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ANALYSIS OF REVITALISATION MODEL BEHAVIOUR FOR THERMAL POWER PLANTS IN DIFFERENT GEOGRAPHICAL AREAS

ANALIZA ODZIVANJA REVITALIZACIJSKEGA MODELA TERMOENERGETSKA POSTROJENJA NA RAZLIČNIH GEOGRAFSKIH LOKACIJAH

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Abstract

The implementation of renewable sources for electricity production into the energy portfolio of European countries has been a priority in recent years, especially taking into account the current geo-political changes. Even though coal is the fuel of the past, its use cannot be put aside that easily; firstly, because of the high fluctuation of electricity production from renewable sources, and secondly because of the possible negative economic impact on the economy resulting from a change in electricity prices when exiting coal. Based on the Rankine process, the authors of this paper designed a solar tower installation with a heliostat field, which enables electricity production based on solar irradiation. This combination also foresees an additional installation for flue gas desulphurisation. This combination of three processes is named the 'revitalisation model' for thermal power plants (TPPs). Based on the computer model and energy market parameters, the authors tested the 'revitalisation model' for pessimistic and optimistic scenarios. In the scope of the paper, the authors analyse the performance of the proposed 'revitalisation model' for three different

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geographical locations – Berlin in Germany, Wuwei in China, and Hyderabad in India. The results of the analysis are described and shown graphically.

Povzetek

Uvajanje obnovljivih virov za proizvodnjo električne energije v energetski portfelj evropskih držav je v zadnjih letih postala prednostna naloga, še posebej zaradi spreminjajočih se geopolitičnih razmer. Premog je gorivo preteklosti, vendar ga ne moremo tako zlahka opustiti. Vodila razloga za to sta veliko nihanje proizvodnje električne energije iz obnovljivih virov in negativni ekonomski vpliv na gospodarstvo, ki bi ga lahko povzročila sprememba cen električne energije s prenehanjem uporabe premoga. Zraven obstoječega procesa Rankine smo zasnovali instalacijo solarnega stolpa s heliostatskim poljem, ki omogoča proizvodnjo električne energije na osnovi sončnega obsevanja. V tej kombinaciji smo tudi predvideli dodatno napravo za razžveplanje dimnih plinov. Ta tri-fazni proces smo poimenovali revitalizacijski model termoenergetskih postrojenj. Na podlagi računalniškega modela in parametrov energetskega trga smo preizkusili model revitalizacije za pesimistični in optimistični scenarij. V članku bomo analizirali uspešnost predlaganega modela revitalizacije za tri različne geografske lokacije – Berlin v Nemčiji, Wuwei na Kitajskem in Hyderabad v Indiji – ter prikazali rezultate analize v pisni in grafični obliki.

1 INTRODUCTION

The proposed 'revitalisation model' comprises three main elements that make up the entire proposed plant. The first component is the Rankine process [1], which represents an existing thermal power plant and has a certain operational energy and exergy efficiency in the process [2]. Coal is the primary fuel of the Rankine process (or steam process). The combustion of coal in a steam boiler releases heat, which generates steam, which is fed into a steam turbine where a shaft drives a generator for electricity production. The second component is the solar power plant, which consists of a solar tower on which the concentrated sunbeam receiver is located, and a field in which heliostatic mirrors are arranged to direct the sun's rays to a common point on the concentrated sunbeam receiver [3-5]. All the absorbed solar energy is concentrated at a certain point, thus obtaining a high temperature and consequently a high concentration of energy at a point on the solar radiation receiver. The working medium in a solar tower plant is a salt solution, which can be heated to a higher temperature than the evaporation temperature of the water. This energy (heat) is used in the evaporator to produce steam, which is conducted from the solar process back to the steam process [6]. This reduces the amount of steam that the steam boiler needs to produce to be able to run the high-pressure and low-pressure steam turbines, which rotate the generator shaft to produce electricity. This enables the energy of solar radiation [7-8] to be used to produce steam, and the load of the steam boiler in the production of steam during solar radiation can be reduced proportionally [9-13] by the amount of steam that can be produced from the solar process. Due to the lower load and production of steam from the steam boiler, the consumption of coal – a fossil fuel – is also reduced, which also reduces the required amount of carbon emission coupons, as the amount of flue gases and greenhouse gas emissions is lower at the lower load of the steam boiler in the steam process.

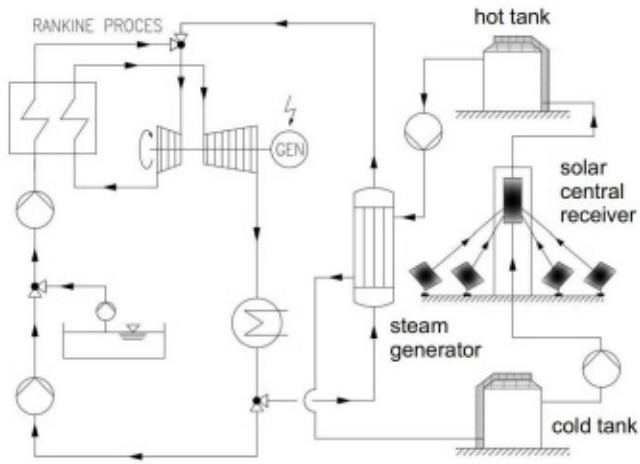

Figure 1: *The proposed 'revitalisation model' combines the traditional Rankine cycle with a solar central receiver system*

The third component of the proposed model of the revitalisation of TPPs is a plant for flue gas cleaning using the wet calcite process, which is most often identified as the best solution based on the guidelines for selecting the best possible technology. The purpose of the plant is primarily to reduce the acidic components in the flue gases and consequently reduce the impact on the environment and living beings. The advantage of the wet process is the cheap and easily accessible reagent as well as the integrity for the environment of the flue gas cleaning by-product and the specimen in it. Properly designed desulphurisation technology can achieve both high levels of purification of acidic components – sulphur dioxide as well as other air pollutants such as dust and some heavy metals [14-15]. As a by-product of flue gas cleaning, gypsum is formed, which can be used for commercial purposes (possible purchase from cement plants and gypsum board manufacturers), or it can be used to stabilise fly ash from the bottom of the steam boiler.

2 OPTIMISTIC AND PESSIMISTIC OPERATION SCENARIOS FOR THE CHOSEN GEOGRAPHICAL LOCATIONS

2.1 Geographical location Velenje, Slovenia

Figure 2, shown below, illustrates the economic performance of the proposed model. As can be seen, with the help of solar energy [16-18], the proposed model is profitable when taking into consideration the optimistic scenario, which covers all the costs of fossil fuels, the flue gas cleaning process, infrastructure maintenance and other regular maintenance costs. In this case, the proposed model would still generate EUR 1,075,400.00 in annual profit. In the figure below, the optimistic scenario is represented by the deletion-related dots and the corresponding right y-axis. The sum of monthly net profits from electricity sales is the annual economic result of the considered scenario.

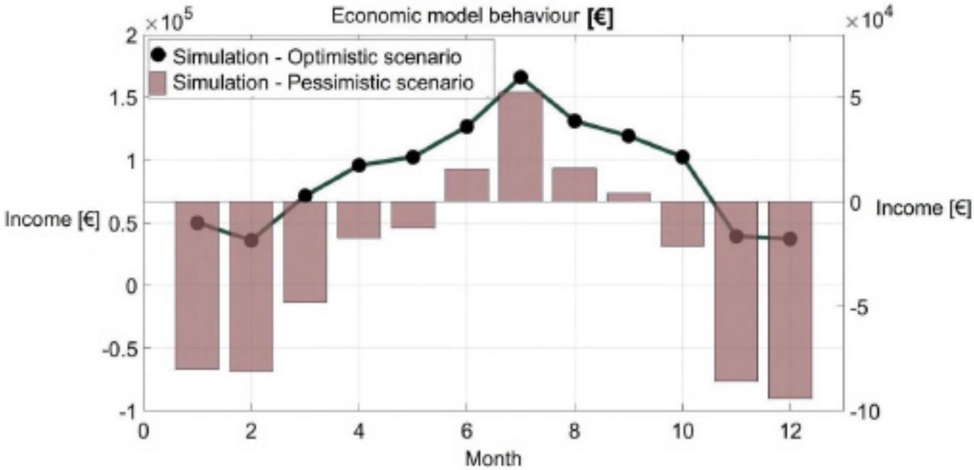

Figure 2: *Economic behaviour of the proposed 'revitalisation model' for the geographical location of Velenje, Slovenia*

Taking into account the pessimistic scenario, the costs of allowances for CO_2 emissions must be added to all the aforementioned costs, as they are a form of taxation for the operation of TPPs. In the case of the pessimistic scenario, assuming that the price of CO_2 emission allowances is expected to be higher with each additional year that a TPP operates, the model would generate EUR 353,050.00 in losses per year. This is not a bad achievement, as, without a central solar tower system, the annual loss of a TPP would be even greater.

As illustrated in Figure 2, the pessimistic scenario is shown with columns and the corresponding left y-axis. The sum of monthly net profits from electricity sales is the annual economic result of the pessimistic scenario under consideration. The proposed model and its economic benefits will play an important role in the transition from conventional fossil fuels to renewable energy sources (RES), as it would allow the simultaneous production of electricity from thermal power and renewable sources – a central solar power plant, thus maintaining a stable electricity distribution network and reducing the consumption of, and dependence on, fossil fuels.

2.2 Geographical location Wuwei, China

For the location of the city of Wuwei, China, effective solar irradiance is shown in Figure 3. Figure 4 illustrates the pessimistic and optimistic scenarios for the chosen location. Table 1 represents the income per corresponding month for the optimistic and pessimistic scenarios.

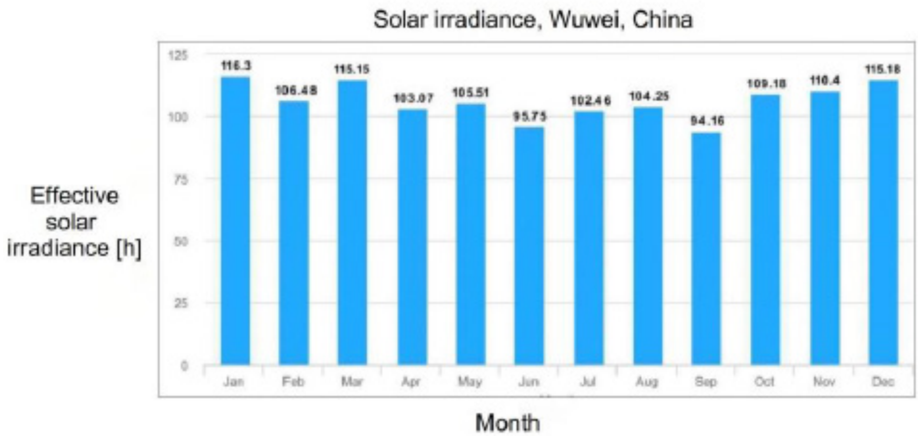

Figure 3: *Effective solar irradiance by month for the geographical location of Wuwei, China [19]*

In Figure 3, it can be seen that the effective sun irradiance expressed in hours per month is equally spread across the whole year. In Figure 4, where the realisation of the model is presented (pessimistic and optimistic scenarios) the operation of the model in the summer months is not that promising, due to the regular monsoon periods during the summer months.

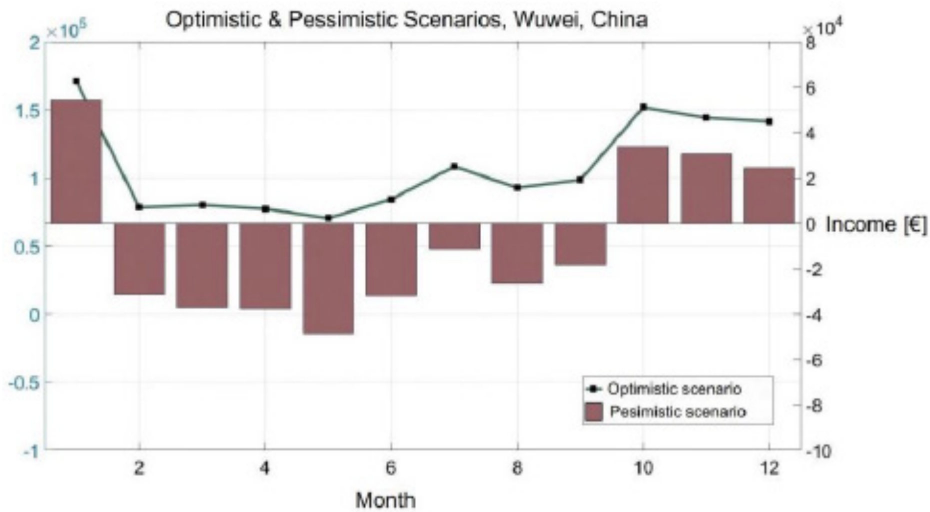

Figure 4: *Economic behaviour of the proposed 'revitalisation model' for the geographical location of Wuwei, China*

***Table 1:** Economic values of model operation for an individual month in the case of optimistic or pessimistic scenarios*

Month	Optimistic scenario [€]	Pessimistic scenario [€]
January	171,020.00	54,138.00
February	78,180.00	-31,591.00
March	80,020.00	-37,073.00
April	77,160.00	-37,709.00
May	70,310.00	-48,579.00
June	84,280.00	-31,960.00
July	108,230.00	-11,227.00
August	92,710.00	-26,416.00
September	98,430.00	-18,101.00
October	151,820.00	33,619.00
November	140,403.00	30,524.00
December	141,340.00	24,256.00
TOTAL:	**1,293,903.00**	-100,119.00

2.3 Geographical location Berlin, Germany

For the location of the city of Berlin, Germany, effective solar irradiance is shown in Figure 5. Figure 6 illustrates the pessimistic and optimistic scenarios for the chosen location. Table 2 shows the income per corresponding month for the optimistic and pessimistic scenarios.

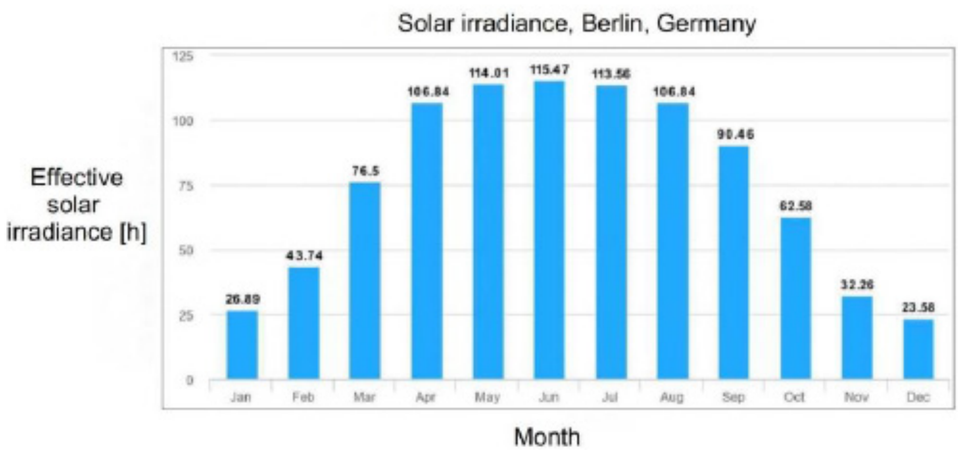

***Figure 5:** Display of the time of effective solar radiation for the city of Berlin, Germany [20]*

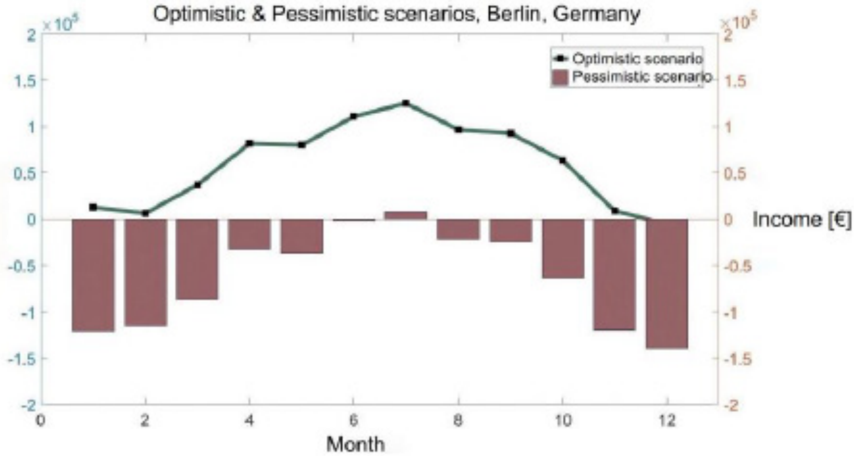

Figure 6: *Optimistic and pessimistic operating scenarios for the city of Berlin*

Table 2: *Economic values of model operation for an individual month in the case of optimistic or pessimistic scenarios*

Month	Optimistic scenario [€]	Pessimistic scenario [€]
January	12,650.00	-120,500.00
February	6,100.00	-115,350.00
March	36,780.00	-87,510.00
April	81,600.00	-32,580.00
May	79,940.00	-37,360.00
June	110,730.00	-1,840.00
July	125,020.00	7,630.00
August	96,470.00	-20,220.00
September	92,610.00	-24,610.00
October	63,230.00	-63,650.00
November	8,570.00	-119,490.00
December	-5,490.00	-139,640.00
TOTAL:	**708,210.00**	-755,120.00

2.4 Geographical location Hyderabad, India

For the location of the city of Hyderabad, India, effective solar irradiance is shown in Figure 7. Figure 8 illustrates the pessimistic and optimistic scenarios for the chosen location. Table 3 represents the income per corresponding month for the optimistic and pessimistic scenarios.

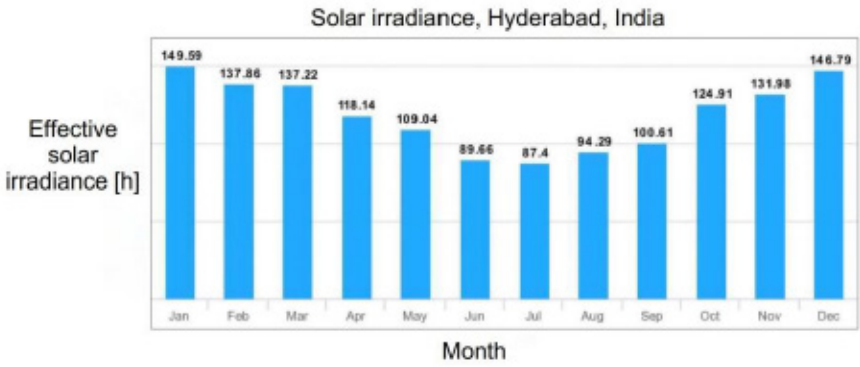

Figure 7: *Display of the time of effective solar radiation for the city of Hyderabad, India [21]*

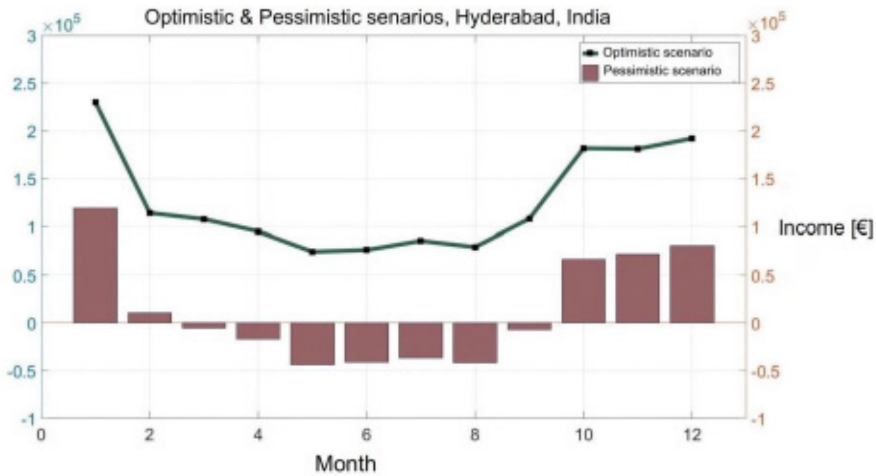

Figure 8: *Optimistic and pessimistic operating scenario of the model for the Hyderabad site*

Table 3: *Economic values of model operation for an individual month in the case of optimistic or pessimistic scenarios*

Month	Optimistic scenario [€]	Pessimistic scenario [€]
January	230,010.00	119,330.00
February	114,300.00	10,380.00
March	107,820.00	-5,170.00
April	95,180.00	-16,890.00
May	74,370.00	-43,860.00
June	76,250.00	-41,120.00
July	85,690.00	-36,570.00

August	79,260.00	-41,720.00
September	108,340.00	-6,990.00
October	181,880.00	66,610.00
November	181,270.00	71,178.00
December	192,150.00	80,940.00
TOTAL:	**1,526,520.00**	156,118.00

3 REVITALISATION MODEL RESPONSE FOR CHANGED MARKET PARAMETERS

The designed model was further analysed by considering the following parameters for the geographical location of the cities of Berlin, Hyderabad and Wuwei:

- number of hours of effective solar radiation
- local coal price
- the price of electricity for the country in which the selected geographical location is located
- the price of carbon dioxide emissions if such a taxation scheme is located in the country of the selected geographical location

3.1 Geographical location Wuwei, China

For the geographical location of Wuwei, China, when analysing the behaviour of the model, the authors considered the change in parameters that depend on local regulations and limits, as shown in Table 4.

Table 4: *Display of considered changed parameters for the location of Wuwei, China*

Parameter	**Quantity**	**Unit**
Coal price	**60.00**	[€ / t]
CO_2 emission coupon price	**/**	[€ / t]
Salaries	**9.50**	[€ / h]
Electricity price	**82.00**	[€ / MWh]

Figure 9 and Table 5 show the graphically and numerically expected realisation of the considered model for the selected location of Wuwei.

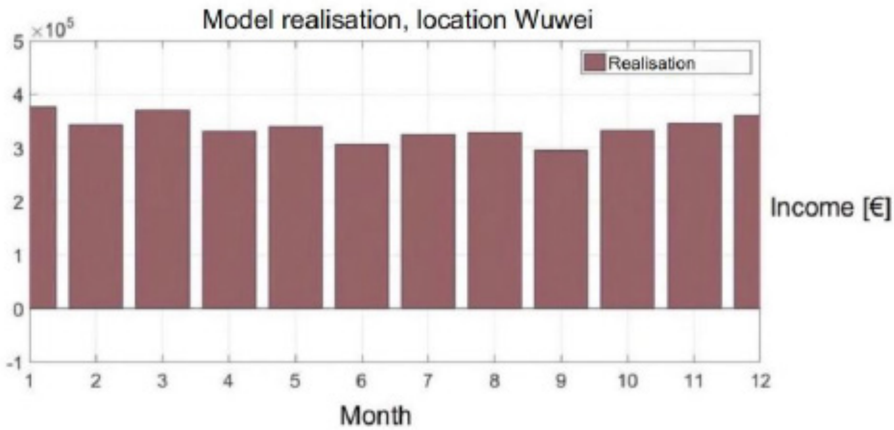

***Figure 9**: Display of the expected realisation of the model based on the changed entry parameters for the location of Wuwei*

***Table 5**: Numerical representation of the expected realisation of the realistic scenario according to the changed entry parameters for the location of Wuwei*

Month	Realistic scenario [€]
January	375,650.00
February	343,480.00
March	370,990.00
April	332,130.00
May	339,600.00
June	307,160.00
July	325,540.00
August	329,490.00
September	294,720.00
October	332,680.00
November	346,000.00
December	360,770.00
TOTAL	4,058,210.00

3.2 Geographical location Berlin, Germany

For the geographical location of Berlin, the analysis of the model behaviour took into account the change in parameters that depend on local regulations and limits, as shown in Table 6.

***Table 6**: Display of considered changed parameters for Berlin, Germany*

Parameter	Quantity	Unit
Coal price	**51.00 – 85.00**	[€ / t]
CO_2 emission coupon price	**25.00**	[€ / t]
Salaries	**30.00**	[€ / h]
Electricity price	**120.00**	[€ / MWh]

***Figure 10**: Illustration of the expected realisation of the model with changed input parameters for the location of Berlin*

***Table 7:** Numerical representation of the expected realisation of the realistic scenario according to the changed entry parameters for the location of Berlin*

Month	Realistic scenario [€]
January	-507,000.00
February	-362,090.00
March	-217,830.00
April	-19,180.00
May	320.00
June	31,700.00
July	530.00
August	-39,210.00
September	-110,040.00
October	-289,830.00
November	-441,730.00
December	-510,920.00
TOTAL	-2.465,280.00

3.3 Geographical location Hyderabad, India

For the geographical location of Hyderabad, the analysis of model behaviour took into account the change in parameters that depend on local regulations and constraints, as shown in Table 8.

Table 8: Display of considered changed parameters for Hyderabad, India

Parameter	Quantity	Unit
Coal price	**70.00**	[€ / t]
CO_2 emission coupon price	**/**	[€ / t]
Salaries	**8,35**	[€ / h]
Electricity price	**95.00**	[€ / MWh]

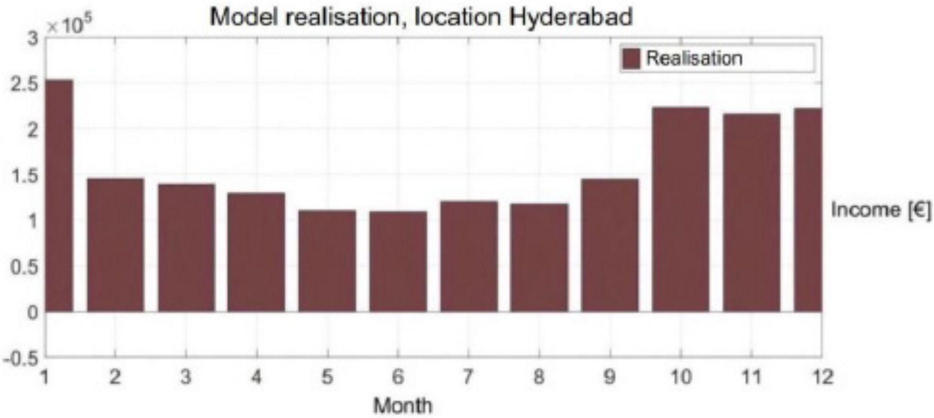

***Figure 11**: Illustration of the expected realisation of the model with changed input parameters for the location of Hyderabad*

***Table 9:** Numerical representation of the expected realisation of the realistic scenario according to the changed entry parameters for the location of Hyderabad*

Month	Realistic scenario [€]
January	252,980.00
February	145,090.00
March	139,520.00
April	128,810.00
May	110,130.00
June	108,970.00
July	120,440.00
August	117,770.00
September	144,400.00
October	223,240.00
November	215,090.00
December	221,840.00
TOTAL	**1,928,280.00**

3 CONCLUSION

Table 10 summarises the results of the considered model for different geographical locations and parameters. The results for two different cases are summarised and shown for three additional locations – Wuwei, Berlin and Hyderabad,. The first example takes into account the change of geographical location only and the consequent change of hours of effective solar radiation. The second example involves changing several parameters. In addition to changes in geographical location, local fuel (coal) prices, local electricity prices, and local labour or personnel prices are also taken into account. When analysing the operation of the plant, it was found that due to high fuel costs, the production of electricity exclusively from steam generated by a steam boiler is unprofitable. Thus, the contribution of the central receiver system (CRS) is essential for the cost-effective operation of the assumed model. As demonstrated by the positive operating scenario, the proposed system would achieve positive market results in the current market situation. In the case of the pessimistic scenario, the system would only operate profitably for four months a year, which is a low amount, however, it should be noted that most TPPs operate at a loss and the state provides financial assistance for uninterrupted electricity production. The pessimistic scenario shows a positive impact of upgrading the CRS system, as the loss at the annual level of operations is reduced almost 10-fold.

Table 10: *Results of the considered model for different geographical locations and parameters*

PARAMETER	Location						
	Velenje	Wuwei		Berlin		Hyderabad	
		①	②	①	②	①	②
Effective sun irradiance [h]	1,112.3	1,267.9	1.267,9	912.7	912.7	1,427.5	1,427.5
Coal savings [t]	25,227	28,984	28.982	20,742	20.701	32,377	32,375
Amount of emitted CO2 [t]	266,508	260,000	260.757	273,300	273.441	255,500	255,538
Amount of cleaned SO2 [t]	111.8	109	109,3	114	114.6	107	107.2
Optimistic scenario [mio €]	**1.07**	**1.29**	**4,05**	**0.71**	**-2.46**	**1.52**	**1.92**
Pessimistic scenario [mio €]	**-0.35**	**-0.10**	/	**-0.75**	/	**0.15**	/

*① - Results of the considered model at the changed geographical locations (number of hours of effective solar radiation)

*② - The results of the considered model with the following parameters changed:

- Number of hours of effective solar radiation
- Consideration of the local coal price
- Observance of the local electricity price
- Taking into account the local price of labour or employees

The model represents a possible upgrade and modernisation of conventional TPPs to ensure an uninterrupted supply of electricity even in the event of an increased disruption in the thermal power system due to the production of electricity from renewable sources. Rising fossil fuel prices, and limiting them, will increase interest in the implementation of the model described and similar solutions.

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Nomenclature

(Symbols)	(Symbol meaning)
t	time
h	hour
CO_2	carbon dioxide
SO_2	sulphur dioxide
€	euros
mio	million
GEN	generator
MWh	megawatt hour