1016/j.energy.2010.07.042.

Price, H. and Kearney, D. 2003. Reducing the cost of energy from Parabolic Trough Solar Power Plants. *ISES 2003: International Solar Energy Conference.* Hawaii Island: National Renewable Energy Laboratory.

Rabah et al. 2016 – Rabah, A., Nimer, H., Doud, K. and Ahmed, Q. 2016. Modelling of Sudan's Energy Supply, Transformation, and Demand. *Journal of Energy* 1–14, DOI: 10.1155/2016/5082678.

Rabl, A. 1976. Comparison of solar concentrators. *Solar Energy* 18(2), pp. 93–111, DOI: 10.1016/0038-092X(76)90043-8.

Remlaoui et al. 2019 – Remlaoui, A., Benyoucef, M., Assi, D. and Nehari, D. 2019. A TRNSYS dynamic simulation model for a parabolic trough solar thermal power plant. *International Journal of Energetica (IJECA)* 4(2), pp. 36–41, DOI: 10.47238/ijeca.v4i2.106.

Santos, J.J.C.S. and Barone, M.A. 2018. Concentrating Solar Power. [In:] I. Yahyaoui (Ed.), *Advances in Renewable Energies and Power Technologies* 1. Elsevier.

Schwarzboezl, P. 2006. *A TRNSYS Model Library for Solar Thermal Electric Components (STEC)*. Reference Manual, Release 3.0. November 2006.

Sribna et al. 2021 – Sribna, Y., Koval, V., Olczak, P., Bizonych, D., Matuszewska, D. and Shtyrov, O. 2021. Forecasting solar generation in energy systems to accelerate the implementation of sustainable economic development. *Polityka Energetyczna – Energy Policy Journal* 24(3), pp. 5–28, DOI: 10.33223/epj/141095.

The World Bank, Source: Global Solar Atlas 2.0, Solar resource data: Solargis 2020. [Online] https://solargis.com/maps-and-gis-data/download/sudan [Accessed: 2022-02-10].

The World Bank, World Bank Global Electrification Database from "Tracking SDG 7: The Energy Progress Report". [Online] https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?end=2019&locations=SD&name_desc=false&start=2018&view=chart [Accessed: 2022-02-10].

TMY2, The University of Wisconsin-Madison, Solar Energy laboratory. [Online] https://sel.me.wisc.edu/trnsys/trnlib/stec/stec.htm [Accessed: 2022-02-10].

Tora, E.A.M. and El-Halwagi, M.M. 2009. Optimal design and integration of solar systems and fossil fuels for sustainable and stable power outlet. *Clean Technologies and Environmental Policy* 11, pp. 401–407, DOI: 10.1007/s10098-009-0198-3.

Zaaraouia et al. 2012 – Zaaraouia, A., Yousfib, M.L. and Saidc, N. 2012. Technical and economical Performance of Parabolic Trough Collector Power Plant under Algerian Climate. *Procedia Engineering* 33, pp. 78–91, DOI: 10.1016/j.proeng.2012.01.1179.

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Projekt modelu skoncentrowanej elektrowni słonecznej z rynną paraboliczną o mocy 1 MW w Sudanie z wykorzystaniem oprogramowania TRNSYS

Streszczenie

Systemy fotowoltaiczne (PV) i skoncentrowanej energii słonecznej (CSP) to obecne światowe trendy w wykorzystywaniu energii słonecznej do wytwarzania energii elektrycznej. Energia słoneczna wytwarzana z ogniw fotowoltaicznych (PV) jest uważana za główną powszechnie stosowaną technologię ze względu na jej niski koszt kapitałowy, jednak stosunkowo niska wydajność ogniw fotowoltaicznych zwróciła uwagę na rozwój i badania nad zastosowaniami silników cieplnych wykorzystujących skoncentrowaną energię słoneczną. W warunkach posiadanego potencjału słonecznego Sudanu wydajność skoncentrowanej energii słonecznej jest większa niż PV. Dlatego niniejsze badanie zostało przeprowadzone w celu zwrócenia uwagi na wykorzystanie CSP w Sudanie, ponieważ udział CSP jest nieznaczny w porównaniu z PV, pomimo przydatności zastosowań CSP do gorącego klimatu Sudanu i wysokich zasobów energii słonecznej. W pracy przedstawiono projekt modelu parabolicznych kolektorów rynnowych (PTC) o mocy 1 MW z wykorzystaniem cyklu Rankine'a z magazynowaniem energii cieplnej (TES) w Sudanie, przyjmując wartości referencyjne elektrowni Gurgaon PTC w Indiach. Zaproponowano projekt elektrowni słonecznej o mocy 1 MW wykorzystującej paraboliczne kolektory rynnowe (PTC) i magazynowanie energii cieplnej. Symulacja została przeprowadzona dla miejsca zlokalizowanego koło Chartumu, o rocznym bezpośrednim napromieniowaniu normalnym (DNI) 1915 kWh/m^2.

Wyniki pokazały, że elektrownia może wyprodukować od prawie 0,6 do 1 MWh w ciągu roku i około 0,9 MWh, przy wykorzystaniu magazynowanie energii cieplnej ze średnią sprawnością cieplną 24%. Te wyniki elektrowni PTC zachęcają do dalszych badań i rozwoju technologii CSP do wytwarzania energii elektrycznej w Sudanie.

Słowa kluczowe: magazynowanie ciepła, termiczne kolektory słoneczne, fotowoltaiczny panel słoneczny, odnawialne źródło energii, elektrownie słoneczne