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ENERGO-ECONOMICS PAYBACK INVESTMENT CALCULATION MODELLING OF GAS-STEAM COMBINED CYCLE POWER PLANT

ENERGETSKO-EKONOMSKO MODEL VRAČILNE DOBE PLINSKO-PARNE ELEKTRARNE S KOMBINIRANIM PROCESOM

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Abstract

The paper deals with energo-economic payback calculation modelling of the combined gas-steam cycle operation, demonstrating the basic characteristic properties of cycle behaviour in different operating regimes and calculating the payback period of the investment. The calculation of the payback period of the investment is based on the calculation of the net present value and with actual obtaining data sets from a recently built gas-steam combined cycle power plant. The results of the calculation modelling show that the gas-steam combined cycle power plant can achieve a useful efficiency of up to 88% in the back-pressure operation of the steam turbine. The useful efficiency of the gas turbine is up to 40%. The payback period of the investment depends on the investment costs, the quantity and market price of the consumed fuel, the quantity

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and market price of the generated electricity and thermal energy. The results show that with a price ratio fuel/electricity of 0.36, the payback period of the investment is 4 years, with a price ratio fuel/electricity of 0.54, the payback period of the investment is as much as 17 years.

Povzetek

Prispevek obravnava energetsko-ekonomski model izračuna vračila delovanja kombiniranega plinsko-parnega cikla s prikazom osnovnih značilnih lastnosti obnašanja cikla v različnih režimih obratovanja in izračunom vračilne dobe investicije. Izračun vračilne dobe investicije temelji na izračunu neto sedanje vrednosti in ob dejanskem pridobivanju nizov podatkov iz nedavno zgrajene plinsko-parne kombinirane elektrarne. Rezultati računskega modeliranja kažejo, da lahko plinsko-parna elektrarna pri protitlačnem obratovanju parne turbine doseže koristni izkoristek do 88 %. Koristni izkoristek plinske turbine je do 40 %. Vračilna doba investicije je odvisna od stroškov investicije, količine in tržne cene porabljenega goriva ter količine in tržne cene proizvedene električne in toplotne energije. Rezultati kažejo, da je pri cenovnem razmerju gorivo/elektrika 0,36 vračilna doba investicije 4 leta, pri cenovnem razmerju gorivo/elektrika 0,54 pa kar 17 let.

1 INTRODUCTION

The construction of new thermal energy systems enables the conversion of internal fuel energy into electricity and thermal energy in a more environmentally friendly way. In energy conversion, ecological awareness in thermal power plants is mainly reflected in the appropriate choice of fuel. To this end, more environmentally friendly processes are increasingly being used in practical applications, which enables the combined conversion of electricity and thermal energy using natural gas. [1] Such a cycle is called a gas-steam combined cycle power plant (*GSCCP*). *GSCCP* consists of a gas turbine (*GT*), a heat recovery steam generator (*HRSG*), a steam turbine (*ST*) and a thermal station for district heating (*DH*). [2] Some other authors also researched the environmental and ecological influences of using of different types of fuels for heat and power generated by *GSCCP*. Luis et al. presented the energy-ecologic efficiency of waste-to-energy plants and carried out the influence of emission abatement and biogenic carbon offset due to biomass regrowth regarding waste-fired plants. [3] Skorek-Osikowska et al. analysed thermodynamic and ecological assessment of selected coal-fired power plants integrated with carbon dioxide capture where they discovered that the post-combustion system allowed for a reduction of the value of the average annual carbon dioxide (CO_2) emission rate aggravating the unit of net electricity produced for 735 kg CO_2/MWh [4]. Silveira et al. studied the ecological efficiency and thermoeconomic analysis of a cogeneration system at a hospital. [5] In reviewing the scientific literature, we have not yet found a paper analysing the energo-economics payback investment model of *GSCCP*.

The *GT* consists of a compressor part, combustion chambers, a turbine part and a generator of *GT*. The compressor part of the *GT* is used to compress the air, which then enters the combustion chambers. Combustion chambers are used for the combustion of natural gas or for the chemical process of converting the internal energy of natural gas into thermal energy. [6] Thermal energy is used to increase the enthalpy value of compressed gas. After the combustion process, compressed gases with increased enthalpy value or flue gases enter the turbine part of *GT*. In the turbine part of the *GT*, the thermal energy of the flue gases is converted into mechanical energy, which is converted into electrical energy by means of the *GT* generator. The flue gases are discharged from the turbine part of the *GT* to *HRSG GT* at a temperature of approx. 560 °C. [7] The main purpose of *HRSG* is to use the residual heat energy of flue gases for the production of high pressure (*HP*) steam, the production of low pressure (*LP*) steam, and for the production of heat for district heating (*DH*). The remaining unused flue gas heat is discharged from the *HRSG* to the surroundings via a chimney at a temperature of approx. 75 °C. [8]

At a pressure of approx. 95 bar and a temperature of approx. 520 °C, *HP* steam is discharged from *HRSG* to a steam turbine (*ST*), where the thermal energy of *HP* steam is converted into mechanical energy, which is converted by means of generator *ST* into electricity. *LP* steam is discharged from *HRSG* to industrial consumers at a pressure of approx. 9 bar and a temperature of approx. 260 °C. The amount of *DH* thermal energy from the *HRSG* depends on the flue gas temperature in the chimney, as the *HRSG DH* system maintains the flue gas temperature above the condensing flue gas temperature which is approx. 75 °C.

ST plant consists of an expansion cylinder, a generator part and a *DH* system. A special feature of the *ST* plant is the backpressure mode of operation, as the *ST* plant does not have a condenser. This means that all the outlet steam from the expansion cylinder is used to generate *DH* heat. A schematic representation of the operation of the *GSCCP* is shown in Fig. 1.

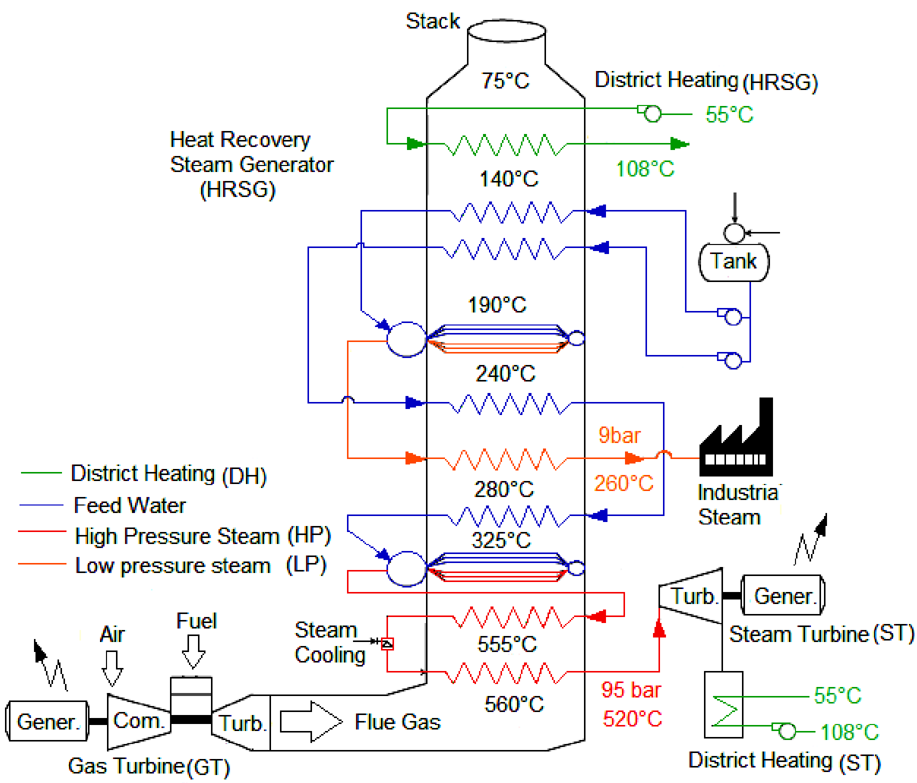

***Figure 1**: A schematic representation of the operation of the GSCCP.*

Other authors have also researched the *GSCCP* thermodynamics operation concepts. Maheshwari et al. studied thermodynamic different configurations of gas-steam combined cycles employing intercooling and different means of cooling in the topping cycle. [9] With vapour absorption inlet air-cooling, Shukla et al. researched thermodynamic investigation of parameters affecting the execution of steam injected cooled gas turbine-based combined cycle power plant. [10] Kafaei et al. researched the best angle of hot steam injection holes in the steam turbine blade cascade. [11] Srinivas et al. carried out sensitivity analysis of steam-injected gas turbine-based combined cycle with dual pressure *HRSG* [12]. When reviewing the literature, we found no paper describing the payback investment models of *GSCCP* with actually obtaining data sets from the recently built plant.

The data sets are obtained from the supervisory control and data acquisition (*SCADA*). [13] *SCADA* continuously, 24 hours a day and 365 days a year, records the most important data sets of the *GSCCP* operation. [14]

The innovation, originality, and contribution to the new knowledge; however, are expressed in the validated energo-economics payback investment calculation modelling of *GSCCP* with actually obtained data from *SCADA* by the recently-built plant. The recently-built plant is located in the middle of Slovenia, which lies in southern central Europe, Fig. 2.

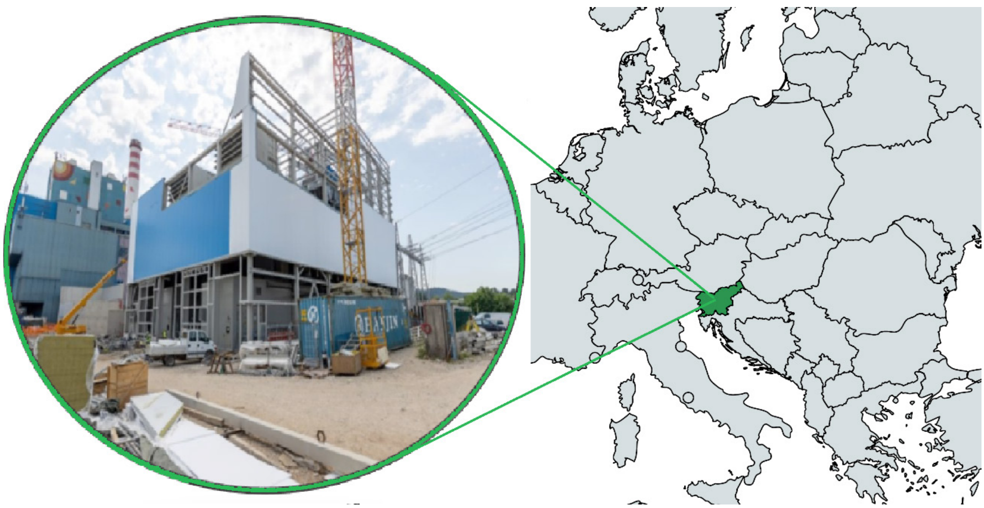

Figure 2*: The recently-built GSCCP in the middle of Slovenia.*

This paper first presents the operation of the system, before turning its attention to the presentation of the energo-economics payback investment calculation model, actual data sets filtration and model validation. Following this, the results are presented. Finally, the concluding part presents the most important findings and discussion.

2 ENERGO-ECONOMICS PAYBACK INVESTMENT CALCULATION MODEL

The energo-economics payback investment calculation model consists of auxiliary units and calculation units. The auxiliary unit of input data contains the database of electric power of the *GT* generator (P_{GTe}), which represents a set of input data to the energo-economic calculation model.

Using a set of input data, the *GT* calculation unit calculates the characteristic properties of *GT* operation, such as consumption and power of natural gas *GT* useful efficiency, etc. The *HRSG* calculation unit calculates the amount of generated *HP* steam, the amount of generated *LP* steam and the amount of generated heat for *DH* using the data obtained from the input unit and the data obtained from the *GT* calculation unit. The results of the *GT* calculation unit and the results of the *HRSG* calculation unit enter the *ST* calculation unit and the calculation unit of the payback period of the investment. All the results of all calculation units are finally combined in a results report monitoring unit. A schematic representation of the operation of the energo-economics payback investment calculation model is shown in Fig. 3.

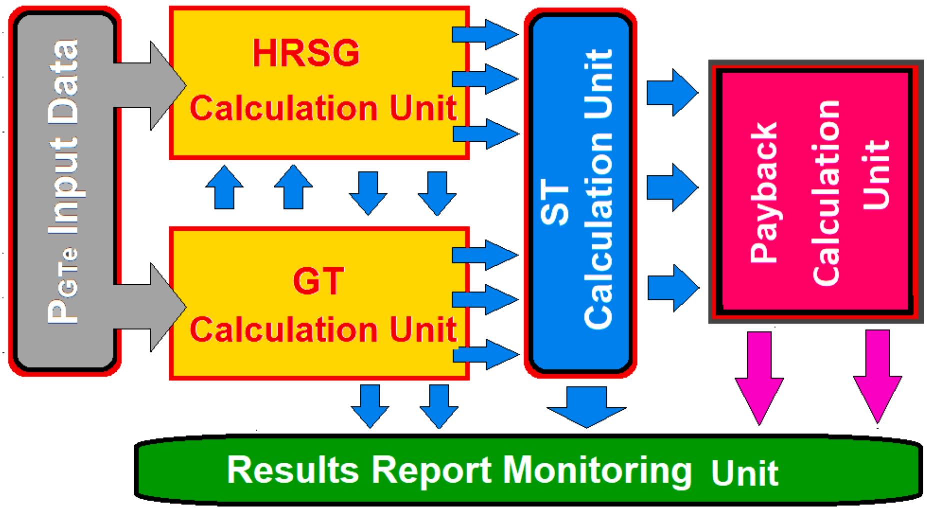

Figure 3: *Schematic representation of the energo-economics payback investment calculation model.*

The energo-economic calculation model is made using actual data sets obtained from *SCADA.* In addition to the consumption of natural gas for *GSCCP* operation, it also calculates the total amount of generated electricity and thermal energy of *GSCCP*, *GT* useful efficiency, *ST* useful efficiency, total *GSCCP* useful efficiency, etc. Beyond the stated values, the mathematical model also calculates the energy flows generated in 5400 hours of *GSCCP* operation. The auxiliary *ST* calculation unit contains an artificial neural network (*ANN*), that calculates the *ST* exhaust steam thermodynamic properties in dependence on the *ST* entering steam quantity and quality. The *ANN*, feed-forward type, is aimed at identifying and modelling the complex nonlinear relationships between the input and the output target of a system. [15] The *ANN* approach is an evolutionary and fast calculation methodology that does not require complex mathematical equations to explain a non-linear and multi-dimension system. [16] The *ANN* that was used in the auxiliary *ST* calculation unit was selected using a validation process. However, the *ANN* architecture that gave the best results in the validation procedure was used in the auxiliary *ST* calculation unit.

The calculation of the payback period of the investment is based on the calculation of the net present value of cash flows and depends on the net cash flow, something which in turn varies according to investment costs, maintenance costs, tax rate, quantity and market price of fuel consumed, quantity and market price of generated electricity and thermal energy, etc.

The *GT* calculation model calculates natural gas consumption for *GSCCP* operation using an equation generated based on *GT* manufacturer data *GSCCP* operation using an equation generated based on *GT* manufacturer data [17]:

$$\dot{m}_{NG} = \left(\left(\frac{0,03858 \cdot P_{GTe}{}^{3} + 0.6959 \cdot P_{GTe}{}^{2} + 0.3383 \cdot P_{GTe} + 4.313^{-6}}{P_{GTe}{}^{2} + \cdot P_{GTe} + 0.294}\right) / 0.752\right) \cdot 3600 \quad (1)$$

where $\dot{m}_{NG}$ is natural gas flow and P_{GTe} is the power of *GT* generator. Now that the natural gas flow for *GSCCP* operation is known, the *GT* calculation unit calculates the power of the natural gas consumed in two different ways. The power of natural gas, taking into account higher calorific value (*HHV*), is calculated by the *GT* calculation unit using the equation: [18]

$$P_{HHV} = \dot{m}_{NG} \cdot HHV = \dot{m}_{NG} \cdot 0.011348 \quad (2)$$

where P_{HHV} is the power of the natural gas taking into account *HHV*. P_{HHV} is used in the economic calculation of natural gas consumption. The *GT* calculation unit calculates the power of the natural gas taking into account lower calorific value (*LHV*) using the equation: [18]

$$P_{LHV} = \dot{m}_{NG} \cdot LHV = \dot{m}_{NG} \cdot 0.01028 \quad (3)$$

where P_{LHV} is the power of the natural gas taking into account *LHV*. P_{LHV} is used in all other process calculations, for example to calculate process useful efficiency, etc. The amount of generated *HP* steam, *LP* steam and generated heat for *DH* is calculated by the *HRSG* calculation unit using the generated equations below. calculations, for example to calculate process useful efficiency, etc. The amount of generated *HP* steam, *LP* steam and generated heat for *DH* is calculated by the *HRSG* calculation unit using the generated equations below. The equations are generated based on the data of the *HRSG* manufacturer. [19]

$$\dot{m}_{HP} = 0.00007994 \cdot P_{GTe}{}^{3} - 0.01236 \cdot P_{GTe}{}^{2} + 0.7599 \cdot P_{GTe} + 0.003202 \quad (4)$$

$$\dot{m}_{LP} = 0.00002231 \cdot P_{GTe}{}^{3} - 0.002278) \cdot P_{GTe}{}^{2} + 0.1225 \cdot P_{GTe} + 0.001664 \quad (5)$$

$$P_{DH-HRSG} = 0.00006536 \cdot P_{GTe}{}^{3} - 0.00707 \cdot P_{GTe}{}^{2} + 0.3642 \cdot P_{GTe} + 0.003177 \quad (6)$$

where $\dot{m}_{HP}$ is *HP* steam mass flow from *HRSG*, $\dot{m}_{LP}$ is *LP* steam mass flow from *HRSG* and $P_{DH\text{-}HRSG}$ is generated *DH* heat from *HRSG*. Now that the amount of generated *HP* steam and *LP* steam is known, the *ST* calculation unit can also calculate the power generated by *ST* generator: [20]

$$P_{STe} = \dot{m}_{HP} \cdot (h_{HP} - h_{OUT}) \cdot 0.9 \quad (7)$$

where P_{STe} is the power of the *ST* generator, h_{HP} is specific enthalpy of *HP* steam and h_{OUT} is specific enthalpy of steam from *ST* expansion cylinder. The thermal power of *LP* steam, which is used for industrial purposes and the heat generated from *ST* for *DH* is calculated by the mathematical model using the equations: [21]

$$P_{LP} = \dot{m}_{LP} \cdot (h_{LP} - 0.126) \quad (8)$$

(9)

where P_{LP} is power of *LP* steam, h_{LP} is specific enthalpy of *LP* steam, 0.126 is specific enthalpy of water at 1 bar and 30 °C, $P_{DH\text{-}ST}$ is the heat generated from *ST* for *DH* system and 0.251 is specific enthalpy of water at 1 bar and 60 °C. The *GT* useful efficiency and the total *GSCCP* useful efficiency is calculated by the mathematical model using the equations: [22]

$$\eta_{GT} = \frac{P_{GTe}}{P_{LHV}} \cdot 100\% \quad (10)$$

$$\eta_{GSCCP} = \left(\frac{P_{GTe}+P_{STe}+P_{DH-HR} \quad +P_{LP}+P_{DH-ST}}{P_{LHV}}\right) \cdot 100\% \tag{11}$$

where η_{GT} is *GT* useful efficiency and η_{GSCCP} is *GSCCG* useful efficiency.

In the calculation of the payback period of the investment, the payback calculation unit takes into account the remaining costs and carries out the calculation in several steps. The payback calculation unit calculates the economic eligibility of the investment, assesses the profit that the investment will yield and, based on the duration of the investment and the discount rate, determines whether the investment will be repaid or not. The payback calculation unit calculates profit by first estimating annual income and deducting energy costs, maintenance costs, operating costs, and depreciation: [23]

$$Prof = Inc - Dep - \sum costs \tag{12}$$

where *Prof* is annual profit, *Inc* is annual income, *Dep* is the annual depreciation, and *costs* are annual costs. In the case of electricity and heat production, the annual income is the product of the annual production of energy products and the price of energy products: [23]

$$Inc = (Pr_{el-ann} \cdot C_{el}) + (Pr_{ther-ann} \cdot C_{ther}) \tag{13}$$

where Pr_{el-ann} is the annual production of electricity, C_{el} is the price of electricity, $Pr_{ther-ann}$ is the annual production of heat and C_{ther} is the price of heat. The payback calculation unit adds to operating costs, financing costs, maintenance costs, etc. Depreciation costs are calculated by the payback calculation unit as the ratio of the value of the investment and the duration of the investment, linear depreciation: [1]

$$Dep = \frac{Inv}{Dur} \tag{14}$$

where *Inv* is investment value, *Dur* and is investment duration. Profit is subject to state tax determined by the effective tax rate. After paying the tax, the net profit remains: [1]

$$Prof_{net} = (1 - tax) \cdot Prof \tag{15}$$

where $Prof_{net}$ is net profit, and *tax* is the effective tax rate. The money coming from the investment is called the net cash flow and consists of the net profit that the investor can freely dispose of and the depreciation that they must allocate for new investments: [1]

$$NCF = Frof_{net} + Dep \tag{16}$$

where *NCF* is net cash flow. The sum of all discounted values of net cash flow over the life of the investment gives the present value of revenue and, if the value of the investment is deducted from it, the payback calculation unit can calculate the net present value: [1]

$$NPV = \sum_{y=1}^{n} \frac{NCF}{(1+int_{rate})^{y}} - Inv \tag{17}$$

where *NPV* is the net present value, which is a basic indicator of the cost-effectiveness of the investment. Only when *NPV* is positive is the investment economical. When we compare two or more investments, the most economical is the one that reaches the highest *NPV*. [1]

3 ACTUAL DATA SET FILTRATION AND MODEL VALIDATION

Actual data set filtration and model validation is the process of determining whether the model accurately represents the behaviour of the actual system. However, it is important to consider the quality of the data, whether it truly represents the system, and if it is the best test of the model. [24] Before the validation procedure, all actual data set should be properly prepared. All data that do not belong to the actual data group, error data, are removed in the filtration process. Error data in an individual data actual group are caused by measurement errors, recording errors, or turbine trip and other measurement failures. An example of an unfiltered and filtered actual data set from the *SCADA* is shown in Fig. 4.

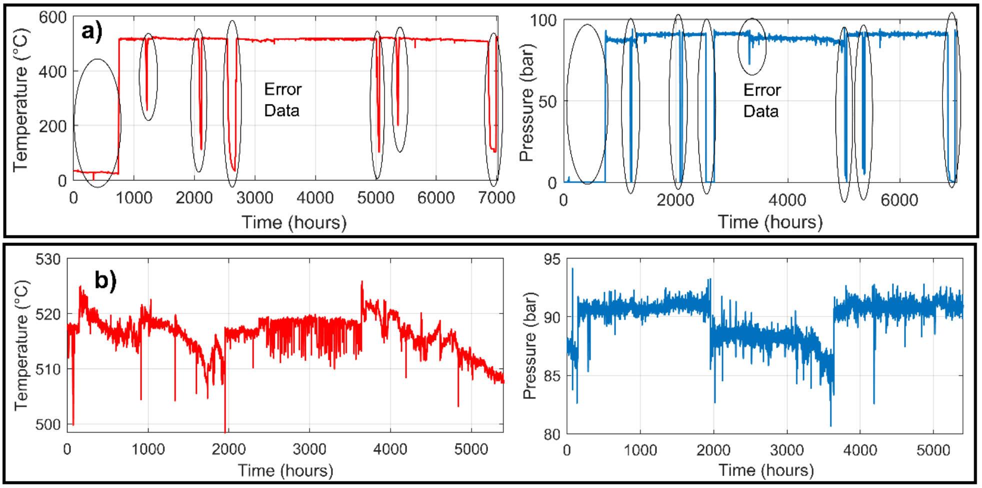

Figure 4: *(a) Unfiltered data from the SCADA system with error data and (b) filtered data used for training and validation of architectures applied in the ST calculation unit.*

Filtered data from the *SCADA* has been used in the *ANN* training and validation process to choose the *ANN* architecture that gave the best results which were applied in the auxiliary *ST* calculation unit. Training an *ANN* is an iterative process in which training data examples are presented to the network one by one, and the values of the weights are adjusted each time. [25] In the *ST* calculation unit development process, an input data set was used during the learning phase, expressed in the [3x5400] matrix form and an output data set equally expressed in the [2x5400] matrix form. For each input data set, which in our case are steam mass flow, steam temperature and steam pressure into the *ST*, there is a specific output data, which are exhaust steam temperature and exhaust steam pressure from the *ST*.

The validation of ANN algorithm structures is carried out by means of the calculations of the error between the results provided by the ANN algorithm structure and the actual process data. The errors can be computed in several ways. The most useful way of error computation is called the mean square error (*MSE*) and is defined as: [26]

$$MSE = \frac{1}{p}\sum_{i=1}^{p}\left(t_j - o_j\right)^2 \tag{18}$$

whereas the root mean square (*RMS*) is defined as follows:

$$RMS = \left|(1/p)\sum_{j=1}^{p}\left[t_j - o_j\right]^2\right|^{1/2} \tag{19}$$

The correlation coefficient (R^2) and mean absolute error (*MAE*) are respectively defined as: [27], [28]

$$R^2 = 1 - \left[\frac{\sum_{j=1}^{p}(t_j - o_j)^2}{\sum_{j=1}^{2}(o_j)^2}\right] \quad (20)$$

$$MAE = \frac{1}{p}\sum_{j=1}^{p}\left|t_j - o_j\right| \quad (21)$$

where t_j is the target value, o_j is the output value, and p is the pattern. The R^2 are normalised ranges between 0 and 1. A very good fit yields an R^2 value of 1, whereas a poor fit result in a value near 0. [27], [28]

Using Eq. 18-21, the *ANN* structures of different architectures have been validated, where the number of hidden layers and the number of neurons in each hidden layer has been changed. The results of the validations of *ANN* structures of various architectures for the selection of the winning structure used in the auxiliary ST calculation unit are shown in Table 1.

Table 1: *Results of validations of ANN structures of various architectures for the selection of the winning ANN algorithm structure used in the auxiliary ST calculation unit.*

Algorithm Architecture	Layers	At Epochs	Data Set Size	MSE	RMSE	R^2	MAE
ANN 20-18-25	5	120	5400	13.5643	3.6830	0.9994	1.5018
ANN 12-10-11	**5**	**112**	**5400**	**10.7807**	**3.2834**	**0.9996**	**1.3753**
ANN 9-7-6	5	164	5400	12.4752	3.5320	0.9995	1.5122
ANN 45-37	4	112	5400	12.6885	3.5621	0.9995	1.5140
ANN 22-21	4	149	5400	12.5996	3.5496	0.9995	1.5002
ANN 12-9	4	167	5400	11.5722	3.4018	0.995	1.4968
ANN 7-9	4	187	5400	13.2776	3.6438	0.9995	1.5565
ANN 60	3	276	5400	11.7001	3.4205	0.9995	1.4307
ANN 40	3	108	5400	14.7699	3.8432	0.9994	1.6032
ANN 20	3	317	5400	12.6844	3.5615	0.9995	1.5384
ANN 12	3	258	5400	13.1586	3.6275	0.9995	1.5341
ANN 5	3	187	5400	15.6925	3.9661	0.9994	1.6541

Table 1 shows that the winning *ANN* structure used in the auxiliary *GT* calculation unit is the structure with 12-10-11 architecture (written in bold), as it has the lowest error rate. The process of creation and the regression of the *ANN* structure, used in the auxiliary *GT* calculation unit, are shown in Fig. 5.

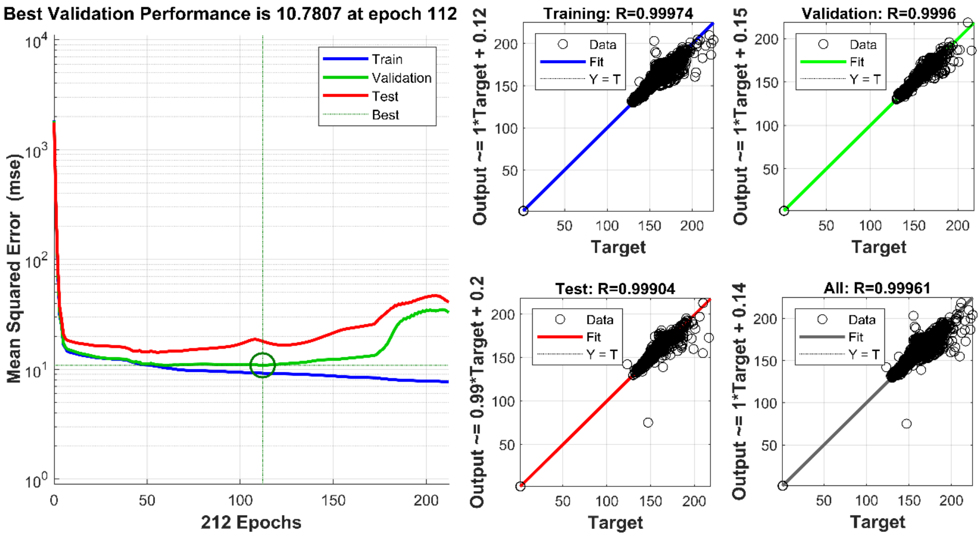

***Figure 5**: Process of creation and regression of the winning ANN non-linear structure used in the simulation model of the non-linear ANN unit.*

The creation of the *ANN* structure, used in the auxiliary *ST* calculation unit, was performed with 212 epochs. The best validation agreement of the *MSE* is 10.7807 and it was reached at the 112th epoch, whereby regression is R^2 0.9996.

4 THE RESULTS OF THE ENERGO-ECONOMIC PAYBACK INVESTMENT CALCULATION MODEL

The results of the energo-economic payback investment calculation model are designed so that the amount and power of natural gas consumed and required for the operation of the *GSCCP* is presented first. Then, the quantities of *HP* steam, *LP* steam and thermal power generated by *GSCCP* are presented. Following this is a presentation of the useful efficiency of *GT* and *GSCCP* operation, energy flows and the amount of greenhouse CO_2 gas released into the atmosphere after 5400 hours of *GSCCP* operation. At the end of the chapter, the results of the calculations of the payback period of the investment depending on the price ratio of the fuel required for the operation of the *GSCCP* and the total generated electricity are presented.

Fig. 6 shows the natural gas consumption for *GSCCP* operation as a function of generator power *GT*. At the power of the *GT* generator of 5 MW, the natural gas consumption amounts to 4341.1 Nm^3/h, a standard cubic metre per hour defined at a natural gas reference temperature of 0 °C and a natural gas reference pressure of 1.013 bar. At the power of the *GT* generator of 30 MW, the consumption of natural gas amounts to 8859.8 Nm^3/h, and at a maximum load of 55 MW of the *GT* generator, the consumption of natural gas for *GSCCP* operation is as much as 13465 Nm^3/h.

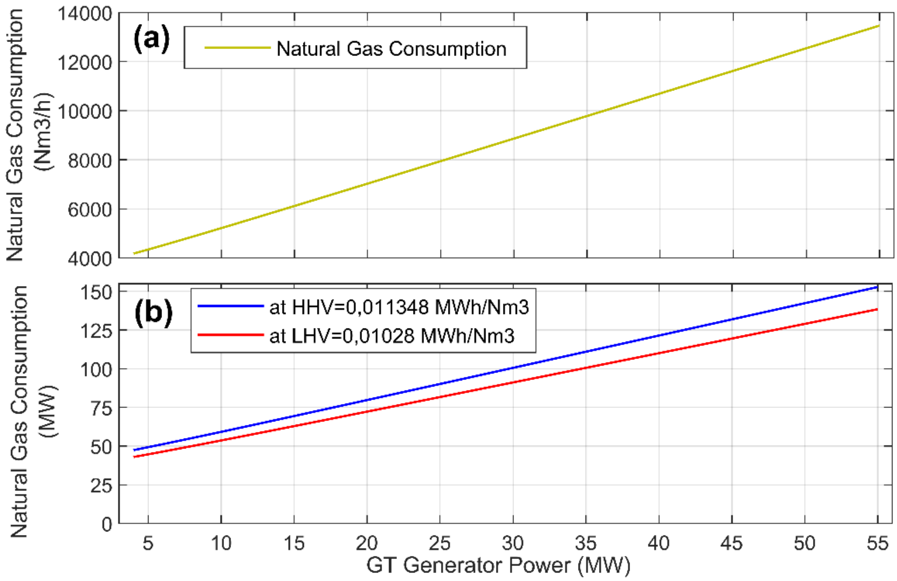

Figure 6: *The results of GT calculation unit; (a) natural gas consumption depending on the load of the GT generator; and (b) power of consumed natural gas taking into account HHV and LHV.*

Fig. 6(b) shows the power consumption of natural gas needed for the *GSCCP* operation. The power of natural gas considering *HHV* is taken into account in the analysis of the payback period of the investment, as the economic cost calculations of gas consumption take into account the *HHV*. The power of natural gas considering the *LHV* is used in all other technological calculations, such as the useful efficiency calculations, etc. It is evident from Fig. 6(b) that at the power of the *GT* generator of 5 MW, the power of the consumed fuel when considering *HHV* is 49.2 MW and when considering *LHV* the power of the consumed fuel is 44.6 MW. At a maximum load of the *GT* generator of 55 MW, the power of consumed fuel amounts to 152.8 MW, when taking into account *HHV,* and 138.4 MW when taking into account *LHV*. However, if the process useful efficiency calculations were based on the *HHV* power of the fuel consumed, they would be significantly lower.

Fig. 7 shows the results of the *HRSG* and *ST* calculation unit. It is evident from Fig. 7(a) that at the power of the *GT* generator of 5 MW, the amount of generated *HP* steam is 3.5 kg/s, the amount of generated *LP* steam is 0.5 kg/s and the generated *DH* heat from *HRSG* is 1.6 MW. At the power of the *GT* generator of 30 MW, the amount of generated *HP* steam is 13.8 kg/s, the amount of generated *LP* steam is 2.2 kg/s and the generated *DH* heat from *HRSG* is 6.3 MW. At the maximum power of the *GT* generator of 55 MW, the amount of generated *HP* steam is 17.7 kg/s, the amount of generated *LP* steam is 3.5 kg/s and the generated *DH* heat from *HRSG* is 9.5 MW.

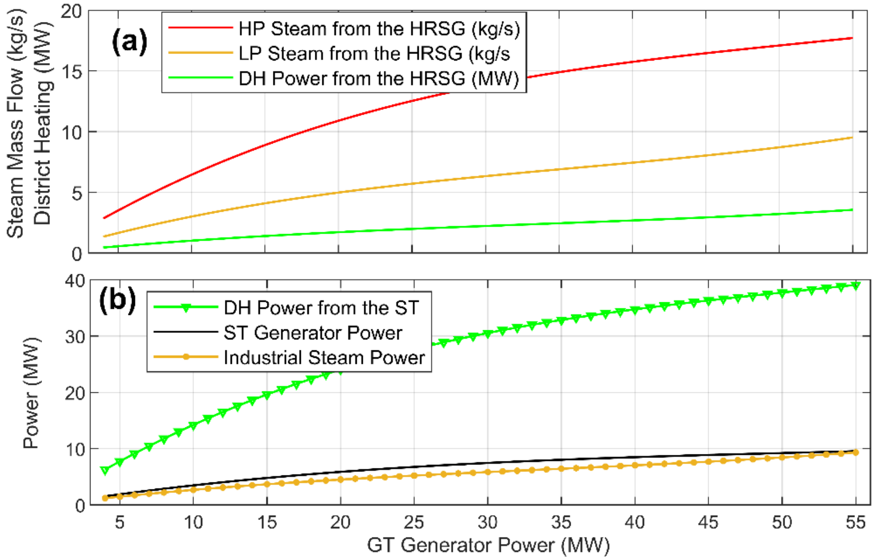

***Figure 7:** The results of HRSG and ST calculation unit; (a) flows of generated HP steam, flows of generated LP steam, generated DH heat from HRSG and (b) generated DH heat from ST, electrical power of ST generator and power of LP steam for industrial use.*

It is evident from Fig. 7(b) that at the power of the *GT* generator of 5 MW, the generated *DH* heat from *ST* is 7.7 MW, the power of the *ST* generator is 1.8 MW and the power of *LP* steam is 1.4 MW. At the power of the *GT* generator of 30 MW, the generated *DH* heat from *ST* is 30.5 MW, the power of the *ST* generator is 7.4 MW and the power of *LP* steam is 5.8 MW. At the maximum power of the *GT* generator of 55 MW, the generated *DH* heat from *ST* is 39.1 MW, the power of the *ST* generator is 9.5 MW and the power of *LP* steam for industrial purposes is 9.3 MW.

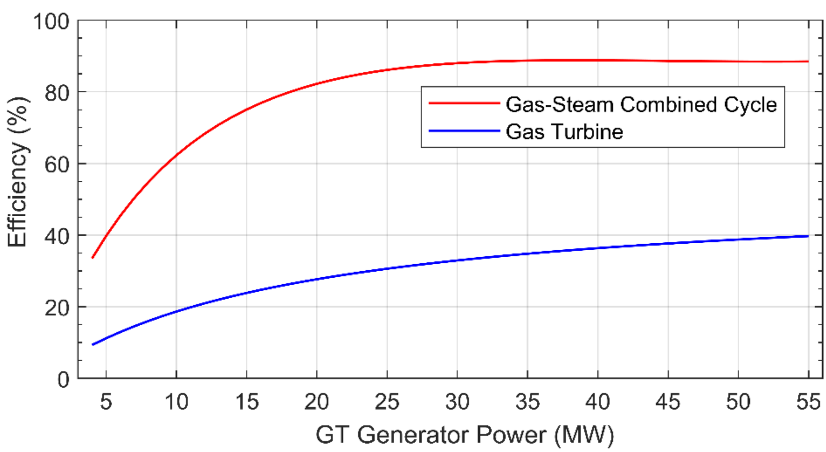

***Figure 8**: GT useful efficiencies and GSCCP useful efficiencies as a function of the power of the GT generator.*

Fig. 8 shows *GT* useful efficiencies and *GSCCP* useful efficiencies as a function of the power of the *GT* generator. At the power of the *GT* generator of 5 MW, the *GT* useful efficiency amounts to 10% and the GSCCP useful efficiency to 39%. At the power of the *GT* generator of 30 MW, the *GT* useful efficiency amounts to 34% and the *GSCCP* useful efficiency amounts to 87%. At the maximum power of the *GT* generator of 55 MW, the *GT* useful efficiency amounts to 40% and the *GSCCP* useful efficiency amounts to 88%.

Fig. 9 shows the energy flows and the amount of greenhouse CO_2 gas released into the atmosphere after 5400 hours of *GSCCP* operation, as the constant 50 MW power of the *GT* generator is taken into account. As much as 768,624 MWh of natural gas are required for 5400 hours of uninterrupted operation, taking into account *HHV*, while 696,475 MWh of natural gas are required when taking into account *LHV*. The *GSCCP* generates 319,793 MWh of electricity, 250,729 MWh thermal energy for *DH* and 45,549 MWh thermal energy of *LP* steam used for industrial purposes. At the same time, the *GSCCP* emits 140,660 tons of greenhouse CO_2 gas into the atmosphere.

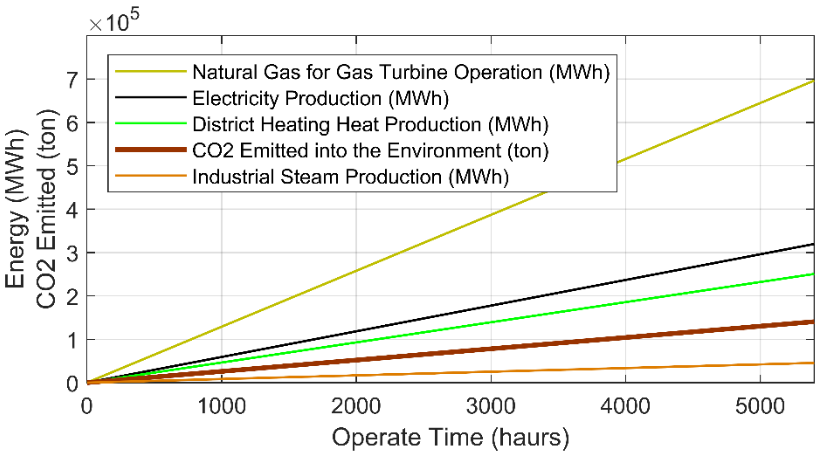

***Figure 9**: Energy flows and the amount of greenhouse CO_2 gas released into the atmosphere after 5400 hours of GSCCP operation.*

The results of the payback calculation unit depending on the ratio of the price of natural gas, taking into account *HHV*, and the price of electricity excluding and taking into account the cost of purchasing CO_2 carbon offsets is shown in Fig. 10. The calculations take into account that *GSCCP* operates 5400 hours per year, the investment costs amount to 75,000,000.00 monetary units, the discount rate is 7%, tax rate is 22%, maintenance costs are 2% of investment costs per year, the price of district heating heat is fixed and amounts to 70.00 monetary units per MWh, the purchase price of carbon offset is fixed and amounts to 70.00 monetary units per tonne of CO_2 emitted, and the power of the *GT* generator is fixed and amounts to 50 MW. In addition to this, the calculation does not take into account a possible subsidy for the production of high-efficiency electricity. The said subsidy can in fact be offset by the cost of purchasing CO_2 carbon offsets. The grey areas in Figure 10 represent the zero balance or payback period of the investment. This subsidy can in fact be offset by the cost of purchasing CO_2 carbon offsets. The grey area in Fig. 10 represents the zero balance or payback period of the investment.

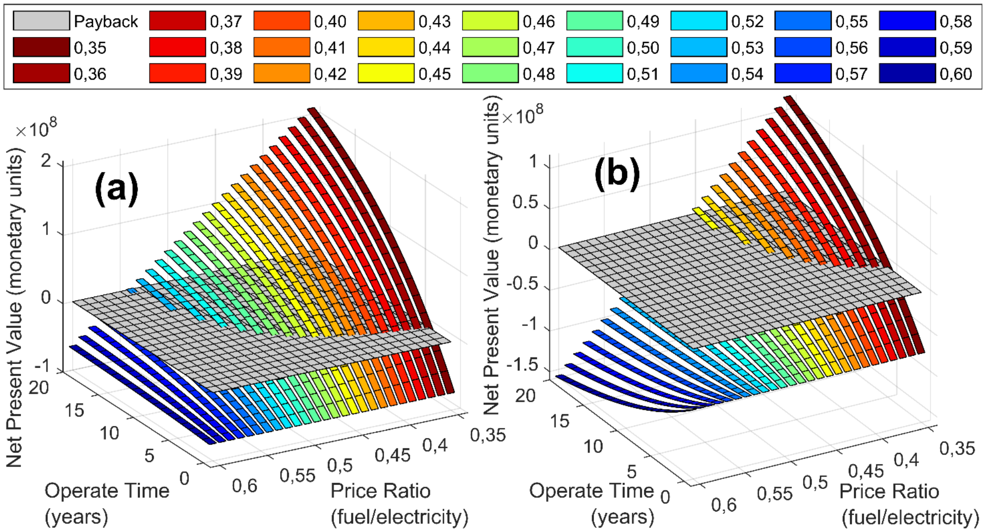

Figure 10: *The calculation of the payback period of the investment depends on the ratio of natural gas prices at HHV value and electricity price; (a) excluding the cost of purchasing CO_2 carbon offsets and (b) taking into account the cost of purchasing CO_2 carbon offsets.*

It is evident from Fig. 10(a) that the payback period of the investment, excluding the cost of purchasing CO_2 carbon offsets, ranges from 4 years for the 0.35 fuel/electricity price ratio and up to 20 years for the 0.49 fuel/electricity price ratio. Without taking into account the cost of purchasing CO_2 carbon offsets at a fuel/electricity price ratio of 0.46, the payback period is 10 years. However, with fuel/electricity price ratios higher than 0.49, the investment does not pay off even across 20 years.

It is evident from Fig. 10(b) that the payback period of the investment, taking into account the cost of purchasing CO_2 carbon offsets, ranges from 7 years for the 0.35 fuel/electricity price ratio and up to 20 years for the 0.42 fuel/electricity price ratio. Taking into account the costs of purchasing CO_2 carbon offsets, the payback period of the investment is 10 years at 0.39 fuel/electricity price ratio. However, with fuel/electricity price ratios higher than 0.42, the investment does not pay off even across 20 years. With fuel/electricity price ratios higher than 0.49, taking into account the cost of buying CO_2 carbon offsets, the cash flow of net present value becomes negative, which means that we start to generate a negative return or loss. The essential importance of the cost-effective operation of the *GSCCP* is therefore dictated by the market dynamics of fuel, electricity and thermal energy prices.

5 CONCLUSION

This paper has presented both the energo-economic calculation modelling of *GSCCP* operation with the basic characteristic properties of the system behaviour in different operating regimes, and the energy flows generated by the uninterrupted 5400-hour operation of the *GSCCP*. The results of the calculation modelling show that the *GSCCP* can achieve a useful efficiency of up to 88% in the backpressure operation of a steam turbine. The useful efficiency of the gas turbine is up to 40.5%. In 5400 hours of continuous operation and 50 MW of uninterrupted constant power, the *GT* generator requires as much as 768,628 MWh of natural gas at *HHV* value and 696,475 MWh of natural gas at *LHV* value. The *GSCCP* generates 319,793 MW of electricity, 250,729 MWh of thermal energy for *DH*, and 45,549 MWh of thermal energy for industrial purposes, while 140,660 tons of CO_2 greenhouse gas are emitted into the environment. The calculation of the payback period of the investment is based on the calculation of the net present value taking into the account the *HHV* value of natural gas. The results of the calculation of the payback period of the investment show that the payback period depends mainly on the market conditions of energy products. At a price ratio of fuel/electricity of 0.35, without factoring in the costs of purchasing CO_2 carbon offsets, the payback period of the investment is 4 years, while at a price ratio of fuel/electricity of 0.49, the payback period is greater than 20 years. The costs of purchasing CO_2 carbon offsets; however, can be offset by revenues from subsidies for high-efficiency electricity generation.

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Nomenclature

Abbreviations

ANN	artificial neural network
DH	district heating
GSCCP	gas-steam combined cycle power plant
GT	gas turbine
HHV	higher heating calorific value
HRSG	heat recovery steam generator
HP	high pressure
LHV	lower heating calorific value
LP	low pressure

MAE	mean absolute error
MSE	mean square error
RMS	root mean square
R^2	correlation coefficient
SCADA	supervisory control and data acquisition
ST	steam turbine
CO_2	carbon dioxide

Parameters

C_{el}	electricity price, monetary unit
C_{ther}	thermal price, monetary unit
costs	annual coast, monetary unit
Dep	annual depreciation, monetary unit
Dur	investment duration, years
h_{HP}	specific enthalpy of HP steam, MJ/kg
h_{LP}	specific enthalpy of LP steam, MJ/kg
h_{OUT}	specific enthalpy of steam from expansion cylinder of ST, MJ/kg
Inc	annual income, monetary unit
Inv	investment value, monetary unit
NCF	net cash flow, monetary unit
NPV	net present value, monetary unit
$P_{DH-HRSG}$	DH generated heat from HRSG, MW
P_{DH-ST}	DH generated heat from ST, MW
P_{GTe}	GT generator power, MW
P_{HHV}	power of natural gas taking into account HHV, MW
P_{LHV}	power of natural gas taking into account LHV, MW
Pr_{el-ann}	annual production of electricity, MWh
$Pr_{ther-ann}$	annual production of heat, MWh