DESIGN OF THERMAL POWER PLANT MODERNIZATION AND REHABILITATION MODEL FOR THE NEW MARKET DEMANDS AND CHALLENGES

by

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The article presents the model for the rehabilitation of existing conventional thermal power plants in order to lower the consumption of fossil fuels. Instead of them, the model uses an alternative energy source – Sun irradiation. The proposed rehabilitation model is theoretically calculated and designed. The model in the software environment MATLAB SIMULINK was developed, based on previous calculations and determined parameters. In this article, the combination of Clausius-Rankine process and solar central receiver system is presented. The model enables simultaneous calculations of exit model parameters for the complete model, based on predetermined entering parameters of the model.

Key words: *Clausius-Rankine process, solar central receiver system, modelling, analysis, MATLAB SIMULINK software environment*

Introduction

The existing energy production infrastructure has a very big role in the transition from existing conventional ways of energy production to the usage of renewables. Rankine process-based thermal power plants were in usage for decades for electricity production. This way of producing electricity is well known and very well analyzed. Kapooria [1] presented an analysis of a thermal power plant working on a Rankine cycle – a theoretical investigation, the in-depth review of the Rankine cycle based thermal power plant. Since the extended use of fossil fuels accelerates the greenhouse effect, the upcoming technologies of energy production are putting forward the use of the alternatives in the energy production process. This is Sun irradiation, water, and wind. The exploitation of solar irradiance is promising a big potential for energy generation. Zhang [2] presented the methodology and results demonstrating the potential of solar central power plants. We must maintain a stable and reliable electricity distribution network. The integration of power production facilities which are based on renewables is putting into the electricity distribution network the disturbances that we would like to avoid. Therefore, we try to find the design of future power plants that will combine the robust and well-known power generation cycle (Rankine process) with upcoming technologies for power generation – solar central receiver system (SCRS). Chao Li [3] presented the possible integration between the aforementioned systems. Murray [4] presented the small-scale SCRS design and analysis, where the combination of SCRS and gas microturbine combination is foreseen. Our research work was fo-

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cused on presenting the hybrid system combined from Rankine cycle and SCRS. The first focus of our work was collecting the input data from Slovenia's energy market, by analyzing the content with the qualitative approach. Based on the content analysis method, we designed a computer model for the revitalization of the thermal power plant. Evaluation and analysis of the obtained results of the computer revitalization model are carried out using a comparative method, given the expected output values of the parameters achieved by the operating references. The main novelty of this paper is the integration of the proposed computer-modeled hybrid system in the European energy market environment and presentation of the expected system response.

Proposed revitalization model

The designed model is schematically presented in fig. 1 and consists of two processes. First is the Rankine process [5] which consists of a boiler [6], high and low pressure steam turbine [7], condenser and necessary system pumps, where the working media is steam. Second, it is a solar central receiver process [8], which consists of the central tower where the concentrated sunbeams from the heliostats, positioned around a central tower, are directed. The working media in the solar cycle is molten salt [9]. The heat exchange between the solar process and the Rankine process takes place inside the heat exchanger [10], which is used as the steam generator, where the heat of the molten salt is transferred to the water. Since the water has 54 °C and molten salt solution exceeds 500 °C, the water is effortlessly transferred back to steam, which is further lead to the steam turbines. Therefore, we can decrease the amount of needed coal for boiler firing in the conventional Rankine process which means lower consumption of fossil fuel [11] (brown coal), lower emissions of GHG gases into our atmosphere and consequently, lower impact on the environment and species in it. Since the energy absorbed from the sun irradiation is costless, it is also beneficial for the economic aspect of operating the thermal power plant [12]. Savings are expected to be introduced through lower fossil fuel consumption as well as a lower amount of needed greenhouse emission coupons for the thermal power plants that present taxation trough the EU Emission Trading System scheme [13]. The important fact of the model is also the possibility to adjust the amount of needed steam for electricity production, produced from the Rankine cycle or solar cycle [14]. That enables to have the central-local control of electricity production either from fossil fuel or solar irradiance inside the boundaries of the thermal power plant, before electricity is dispatched out of the thermal power plant, further to the distribution network. This factor is important for maintaining reliable and error-free electricity network distribution.

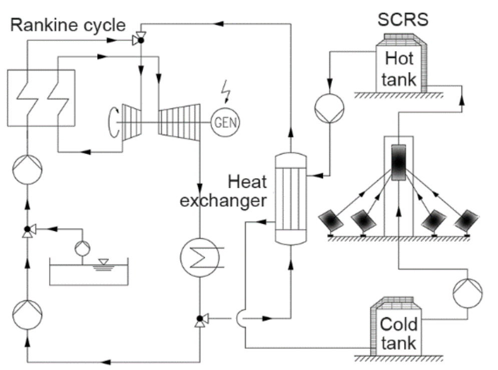

Figure 1. Schematic presentation of combining the Rankine process with SCRS

Theoretical designing of the model

Rankine process design

Primarily we need to define the operating points of the Rankine process. It is designed to operate between seven design points of compressing or expanding the working fluid media [15]. These design points are presented in the temperature-entropy diagram in fig. 2. Each design point of the Rankine process diagram has defined its own temperature and pressure. In tab. 1 temperature and pressure in each of the seven design points are presented.

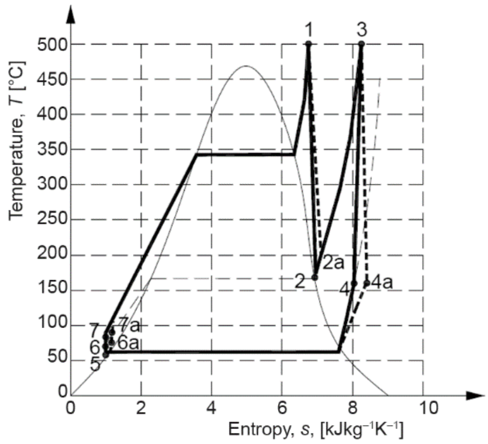

Figure 2. Rankine process in the temperature entropy diagram; the dashed lines and points 2a, 4a, 6a, and 7a present the irreversibility of turbine and pump processes; *1-2 – high pressure steam turbine expansion, 2-3 – steam reheating, 3-4 – low pressure steam turbine expansion, 4-5 condenser, 5-6 – condensate pump, 6-7 – steam boiler pump, 7-1 – steam boiler*

Table 1. Temperature and pressure parameters in corresponding design point of the Rankine process

State point	Temperature [°C]	Pressure [bar]	Additional process parameter
1	500	80	
2	155.2	4	$\dot{m}_{\text{steam}}$ = 30 kg/s
3	500	4	
4	153.5	0.2	$\dot{m}_{\text{fuel}}$ = 5.2 kg/s
5	54	0.2	
6	54	4	H_{fuel} = 20.94 MJ/kg
7	54	80	

The ideal and actual power of high 1-2 and low pressure steam turbines 3-4, as well as the total combined power of both steam turbines [16], are defined with the following equations:

$$P_{\text{ideal}} = \dot{m}_{\text{steam}}(h_i - h_{i+1,\text{ideal}}) \tag{1}$$

$$P_{\text{actual}} = \dot{m}_{\text{steam}}(h_i - h_{i+1}) \tag{2}$$

$$P_{\text{T,total}} = P_{\text{HPT,actual}} + P_{\text{LPT,actual}} \tag{3}$$

With these two previous two parameters, we can further define the energy efficiency of the high and low pressure steam turbines:

$$\eta_{\text{steam\_turbine}} = \frac{P_{\text{actual}}}{P_{\text{ideal}}} = \frac{h_i - h_{i+1}}{h_i - h_{i+1,\text{ideal}}} \tag{4}$$

The reheating of the steam from the exit of the high pressure steam turbine and before entering the low pressure steam turbine 2-3 is foreseen. The specific heat for reheating of the steam and the needed heat flux input is defined:

$$q_{\text{in}} = h_{i+1} - h_i \tag{5}$$

$$Q_{\text{in}} = \dot{m}_{\text{steam}} (h_{i+1} - h_i) \tag{6}$$

After the steam expansion in the low pressure steam turbine, the steam is led to the condenser 4-5, where the working media is fully condensed to water. In order to achieve that, we need to release heat flux out of the process cycle into the surroundings:

$$\dot{Q}_{\text{out,condenser}} = \dot{m}_{\text{medium}} (h_i - h_{i+1}) \tag{7}$$

Two pumps help to circulate the media in the cycle, condensate pump 5-6 and steam boiler pump 6-7. These two pumps are calculated the specific work of the pump and operating power.

$$W_{\text{pump}} = h_{i+1} - h_i \tag{8}$$

$$P_{\text{pump}} = \dot{m}_{\text{medium}} W_{\text{pump}} \tag{9}$$

From the steam boiler pump, the working media is further led through the steam boiler pump to a steam boiler, where the aggregate state of the working media is, with the help of the heat flux from burning fossil fuel, changed again from the water to steam 7-1:

$$q_{\text{in,boiler}} = h_i - h_{i+1} \tag{10}$$

$$\dot{Q}_{\text{boiler}} = \dot{m}_{\text{steam}} [(h_1 - h_7) + (h_3 - h_2)] \tag{11}$$

The energy efficiency of the steam boiler is defined with the equation below, where the $\dot{m}_{\text{fuel}}$ is the mass inflow of the fossil fuel in the steam boiler, and the H_{fuel} is the calorific value of the considered fossil fuel (coal), that is being burned in the steam boiler, for steam to drive the turbine:

$$\eta_{\text{boiler}} = \frac{\dot{m}_{\text{steam}} q_{\text{in,boiler}}}{\dot{m}_{\text{fuel}} H_{\text{fuel}}} \tag{12}$$

The energy efficiency of the Rankine process is defined with the help of the following equation:

$$\eta_{\text{Rankine}} = \frac{P_{T,\text{total}}}{\dot{Q}_{\text{boiler}}}, \quad \eta_{\text{Rankine}} < 1 \tag{13}$$

In order to define the exergy efficiency of the Rankine process [17], which gives us the degree of irreversibility of the process, the specific exergies e_i [18] in process points 1, 3, and 7 are defined. Based on calculated specific exergies, the exergy efficiency of the process is:

$$e_i = h_i - h_{\text{ambient}} - T_{\text{ambient}} (s_i - s_{\text{ambient}}) \tag{14}$$

$$\varepsilon_{\text{Rankine}} = \frac{P_{T,\text{total}}}{\dot{m}_{\text{steam}} (e_1 + e_3 - e_7)} \tag{15}$$

The high pressure steam turbine shaft output is 19.1 MW at 85% operating efficiency. The low pressure steam turbine shaft output is 20.8 MW at 90% operating efficiency. Combined steam turbines output on the shaft is expected to be 39.9 MW. This shaft is further driving the generator for electricity production purposes. The steam is heated in the steam boiler to 500 °C at 80 bar pressure. After the expansion of the high pressure steam turbine, the temperature and pressure are lowered to 155 °C and 4 bar. With the reheating of the steam, the temperature and pressure rise again at 500 °C and 80 bar. With the expansion of the steam in a low pressure steam turbine, the temperature and pressure reach the values of 153.5 °C at 0.2 bar. From the exit of the low pressure steam turbine, the steam is forwarded to the condenser. The water is further transported to the steam boiler with the support of the condensate and boiler pump. The condensate pump and boiler pump raise the pressure of the water from 0.2 bar to 4 bar and from 4 bar to 80 bar correspondingly. From there, the water is lead back to the steam boiler where it is steamed and send to the high and low pressure turbines. The general design parameters of the Rankine process are presented in tab. 2.

Table 2. General calculated and designed parameters of Rankine process

Parameter	Mark	Quantity	Unit
Steam boiler capacity	Q_{boiler}	116	MW
Condenser capacity	$Q_{\mathrm{condenser}}$	76.8	MW
High pressure steam turbine shaft power	$P_{\mathrm{HPT,\ actual}}$	19.0	MW
Low pressure steam turbine shaft power	$P_{\mathrm{LPT,\ actual}}$	20.9	MW
Steam turbine total shaft power	$P_{\mathrm{T,\ total}}$	39.9	MW
Energy efficiency of the Rankine process	η_{Rankine}	34.2	%
Exergy efficiency of the Rankine process	$\varepsilon_{\mathrm{Rankine}}$	54.6	%

Solar central receiver system design

The SCRS consists of a heliostat field and central tower on top of which the sunbeam receiver is positioned. Heliostats direct the sunbeams to one center point, where a high temperature of 500 °C is achieved, in order to heat up the working medium of the solar cycle – molten salt. Heated molten salt is further led to the heat exchanger between the Rankine process and SCRS, to generate the steam for the Rankine process’s high and low pressure steam turbines. When the conditions enable the steam production with the heat from the SCRS, the proportional smaller amount of fossil fuel consumption in the steam boiler is achieved. To define the rated capacity of the SCRS we need to consider the technical limitations of steam boilers. It is not advised to frequently turn down the steam boilers, since there is needed an extensive amount of the fuel (usually heating oil) for the steam boiler to start again, before loading the coal to the boiler as the main fuel. This process of starting up the steam boiler is costly for the operator because of the high heating oil market price. From that aspect, we designed the process in a manner, that steam boiler always operates with at least 50% up to 100% of its rated capacity. The steam boiler operates at 100% load when there is not available any sun irradiance. That gives the basis for the capacity design of the SCRS as schematically presented in fig. 3:

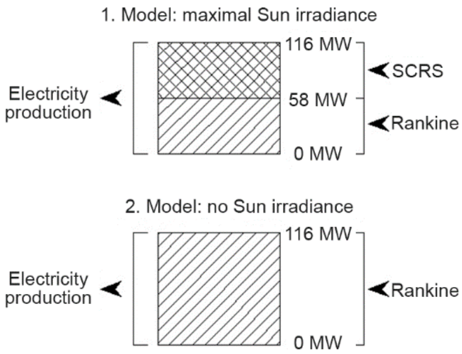

Figure 3. Schematic presentation of two possible scenarios for the proposed model operating with maximal Sun irradiance and with no sun irradiance

$$\dot{Q}_{\mathrm{SCRS}} = \delta_{\mathrm{solar\_share}} \dot{Q}_{\mathrm{boiler}} \tag{16}$$

When the needed net capacity of the SCRS is defined, we shall also define the total capacity of the solar part, due to its losses in the aspect of the heliostat field and solar receiver.

$$\dot{Q}_{\mathrm{total,SCRS}} = \frac{\dot{Q}_{\mathrm{net,solar}}}{\eta_{\mathrm{field}}\eta_{\mathrm{receiver}}} \tag{17}$$

Designing the SCRS is specific for every geographical location and it requires the individual approach [19]. Based on the chosen geographical location the design point irradiance (DPI) is defined, which tells the amount of Watts per square meter of the solar irradiance, that we can expect for the desired geographical location. With fixed design point irradiance, the total net surface of the heliostat reflective area can be determined.

$$A_{\mathrm{total,heliostats}} = \frac{\dot{Q}_{\mathrm{total,SCRS}}}{\mathrm{DPI}} \tag{18}$$

Based on eq. (19) and the design parameters of the individual heliostat, the total number of needed heliostats in the heliostat field can be defined with the eq. (20), where the total needed reflection area of the heliostat field is divided by reflection area of the one individual heliostat. When the number of heliostats in the heliostat field is defined, we design the positioning of the heliostats around receiver:

$$n_{\mathrm{heliostats}} = \frac{A_{\mathrm{total,heliostats}}}{A_{\mathrm{individual,heliostat}}} \tag{19}$$

In tab. 3 the general design parameters of the SCRS are gathered.

Table 3. General design parameters of the SCRS

Parameter	Mark	Quantity	Unit
Solar share	$\delta_{\mathrm{solar\_share}}$	50	%
Solar central receiver system capacity	$\dot{Q}_{\mathrm{SCRS}}$	58	MW
Heliostat field operating efficiency factor	η_{field}	0.75	–
Solar receiver operating efficiency factor	η_{receiver}	0.85	–
Total solar central receiver capacity due to losses	$\dot{Q}_{\mathrm{total,SCRS}}$	90.9	MW
Design point irradiance	DPI	790	W/m^2
Total surface of the heliostat field	$A_{\mathrm{total,heliostats}}$	115063	m^2
Surface area per one heliostat	$A_{\mathrm{individual,heliostats}}$	120	m^2
Number of needed heliostats in the heliostat field	$n_{\mathrm{heliostats}}$	958	pcs

Structuring the model in MATLAB SIMULINK

After theoretical designing and defining the operational parameters of both, Rankine and SCRS, the computer model of the complete presented system is designed. The computer model as a whole consists of sub-systems, where each sub-system presents the operating system element of the Rankine or SCRS. The schematic signal wiring diagram for the high pressure steam turbine and also the low pressure steam turbine is shown in fig. 4. Based on inlet and outlet temperatures and pressures for high and low and steam turbine, the real enthalpy on the inlet and outlet of turbines is defined. Parallel with real enthalpy also ideal enthalpy is defined. Quotient between the real shaft output and ideal shaft output of the steam turbine gives the operating efficiency of the steam turbine.

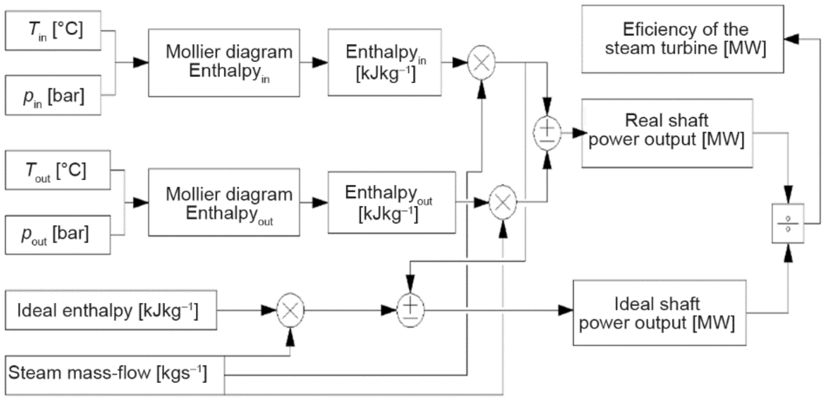

Figure 4. Schematic diagram for a high pressure steam turbine

After the steam expansion on the exit of the high pressure steam turbine, the reheating of the steam is next. The schematic diagram for the steam reheating sub-system is shown in fig. 5. The wiring diagram for this sub-system corresponds also to the condenser, condensate and also boiler pump with different parameters on the inlet and consequently different results on the outlet of the sub-system. The product between the difference of the real enthalpy on the outlet and the system steam mass-flow gives the needed heat flux of, for example, condenser, to successfully fully condensate the working media in the Rankine process. The thermal power of the steam boiler is defined with the sum of the differences of enthalpies in points 1, 7 and 2, 3, multiply by the system steam mass-flow, as shown in fig. 6. The steam boiler efficiency is defined with quotient between the product of the difference of enthalpies in points 1, 7, which is multiplied with system steam mass-flow, and the product between the calorific value of used coal and fuel mass-flow. The definition of the specific exergies in the system is also important since they define the exergy efficiency of the system. The exergy efficiency defines the irreversibility of the process. Fully reversible processes have exergy efficiency 1, fully irreversible processes have exergy efficiency 0. Specific exergy is defined in the

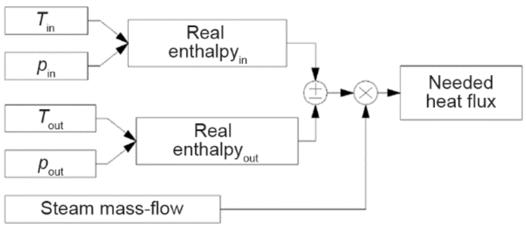

Figure 5. Schematic diagram for steam reheating between two turbines

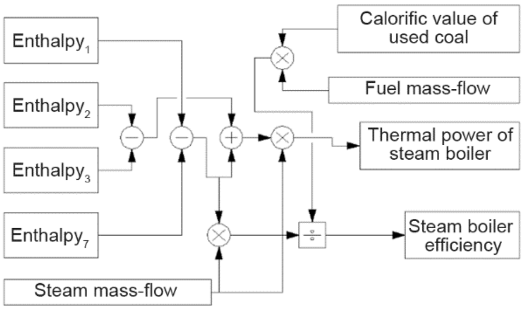

Figure 6. Schematic diagram for the definition of steam boiler thermal power capacity and efficiency

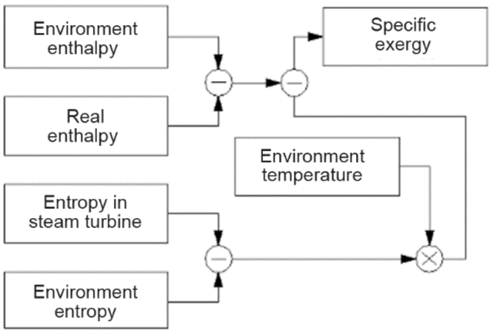

Figure 7. Schematic diagram for the definition of the specific exergy

following point of the process: 1 – an inlet of the high pressure steam turbine, 3 – an inlet of the low pressure steam turbine, 7 – an inlet of the steam boiler. Figure 7 shows the wiring diagram for the definition of the specific exergy in the system operational point 1 – an inlet of the high pressure steam turbine. In fig. 8, the diagram for the SCRS is presented. Based on the theoretical design of the SCRS, the maximal solar share in the system is determined, taking into consideration the chosen fossil fuel and steam boiler type with corresponding thermal capacity. Every system has its own losses, also the sub-system in fig. 8. Presumed losses are the heliostat field, central solar receiver efficiency, and parasite thermal system losses. When we apply the aforementioned losses to the net heliostat field thermal capacity, the total needed thermal capacity of the solar system can be defined. Based on that information and the surface area of each individual heliostat, we can further determine the number of the heliostats required in the heliostat field in order to supply the central solar receiver with a sufficient amount of concentrated solar irradiance. When the effective sun irradiance in the desired time-lapse for a chosen geographical location is specified, the amount of the electricity produced from the presented hybrid system can be defined. The more of the solar irradiance desired geographical location offers, the higher is the amount of heat obtained from the solar cycle. Hence, a lower supply of heat from the steam boiler is needed. That means lower fossil fuel consumption and consequently lower greenhouse emissions into our atmosphere. With lower greenhouse emissions, also the amount of greenhouse emissions coupons (in EU member states) is decreased, which is beneficially for the electricity consumer price. An important aspect of the

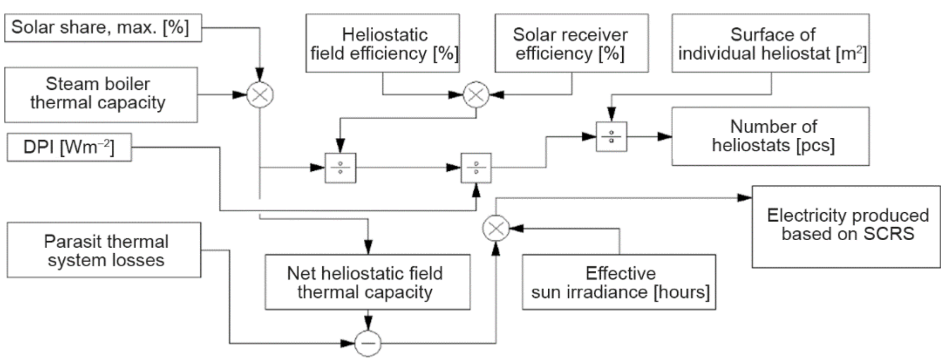

Figure 8. The SCRS schematic diagram

presented model is also economically sustainable operation of the existing, conventional thermal power plant. With the supply of the heat from a renewable source (Sun), the costs of the conventional power generation cycles are lowered, which results in achieving the economically favorable electricity production [20] and more competitive prices on the electricity market. Also, the negative environmental impact of the conventional thermal power plant is reduced since the CO_2 emissions and the dust pmx particles are lowered.

Results

The SCRS contributes the energy in the means of the heat from the irradiance of the sun. The Sun irradiance changes and is different for every geographical location. When designing our model, we included the solar irradiance of the city Velenje, Slovenia, where also other relevant energy production infrastructure is located. In fig. 9 the solar input of the SCRS is presented. It is presented as the average solar input through the daily cycle of the 24 hours of the corresponding month. As expected, the months with the highest solar input contribution are summer months from June to August. In the wintertime period is the solar input of the designed model correspondingly smaller. Through the warmer part of the year we can expect the solar input of the designed system up to 23 MW (highest peak in month August) and in the colder part of the year, approximately half of this value 10 MW (lowest peak in month December). The peak of the solar irradiance is achieved in the midday hours, the duration of the solar irradiance is dependent on the Sun path and the length of the day time period. To observe more detailed how the solar input from the SCRS affects the operation of the presented hybrid system, we formed fig. 10. The dotted trendline presents the coal consumption in the Rankine process when there is no interaction from the SCRS, so it presents the coal consumption of the conventional thermal power plant installation during the average yearly period. The solar share is presented as available MW from SCRS against the total MW capacity of both systems, expressed in percentages. From fig. 10, we can observe that the solar share input to the designed model for electricity generation is inversely proportional to the coal consumption in the conventional cycle [21]. The higher the solar share, the lower is coal consumption. For low coal consumption is beneficial to achieve as high solar share input as possible. By this, we are limited with the space available around the existing conventional thermal power plants for the purpose of solar central receiver heliostat field placement. Another limitation is also available sun irradiance of the chosen geographical location. Figure 11 presents

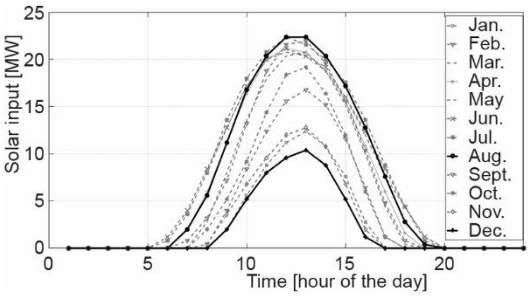

Figure 9. Solar input of the SCRS as the function of the solar irradiance for the chosen geographical location and expected power production from the solar part of the designed model: *Source of data for solar irradiation: https://meteo.arso.gov.si/met/sl/climate*

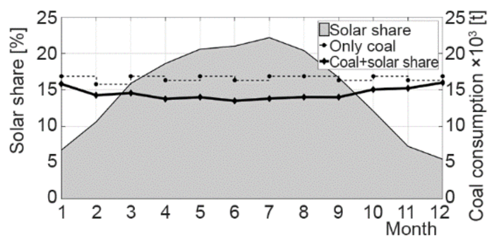

Figure 10. Solar share *vs.* coal consumption for the designed analyzed model; the dotted trendline presents the reference as coal consumption of the conventional thermal power plant without a SCRS

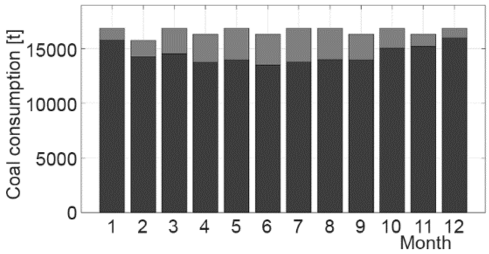

Figure 11. Coal consumption without and with a SCRS attached to the conventional thermal power plant; light colored top of the bar marks the saved amount of coal

the comparison between the coal consumption of the conventional thermal power plant *vs.* our proposed model that adopts a SCRS. The light colored tops of the bars in chart mark the coal consumption savings of the presented hybrid system. The total amount of coal saved in our analyzed case would be 25227 tonnes of coal on a yearly basis. Assuming the average price for the one tonne of coal at 68.5 €, the savings would be 1.72 M €. Furthermore, with less burned fossil fuel, also less carbon dioxide is emitted into the atmosphere. Corresponding to the amount of the coal that is saved and not burned in the steam boiler, because the energy obtained from the SCRS substitutes it, the CO_2 emission is lowered by 38635 tones on yearly basis. As aforementioned, it is market-driven. Government regulator is lowering the amount of the coupons available for the polluters on a yearly basis, therefore the prices of the coupons are rising. The price of the emission coupon which allows emitting one tonne of carbon dioxide to our atmosphere has raised to 25 € per ton. With that price of the emission coupons, also that cost is no longer irrelevant for the thermal power plant operation. Applying market price of the emission coupons to the amount of the CO_2 emissions that would be emitted to the atmosphere from the thermal power plant without the SCRS, we can conclude, that savings of 0.96 M € can be achieved, from the aspect of not purchasing the emission coupons. The total economic benefit of the revitalization model is mainly dependent on the amount of saved fossil fuel and CO_2 emission coupons. Together, they can result in 2.68 M € of thermal power plant operational cost savings per year, for the presented corresponding model. The investment costs for the proposed system are defined as follows: direct costs of heliostats 17.298 M € (concrete, steel constructions, mirrors, electrical drives), indirect costs of heliostats 1.250 M € (designing, production, assembly, construction machinery), and cost of equipment for energy conversion 31.5 M € (reservoirs, heat exchanger, control system). The summary of investment costs is 50.048 M €.

Conclusions

The changes in the electricity production and supply market dictate the changes to which the electricity producer needs to adapt. With decreasing electricity production from conventional power plants, we need to find other sources of electricity production. As seen in the past decade, we substitute the production of electricity from fossil fuel-based power plants with solar and wind power plants. However, for the stable and reliable energy and electricity distribution network, the presence of conventional thermal power plants is crucial. In this paper, we proposed and designed the model on how to upgrade and adjust the conventional thermal power plants with the Rankine process to the new environmental demands on the energy market. The proposed model was designed in the MATLAB SIMULINK software environment and the behavior simulation and performance results were numerically and graphically presented. For the chosen geographical location, the given simulated results are promising. The coal consumption is lowered around 25000 tonnes, and CO_2 emissions are lowered for around 38600 tones. There are presented limitations of the model, such as ensuring sufficient space around the premises and geographical location with sufficient Sun irradiance for the optimal design and operation of the proposed model. The energy from the Sun is free and we should exploit this free energy as much as possible. The proposed model of upgrading our current thermal power plants is environmentally acceptable since it does not produce any harmful gases and emissions into the environment and air. The model can be adopted by any existing electricity production facility that is based on the Rankine process, taking into consideration the previously stated constraints that may apply to each individual location of the existing thermal power plant.

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