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Revija Journal of Energy Technology (JET) redno izhaja že petnajsto leto zapored. V tem času so bili v reviji objavljeni številni zelo zanimivi članki priznanih strokovnjakov. Marsikateremu mlademu raziskovalcu je prav revija JET predstavljala odskočno desko za njegov nadaljnji razvoj, številni so pozneje objavili svoje prispevke celo v najbolj priznanih znanstvenih publikacijah na svojem raziskovalnem področju. Revija je namenjena objavi znanstveno-raziskovalnih in strokovnih dosežkov na področju energetike ter zajema širok spekter tehničnih, ekonomskih in pravnih dosežkov s področja proizvodnje, transporta in pretvorbe energije. Velik poudarek je namenjen tudi izrabi obnovljivih in alternativnih virov energije, kakor tudi varovanju okolja. Revija je ves čas izhajala pod okriljem Fakultete za energetiko, dokler Senat Fakultete za energetiko Univerze v Mariboru ni sklenil, da bo z letom 2023 znanstveno revijo JET začela izdajati Univerzitetna založba Univerze v Mariboru. To avtorjem prispevkov in bralcem ne prinaša bistvenih sprememb. Kot odgovorni urednik revije se bom skupaj s svojo ekipo še naprej trudil za objavljanje zanimivih člankov. Rad bi se zahvalil vsem soustvarjalcem revije, avtorjem ter seveda tudi recenzentom za njihov trud in neprecenljiv prispevek, še posebej pa mag. Sonji Novak za zelo dobro sodelovanje pri ustvarjanju revije JET, ter upam, da bo naše sodelovanje še naprej potekalo v tem duhu.

Vsem bralcem želim obilo užitkov pri branju nove številke revije.

Jurij AVSEC

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Dear Readers of the Journal of Energy Technology (JET)

The Journal of Energy Technology (JET) is entering its 15th consecutive year of regular publication. During this time, the Journal has published a number of very interesting articles by renowned experts. For many young researchers, JET has been the catalyst for their further development, and many have gone on to publish their papers in some of the most acclaimed journals in their field of research. The Journal is dedicated to the publication of scientific research and professional developments in the field of energy and covers a wide range of technical, economic and legal breakthroughs in the field of energy production, transport and conversion. A strong emphasis is also placed on the use of renewable and alternative energy sources, as well as on environmental protection. The Journal used to be published by the Faculty of Energy Technology until the Senate of the Faculty of Energy Technology of the University of Maribor decided that the scientific journal JET will be published by the University Publishing House of the University of Maribor as of 2023. I am confident that the authors of the articles and our readers will not in any way be affected by this change. As Editor-in-Chief, I will continue to work hard with my team to publish interesting articles. I would like to thank all the contributors to the Journal, the authors and, of course, the reviewers for their efforts and invaluable contributions, and especially mag. Sonja Novak for her priceless input in the creation of JET, and I hope that our cooperation will continue in this spirit.

I wish all readers a lot of pleasure in reading the new issue of the magazine.

Jurij AVSEC
Editor-in-chief of JET

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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

Dušan Strušnik^{1‡}, Jurij Avsec²

Keywords: calculation, efficiency, investment, market, modelling, payback

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 koristen izkoristek do 88 %. Koristen 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 thermo-economic analysis of a cogeneration system at a hospital. [5] In reviewing the scientific literature, we have not yet found a paper analysing the energy-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 *HRS*G 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 *HRS*G 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 *HRS*G 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 *HRS*G 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 *HRS*G depends on the flue gas temperature in the chimney, as the *HRS*G *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.

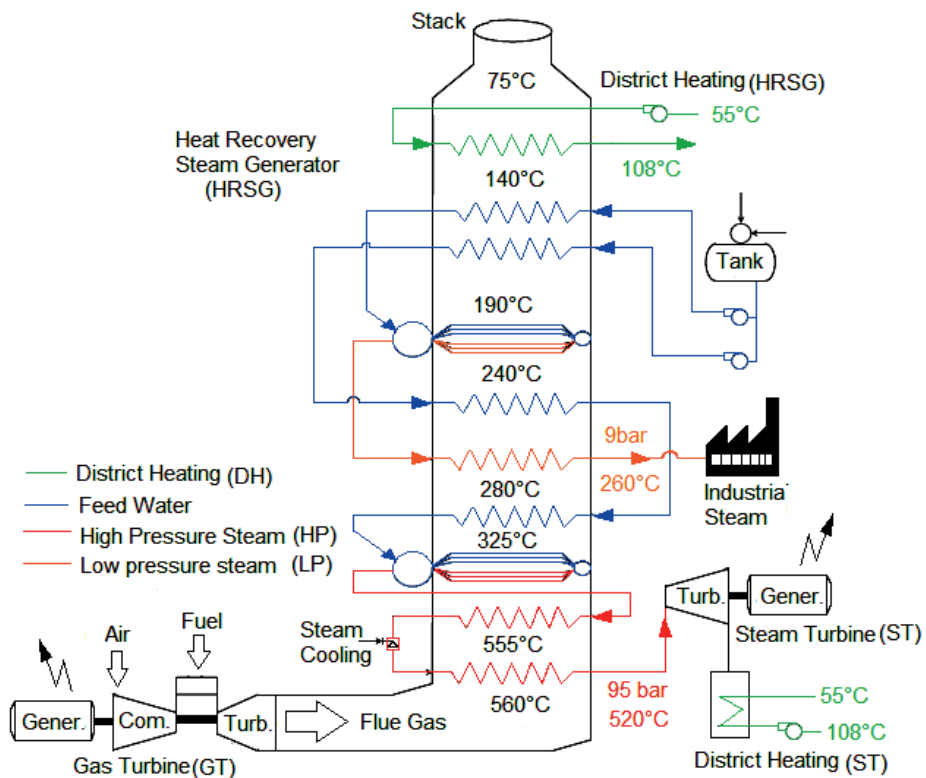


Figure 1: A schematic representation of the operation of the *GSCCP*.

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] Kafei 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.

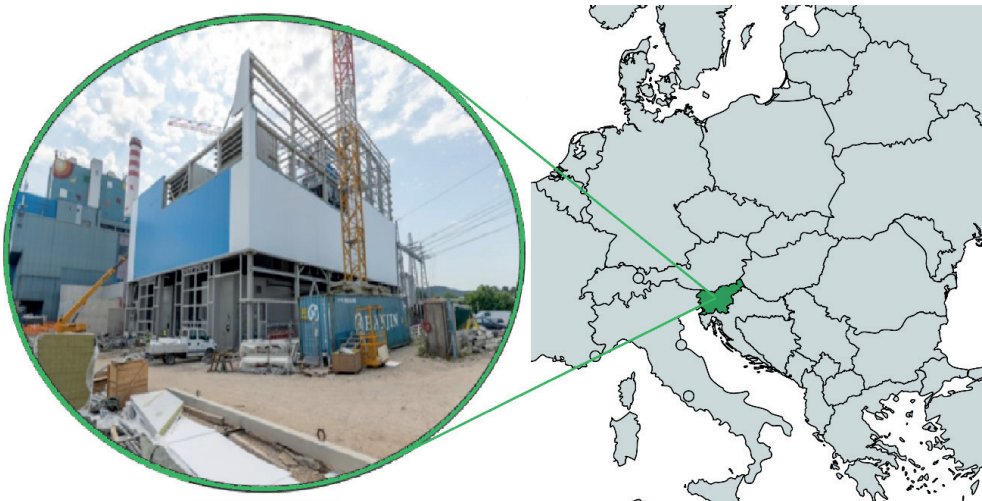


Figure 2: The recently-built GSCCP in the middle of Slovenia.

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.

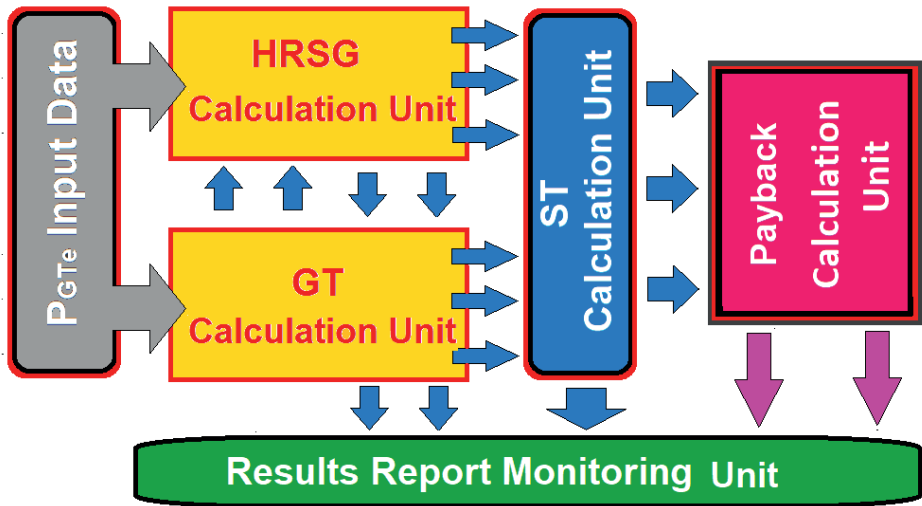


Figure 3: Schematic representation of the energo-economics payback investment calculation model.

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]:

$$\dot{m}_{NG} = \left(\left(\frac{0.03858 \cdot P_{GTe}^3 + 0.6959 \cdot P_{GTe}^2 + 0.3383 \cdot P_{GTe} + 4.313 \cdot 10^{-6}}{P_{GTe}^2 + P_{GTe} + 0.294} \right) / 0.752 \right) \cdot 3600 \quad (1)$$

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 $P_{DH-HRSG}$ 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-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]

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

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

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]

$$Prof = Inc - Dep - \sum costs \quad (12)$$

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]

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

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]

$$Dep = \frac{Inv}{Dur} \quad (14)$$

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]

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

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]

$$NCF = Prof_{net} + Dep \quad (16)$$

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]

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

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.

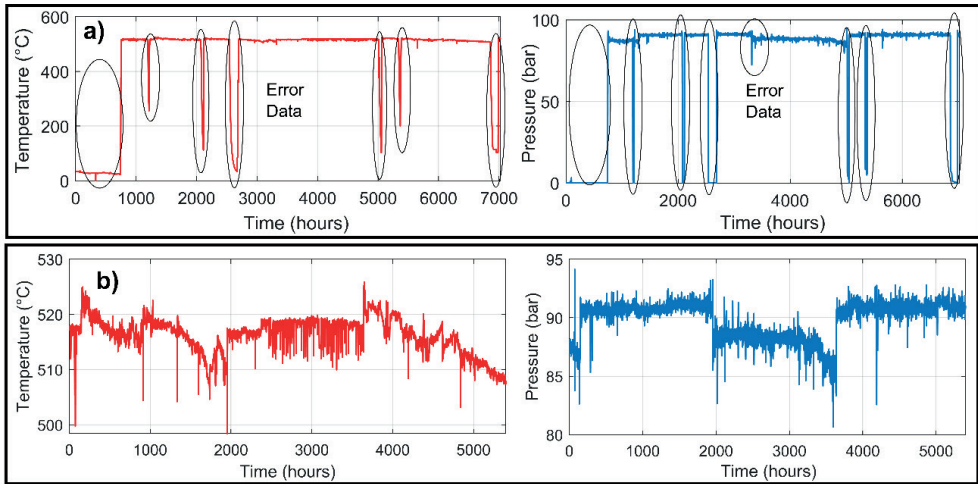


Figure 4: (a) Unfiltered data from the SCADA system with error data and (b) filtered data used for training and validation of architectures applied in the *ST* calculation unit.

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]

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

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

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

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

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

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

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.

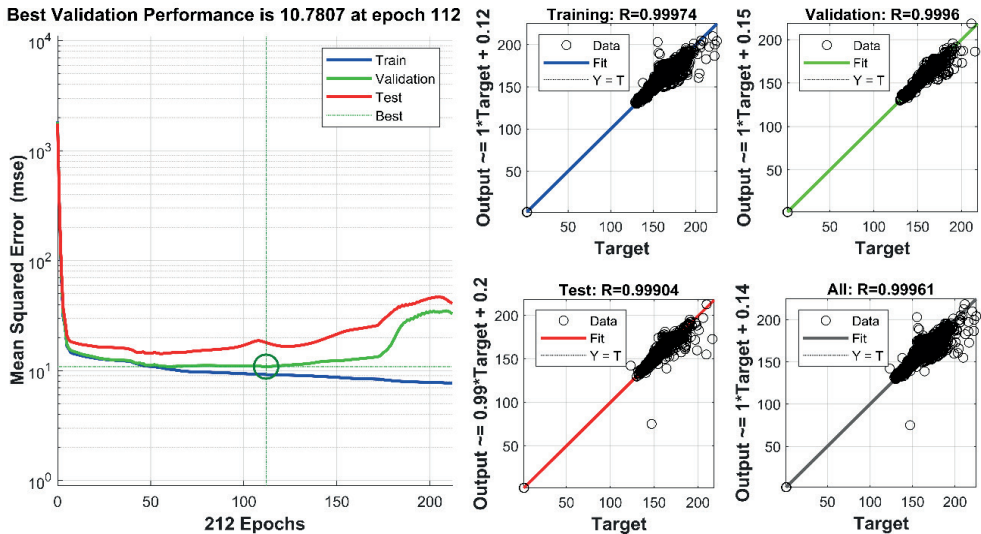


Figure 5: Process of creation and regression of the winning ANN non-linear structure used in the simulation model of the non-linear ANN unit.

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 .

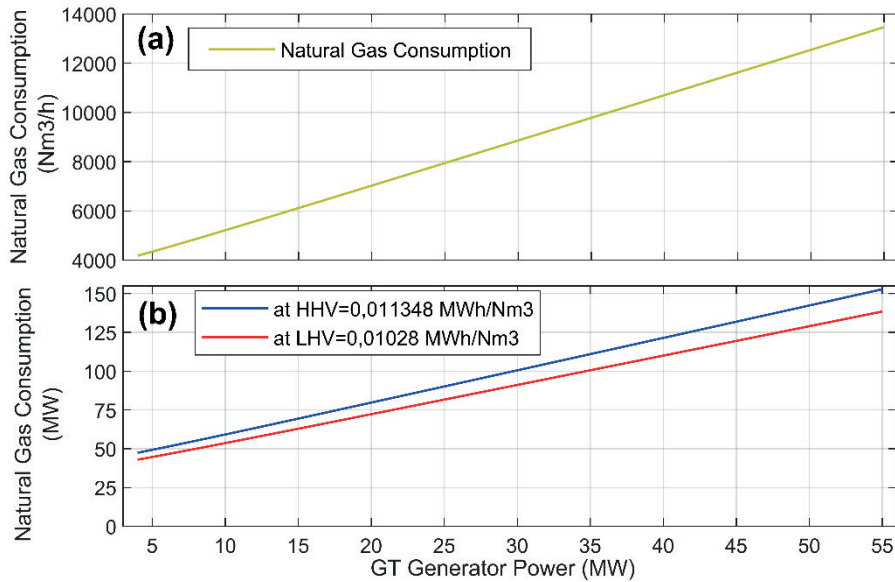


Figure 6: The results of GT calculation unit; (a) natural gas consumption depending on the load of the GT generator; and (b) power of consumed natural gas taking into account HHV and LHV.

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.

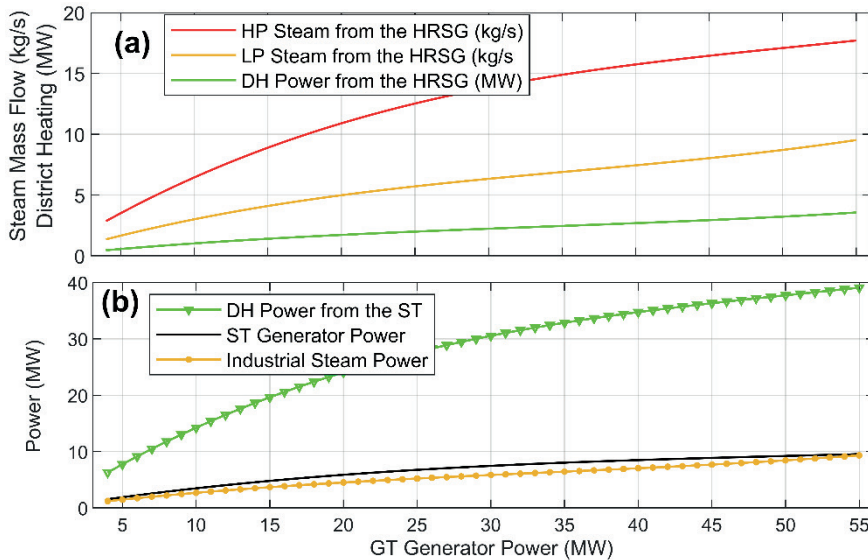


Figure 7: The results of HRSG and ST calculation unit; (a) flows of generated HP steam, flows of generated LP steam, generated DH heat from HRSG and (b) generated DH heat from ST, electrical power of ST generator and power of LP steam for industrial use.

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.

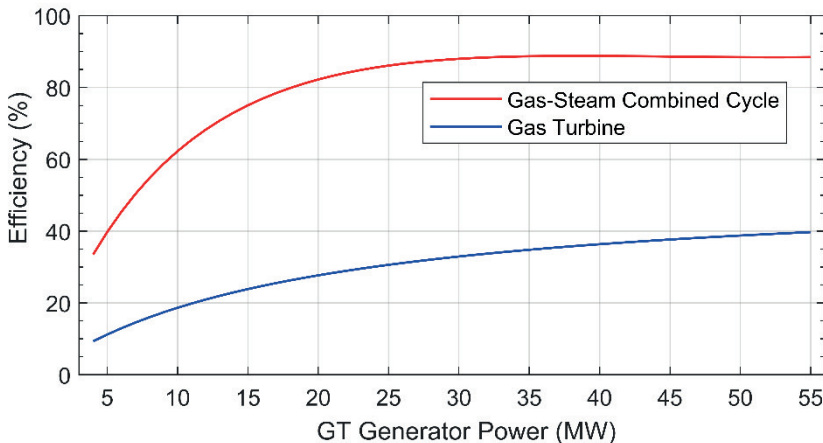


Figure 8: GT useful efficiencies and GSCCP useful efficiencies as a function of the power of the GT generator.

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.

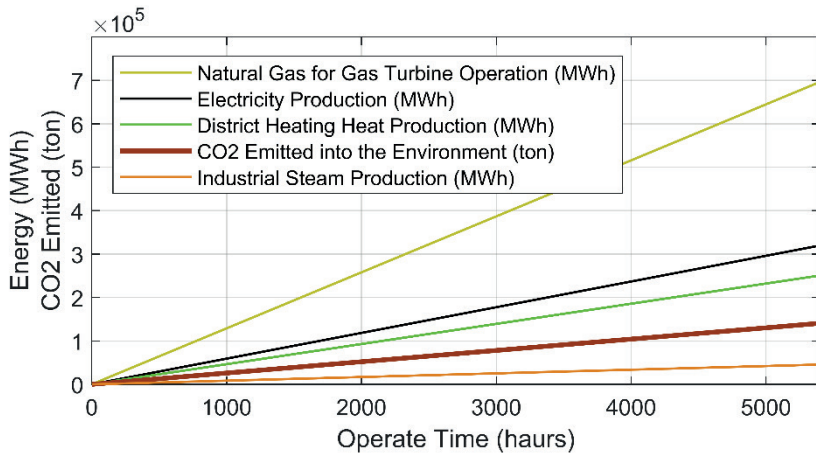


Figure 9: Energy flows and the amount of greenhouse CO_2 gas released into the atmosphere after 5400 hours of *GSCCP* operation.

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.

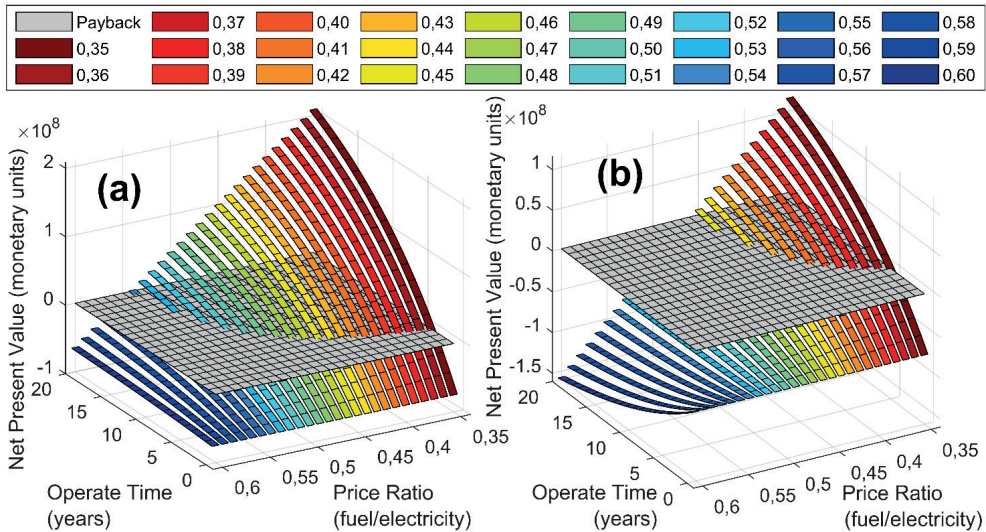


Figure 10: The calculation of the payback period of the investment depends on the ratio of natural gas prices at HHV value and electricity price; (a) excluding the cost of purchasing CO₂ carbon offsets and (b) taking into account the cost of purchasing CO₂ carbon offsets.

It is evident from Fig. 10(a) that the payback period of the investment, excluding the cost of purchasing CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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
HRSR	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
CO₂	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_{GT_e}	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

MONITORING AND ASSESSMENT MECHANISM OF JUST ENERGY TRANSITION TRAJECTORIES. DO JUST TRANSITION OBSERVATORIES MATTER?

MEHANIZEM SPREMLJANJA IN OCENJEVANJA TRAJEKTORIJ PRAVIČNEGA PREHODA NA PODROČJU ENERGIJE. ALI SO OPAZOVALNICE PRAVIČNEGA PREHODA POMEMBNE?

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Keywords: just transition, monitoring mechanisms, observatory, governance

Abstract

The primary aim of the European Green Deal is to move towards climate neutrality in a socially just and inclusive way. To this end, the EU has set up the so-called 'Just Transition Mechanism' (JTM), which will provide funding and technical assistance to the regions of the EU most affected

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by the transition to a green economy. However, in addition to securing sufficient resources and providing technical assistance for their utilisation, a critical factor for the successful outcome of the transition in coal-dependent regions is the establishment of effective monitoring/assessment mechanisms and place-based governance models. This reflects the departure of European politics from horizontal and one-size-fits-all policies. This is done for two reasons: (a) the utilisation of local knowledge and local territorial capital deals better with problems and (b) the transfer of the level of decision-making and implementation of policies as close as possible to the citizens to whom they concern. An effective governance model; however, should be accompanied by an effective mechanism for scientifically monitoring, analysing, evaluating, and formulating substantiated policy proposals. Setting up and operating a Just Transition Observatory could be a valuable support mechanism, provided it has the presumption of multi-level expertise and objectivity, deep knowledge of local specificities and legitimacy to institutionally represent the public interest at the local level. Such an Observatory could function as an independent evaluation body (with periodic reports or focused studies) in the course of the Energy Transition Programmes, identifying potential difficulties, recording impacts, results and outcomes, as well as providing policy recommendations. Given that Just Transition Plans include a number of important transformational policies and transformative plans, the crucial question that arises is whether regional and central policy makers have the tools to evaluate these transformational policies and transformative projects. In this regard, it is necessary to design evaluation models based on predefined indicators and criteria that will be jointly defined in the context of public consultation. This will ensure objectivity on the basis of commonly agreed indicators and objectives, while also guaranteeing the legitimacy and acceptance of both strategic policies and specific investment plans. This paper attempts to examine to what extent there is room for the establishment of 'Just Transition Observatories' Platforms along the coal-dependent areas. More specifically, the potential of such mechanism to monitor, analyse and evaluate clean energy transition, and provide robust policy recommendations, will be explored. To this end, Just Transition Observatories will operate as an independent evaluation mechanism producing evidence-based reports and studies on clean energy transition. Thus, the Observatories will be able to deliver periodic reports based on indicators, comparative analysis and policy recommendations. In addition to this, such mechanisms could enhance networking at the EU, national and local level, mobilising scientific dialogue and debate on clean energy transition.

Povzetek

Primarni cilj evropskega zelenega dogovora je premik k podnebni nevtralnosti na socialno pravičen in vključujoč način. V ta namen je EU vzpostavila t. i. Mehanizem za pravični prehod (JTM), ki bo zagotovil finančno in tehnično pomoč regijam EU, ki jih je prehod v zeleno gospodarstvo najbolj prizadel. Poleg zagotavljanja zadostnih virov in tehnične pomoči za njihovo uporabo pa je ključni dejavnik za uspešen prehod v regijah, odvisnih od premoga, vzpostavitev učinkovitih mehanizmov spremljanja/ocenjevanja in modelov upravljanja na podlagi krajev, kar izraža odklone evropske politike od horizontalnih politik in politike ene velikosti za vse. To se izvaja iz dveh razlogov: (a) uporaba lokalnega znanja in lokalnega teritorialnega kapitala učinkovitejše rešuje probleme in (b) prenos ravni odločanja in izvajanja politik čim bližje državljanom, ki se jih neposredno tičejo. Učinkovit model upravljanja pa mora spremljati učinkovit mehanizem znanstvenega opazovanja, analiziranja, ocenjevanja in oblikovanja utemeljenih političnih predlogov. Vzpostavitev in delovanje Observatorija za pravični prehod bi lahko bil dragocen podporni mehanizem, če bi imel predpostavko o večnivojskem strokovnem znanju in objektivnosti, globokem poznavanju lokalnih posebnosti in legitimosti za institucionalno zastopanje javnega interesa na lokalni ravni. Takšen observatorij bi lahko deloval kot neodvisno ocenjevalno telo (z občasnimi

poročili ali osredotočenimi študijami) poteka programov energetskega prehoda, pri čemer bi prepoznaval morebitne težave, beležil vplive, rezultate in izide ter tudi predlagal politična priporočila. Glede na to, da načrti pravičnega prehoda vključujejo številne pomembne transformacijske politike in transformativne načrte, se postavlja ključno vprašanje, ali imajo regionalni in centralni oblikovalci politik orodja za ovrednotenje teh transformacijskih politik in transformativnih projektov. Pri tem je potrebno oblikovati modele vrednotenja na podlagi vnaprej določenih indikatorjev in meril, ki jih bomo opredelili v okviru javne razprave. To bo na eni strani zagotovilo objektivnost na podlagi skupno dogovorjenih kazalnikov in ciljev ter na drugi strani legitimnost in sprejemljivost tako strateških politik kot posebnih naložbenih načrtov. Ta dokument skuša preučiti, v kolikšni meri obstaja prostor za vzpostavitev platform observatorijev za pravični prehod vzdolž območij, ki so odvisna od premoga. Natančneje bo preučen potencial mehanizma za opazovanje, analizo in vrednotenje prehoda na čisto energijo ter za zagotavljanje trdnih političnih priporočil. V ta namen bodo observatoriji pravičnega prehoda delovali kot neodvisen ocenjevalni mehanizem, ki bo pripravljaj poročila in študije o prehodu na čisto energijo, ki temeljijo na dokazih. Na podlagi tega bodo observatoriji lahko predložili redna poročila, ki bodo temeljila na kazalnikih, primerjalnih analizah in priporočilih politike. Poleg tega bi lahko takšni mehanizmi okrepili povezovanje tako na ravni EU kot na nacionalni in lokalni ravni ter spodbudili znanstveni dialog in razpravo o prehodu na čisto energijo.

1 INTRODUCTION

Clean energy transition represents a topic that has received increased attention from policy makers across Europe, shedding light on the multifaceted interplay of socio-economic, technological and environmental aspects of the transition. To this end, just transition means that society shares both tangible and intangible costs and benefits of transitioning to a low-carbon economy in a socially-just trajectory (Petrakos et al, 2021, Topaloglou 2020, 2021). In this sense, transition can be seen as a means to tackle persistent problems related to transformative and cross-cutting changes, that calls for multi-level governance in light of climate challenges and all-embracing major shifts in governance approaches (Topaloglou and Ioannidis, 2022; Van Engelenburg and Maas, 2018; Jordan et al., 2015). However, in addition to securing sufficient resources and providing technical assistance for their utilisation, a critical factor for the successful outcome of the transition in coal-dependent regions is the establishment of effective monitoring and assessment mechanisms and place-based governance models.

The added value of efficiency measurement for policy formation and evaluation is plainly cited by Lord Kelvin 1824-1907, *'To measure is to know. If you cannot measure it, you cannot improve it. When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind'* (Thomshon, 1916). Given that Just Transition Plans include a number of important transformational policies and transformative plans, the critical question that arises is whether Just Transition Observatories in coal-dependent regions matter, and whether they aim to provide to policy makers the tools to monitor and evaluate transformational policies and transformative projects. In this regard, it is necessary to design evaluation models based on predefined indicators and criteria that will be jointly defined in the context of public consultation.

This paper's scope is, first, to address the main challenges of green strategy and climate neutrality in Europe in terms of policymaking and the need for monitoring mechanisms. Secondly, it seeks to critically review the relative scientific discussion. Thirdly, this paper aims to introduce a conceptualisation of the Just Transition Observatory by testifying its need against various critical socio-economic factors.

The paper is organised as follows. The subsequent section provides a critical theoretical review on the nature of energy transition and the need for monitoring mechanisms. Then, the following section outlines just energy transition policymaking. Section 3 attempts to provide a conceptualisation of a Just Energy Observatory, while Section 4 focuses on the analysis of two selected indicators that could be embedded in the Just Energy Observatory. The final section provides various conclusions and policy recommendations.

2 LITERATURE REVIEW

Over the last decade, innumerable studies have examined the complex interplay of social, economic, environmental, and technological aspects of energy transitions. Although the evidence is mixed, it should be a relatively safe prediction to argue that energy transition can be delivered only if there is a co-evolution of technology, policy, infrastructure, scientific knowledge, social, and governance practices in order to foster regime destabilisation (Geels, 2011). Given the multi-level and multi-faceted character of climate change, the issue of monitoring energy transition has received surprisingly little attention, not just by scholars but also by practitioners and policy-makers. While a plethora of scholarly publications are available addressing governance of energy transition at the local and national level (Betsil and Bulkelev, 2006; Kemp et al, 2007; Loorbach et al, 2007), there have been remarkably few that have focused on the governing of energy transition based on monitoring and assessing mechanisms. The need for tailored approaches to energy transition is very apparent in regions that currently have or have an inheritance of carbon-intensive productive bases (Topaloglou, 2021). For these regions, due to the dominant presence of carbon intensive industry in local economies, the move to a low-carbon economy will deeply influence local jobs, industry infrastructure, and the entirety of the regional economy.

From a policy-making point of view, transition management takes place in a multi-actor environment, placing particular emphasis on the role of central government as an agent of change. At the same time, the role of local and regional authorities, energy business actors, key stakeholders and civil society organisations appears to be of great importance. OECD (2013), in a working paper entitled 'monitoring the transition to a low-carbon economy', argues that local governments, together with other local institutions, will be central agents in the success of the transition of regional areas to low-carbon economies (OECD 2013). Local governments typically hold multiple roles as decision-makers, planning authorities, managers of municipal assets, operators of local energy providers and role models for the public (ICLEI 2012). Local government also has an important amount of land property and a large degree of impact over land-use policies, which means they can influence, to some extent, the regulatory limits for energy activities (Miranda and Larcombe, 2012). Seen in this respect, Petrakos et al, (2021), argue that the endeavour of transition requires a multi-level governance environment that influences the decision-making process, the financial means, and interventions.

As a result, transition arenas usually unfold in a multi-actor development of visions, deliberative decision, and policymaking, as well as coordination of actions to set up, manage and evaluate

transition experiments that contribute to niche development (Loorbach, 2008). To this end, a major limitation of an effective clean energy transition process is the lack of a comprehensive and defensible monitoring mechanism for collecting, collating, analysing, assessing, and providing policy recommendations at multiple scales. Evidence shows that so far, the existing data are very incomplete, fragmented, heterogeneous and not easily available to end users (Hoppe and Miedema, 2020).

This observational framework seems to be lacking at present, yet it would significantly help in identifying, monitoring, and evaluating the just energy transition. The outcomes of such an Observatory, could be used to develop and evaluate a targeted and effective just energy transition. In this aftermath, the multidimensional nature of energy transition calls for a multi-indicator framework for effective measuring and monitoring, gaining greater recognition in literature (Kagimu & Ustun, 2016) and deserves to be replicated. Such a framework would offer the possibility of establishing specific monitoring mechanisms to observe just energy transition in each area, strongly affected by climate change. Through the deliberative process of deciding ‘what’ to measure, monitor and use as indicators for performance, stakeholders can develop a shared understanding and responsibility for developing and populating indicators (OECD, 2015). Therefore, this monitoring mechanism should reflect the views of different actors and emphasise the engagement of all key-stakeholders (Topaloglou and Ioannidis, 2022), taking into account the various institutionalised modes of social coordination to provide collective goods (Börzel and Risse, (2010).

A crucial factor in the transition monitoring mechanism seems to be the prioritisation of indicators to track progress and effectiveness of interventions, given the amount of public and private investment and projects being made in each of these areas to facilitate the transition. Evidence shows that agreement on a set of common indicators for measuring and populating these indicators requires stakeholder engagement to inform and validate the indicator selection process. It is noteworthy that while many initiatives at the national and local level can certainly be found, there is also a significant number of inconsistencies and a lack of agreement concerning the indicators needed to be analysed and assessed. It is widely recognised that energy transition indicators must begin from a baseline. If we are to accurately assess energy transition, then this baseline will need to incorporate the critical local assets. Each area has an array of existing production base, including the labour force and capital stock (OECD, 2015). These initial conditions and assets shape the trajectory of the local area’s pathway to a climate neutral paradigm. To this end, local trajectories will be unique for each area because of the different compositions of stocks and activities (Topaloglou, 2021).

3 JUST ENERGY TRANSITION POLICYMAKING

The adoption of the 17 Sustainable Development Goals (SDGs) by the UN in the 2030 Agenda reflects the just transition policymaking at a global level. The SDGs aim to ensure sustainable global, social and economic development as well as universal peace. At European level, seen from a just transition perspective within the context of the European Green Deal, the European Commission has set out a roadmap for a new growth policy for the EU towards climate neutrality by 2050, aiming to leave no person and no region behind. The European Green Deal for the European Union (EU) and its citizens is a new growth strategy that aims to transform the EU into a fair and prosperous society, with a modern, resource-efficient and competitive economy

where there are no net emissions of greenhouse gases in 2050 and where economic growth is decoupled from resource use. The main goals that need to be monitored and assessed deal with climate ambition targets, supplying clean, affordable and secure energy, accelerating sustainable mobility, designing the 'Farm to Fork Strategy', preserving and restoring biodiversity and supporting a zero-pollution policy. From the above, an effective mechanism able to monitor and assess the fulfilment of these ambitious goals is vital.

In this setting, the Just Transition Mechanism focuses on the regions and sectors that are most affected by the transition due to their dependence on fossil fuels. The mechanism consists of three pillars. Firstly, the Just Transition Fund, secondly, a dedicated scheme under the InvestEU programme, and thirdly, a public sector loan facility provided by the European Investment Bank to mobilise additional investments in the regions concerned. The Just Transition Fund receives the lion's share aiming to support the territories most affected by the transition and for preventing an increase in regional disparities, as well as mitigating any negative repercussions on employment.

To accomplish the above objectives, the Just Transition Fund supports transformative investments in the involved areas, the reduction of GHG emissions, the regeneration of local economies, the reskilling of workers and technical assistance. Support will also be available for all Member States, focused on regions that are the most carbon-intensive or with the most people working in fossil fuels. Member States can gain access by preparing Territorial Just Transition Plans that cover the period up to 2030, identifying the territories that should receive the most support. These Plans should also set out ways to best address social, economic, and environmental challenges.

Given that many people and citizens are vulnerable to the transition, the Just Transition Mechanism aims to protect them by facilitating employment opportunities in new sectors, offering both reskilling and upskilling support, improving energy-efficient housing, fighting energy poverty, and facilitating access to clean, affordable and secure energy. On the other hand, companies and sectors active in carbon-intensive industries can be supported by the Just Transition Mechanism through creating attractive conditions for public and private investment, providing easier access to loans and financial support, investing in the creation of new firms, SMEs and start-ups, and devoting themselves to research and innovation activities.

In parallel, all Member States have embedded in their National Energy and Climate Plans (NECPs) targets, policies, and measures to reach the ambitious goals towards EU climate neutrality by 2050. It is worth noting that according to EC working Documents (EC 275, 2021), proposals to extend the geographical scope to territories where there is no clear transition process with an associated negative socio-economic impact by 2030 or before, should not be accepted. In this context, the TJTPs should describe the transition process at national and local levels, including a timeline for key transition steps towards 2030 and 2050 climate targets, in compliance with the respective NECP. The TJTP will also need to demonstrate clear evidence of a transition process and its impact at the level of the concerned territory in the near future. Based on the requirements of the TJTPs, several social, economic and environmental indicators are mandatory for monitoring and reporting (EC, 2020).

Having touched upon just transition policymaking, it is also necessary to address an appropriate framework of a Just Transition Observatory in the coal-dependent regions aiming to create a replicable model focusing on the governance of the energy transition applicable in each Euro-

pean region. These regions must integrate just energy transition policies into social, energy and environment policies from a multi-level governance perspective.

4 CONCEPTUALISATION OF A JUST TRANSITION OBSERVATORY

In order to conceptualise the proposed monitoring mechanism, it is useful to start from the assumption that the Just Transition Process deals with a drastic restructuring of the regional economic model and environmental and societal status, something which is well-established and has been operative for many decades. Thus, this transition process requires fast and robust actions in order to shift the local economy towards a sustainable, resilient and just development model by introducing coal-dependent areas to a carbon-free regime (Giannakopoulos et al, 2022).

Furthermore, we consider that the transition process goes beyond the boundaries of the phasing out of the carbon/lignite industry, tackled by Just Transition Mechanism, and instead involves shaping a new holistic regional development paradigm, which requires new infrastructure, new skills, and new business activities under a new regional branding. Within this context, a significant amount of information should be collected, assessed and discussed in order to support actions and measures, as well as to evaluate their progress and success. Due to the multidisciplinary character of the transition process and the involvement of EU, national, regional and local authorities/stakeholders, centralised and specialised data handling monitoring is considered a crucial parameter of success.

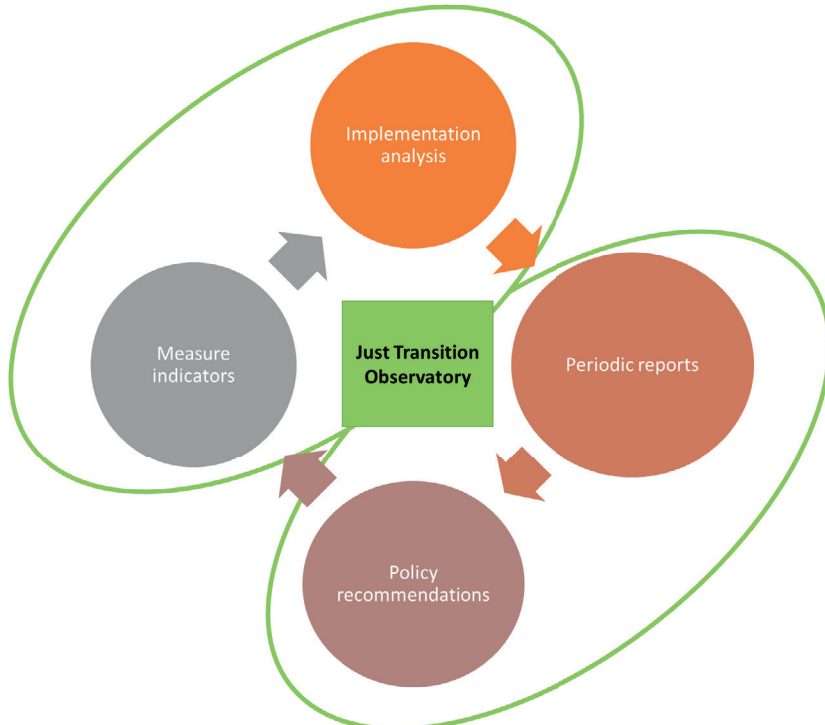


Figure 1: Conceptualization of a Just Transition Observatory.

Additionally, we suggest that the Just Transition Observatories act as an independent mechanism that combine the Just Transition needs with the broader climate policies, measures and initiatives as formed in different levels (national, regional, municipal), in order to facilitate the transformation of local entities to a zero-carbon era. To this end, Just Transition Observatories' Platform along coal-dependent areas could incorporate data and information indicatively regarding NCEPs, TJTPs, ROPs, OECD SDGs reports, Covenant of Mayors reports, EUROSTAT, National Statistics etc., producing evidence-based reports and studies on clean energy transition, as well as comparative studies on transition processes on a regional and EU basis.

Taking into consideration the above analysis, Figure 1 illustrates the conceptual approach of the Just Transition Observatory articulated on an input-output logic. The input segment involves measurements based on predefined indicators and implementation analysis. The output part consists of periodic reports which assess the implementation and consistency with the predefined goals and policy recommendations aiming to improve transition policy efficiency.

Figure 2 demonstrates the critical stakeholders who should be actively involved in a Just Transition Observatory, such as central and local governments, academic and research institutions, the energy companies, the main societal actors and the European Commission.



Figure 2: Stakeholders of a Just Transition Observatory.

Attempting to ensure the viability of the proposed monitoring mechanism, Figure 3 identifies the potential funding resources of the Just Transition Observatory, consisting of EU, national and private funds.

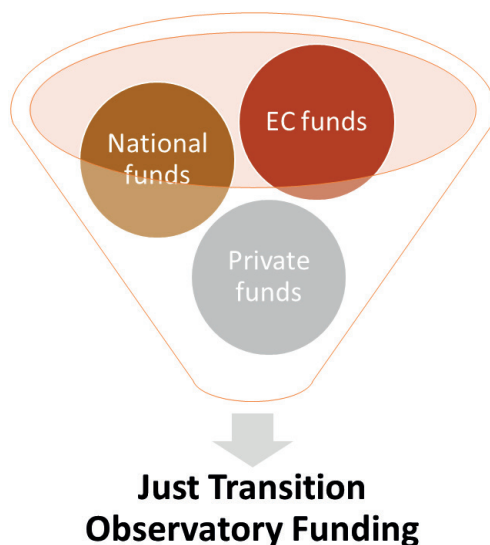


Figure 3: Funding of a Just Transition Observatory.

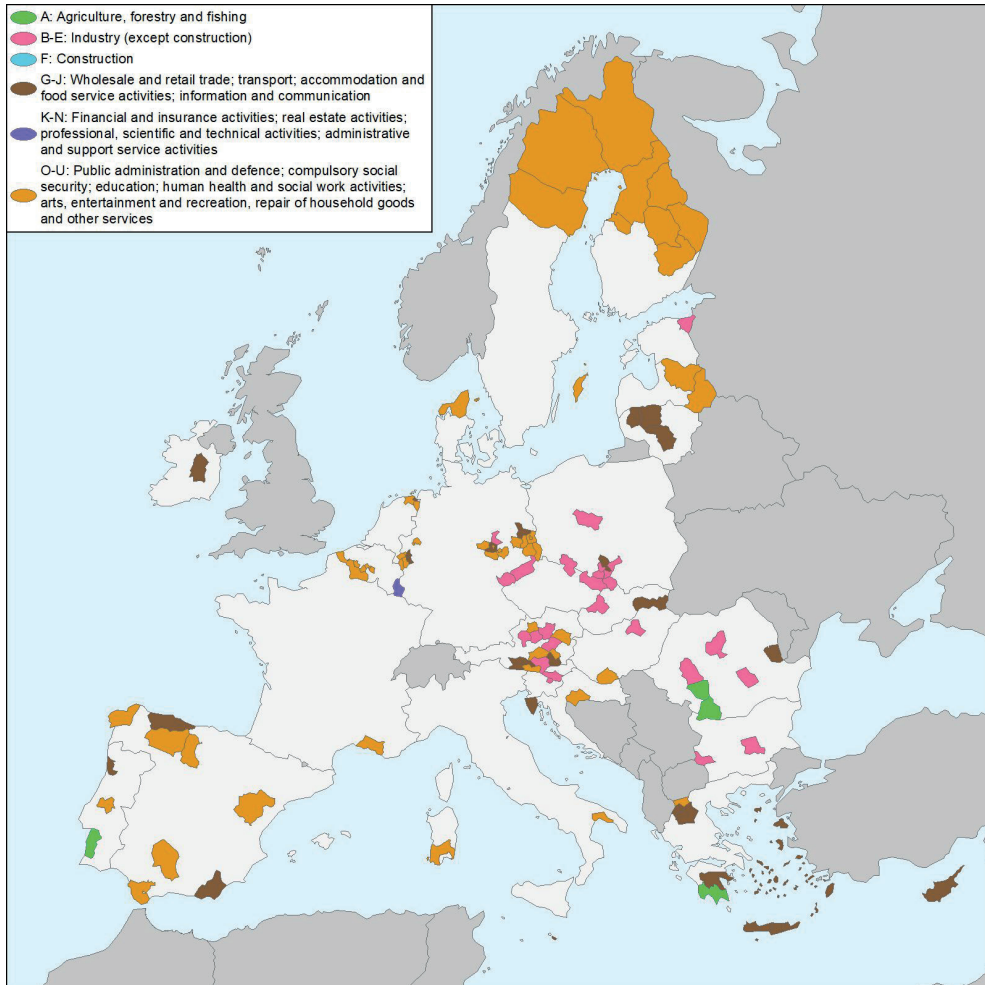
5 ANALYSIS

In order to ascertain the foreseen outcome of the discussed structure of the Just Transition Observatory, a preliminary analysis of selected parameters was carried out. Taking into consideration that employment, Gross Value Added and business environment growth are critical issues for just regional transition, an analysis of their characteristics at the regional level was carried out.

This work focused on the Just Transition Mechanism (JTM) territories, initiating their radical change from a heavily-dependent on CO₂ emissions technological and economical model to a climate-neutral economy. It must be mentioned that during the period 2021-2027, a goal of around €55 billion will be mobilised for the most-affected regions under the target, in order to ensure that no one will be left behind.

An analysis of the position of sectors' shares in the TJTP areas with respect to the national share, as well as the maximum and minimum share in all NUTS3 countries' areas, was carried out. In the following Map 1, we can see the dominant economic sector regarding employment in TJTP areas. For reasons of discussion, only four selected cases are presented, dealing with Germany, Greece, Bulgaria, and the Czech Republic, illustrated in Figure 4. Based on a level of further analysis, conclusions can be drawn for each individual area, with respect to their national position and national/local policies, as well as for groups of areas. For example, for many sectoral cases, a wide spread is observed, while for other cases, all national TJTP areas are either below the average national share (e.g. [K-N] Greece, [G-J] Bulgaria, [K-N] the Czech Republic) or above it ([B-E] & [O-U] the Czech Republic).

The selection of the countries examined, namely Germany, Greece, Bulgaria and the Czech Republic, was made with respect to the representation of significant dependency on the coal/lignite industry, phase out discussion readiness, and countries' profiles.



Map 1: Employment: Dominant sector per TJTP area (2019). Data source: Eurostat

Amongst TJTP areas, [O-U] sector is dominant in 55 cases, representing 16.1% of the total number of employees, which deals with 19.9 million people for total areas (28.9% sectors total share in all TJTP areas). In addition to this, significant impact presents [G-J] dealing with 33 areas of 8.6% employees (27.0% share in total TJTP areas) and [B-E] in 26 areas with 7.5% (18.5% share in total TJTP areas). Sector [A] is dominant in only four areas related to 0.9% employees (5.3% share in total TJTP areas) and [K-N] deals with 1 area and 0.7% (13.4% share in total TJTP areas). Sector [F] has a total share of 6.8% in all TJTP areas in not governing any examined area. It must be noticed that [O-U] presents a key position as a local and total areas sector, while [G-J] and [B-E] are crucial in long scale with less significance in local scale.

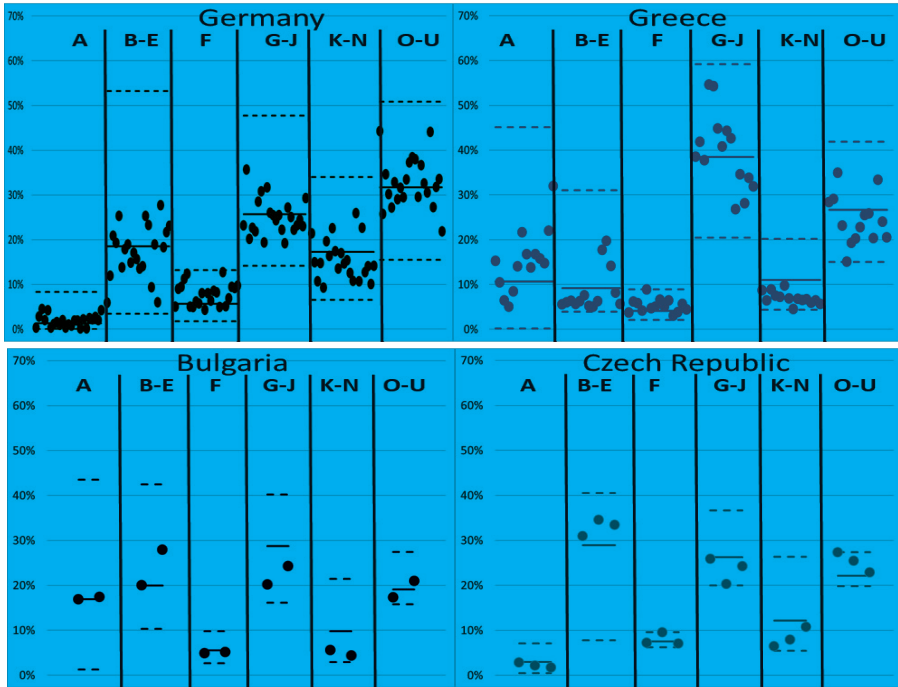
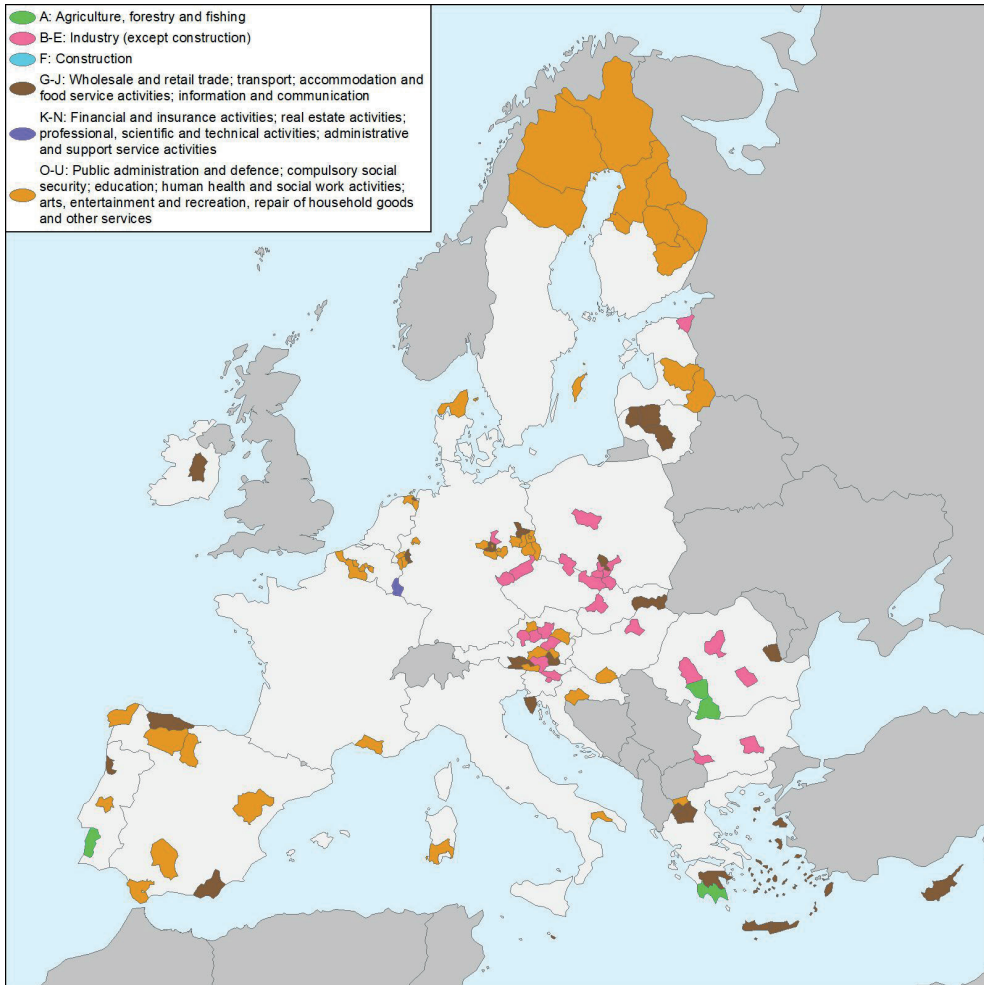


Figure 4: Percentage of employment per TJTP areas in Germany, Greece, Bulgaria, Germany and the Czech Republic compared to national characteristics (2019).

Taking into consideration Gross Value Added (GVA), as we can see in Map 2, amongst TJTP areas, [B-E] sector is dominant in 50 cases representing 10.1% of the total examined areas GVA, which deals with 1,019.486 €, (21.6% sectors total share in all TJTP areas), followed by sector [O-U] dealing with 42 areas of 11.5% total GVA (24.0% share in total TJTP areas). Sector [G-J] is dominant in 21 areas with 5.0% (22.2% share in total TJTP areas) and [K-N] in only 6 areas related to 5.5% (23.5% share in total TJTP areas). Sectors [A] with a total share of 2.4% and [F] with 6.2% share in all TJTP areas are not governing any examined area. Moreover, in this case, we can see that [O-U] presents a key position as a local and total areas sector, followed by [B-E], while [G-J] and [K-N] are significant in long-scale analysis.

In Figure 5, the analysis of the position of the sectors' shares in the TJTP areas GVA, with respect to the national share, as well as the maximum and minimum share in all NUTS3 countries' areas, is illustrated for the same selected countries as above. In addition to this, in this case, a wider spread is observed for numerous sectoral contributions in individual areas amongst countries, resulting in required specific local policies, while in other cases sectoral measures may arise. In the countries examined, all national TJTP areas are either below the average national share (e.g. [G-J] Bulgaria, [G-J] & [K-N] the Czech Republic) or above it ([A] Bulgaria).



Map 2: Gross Value Added: Dominant sector per TJTP area (2019). Data source: Eurostat.

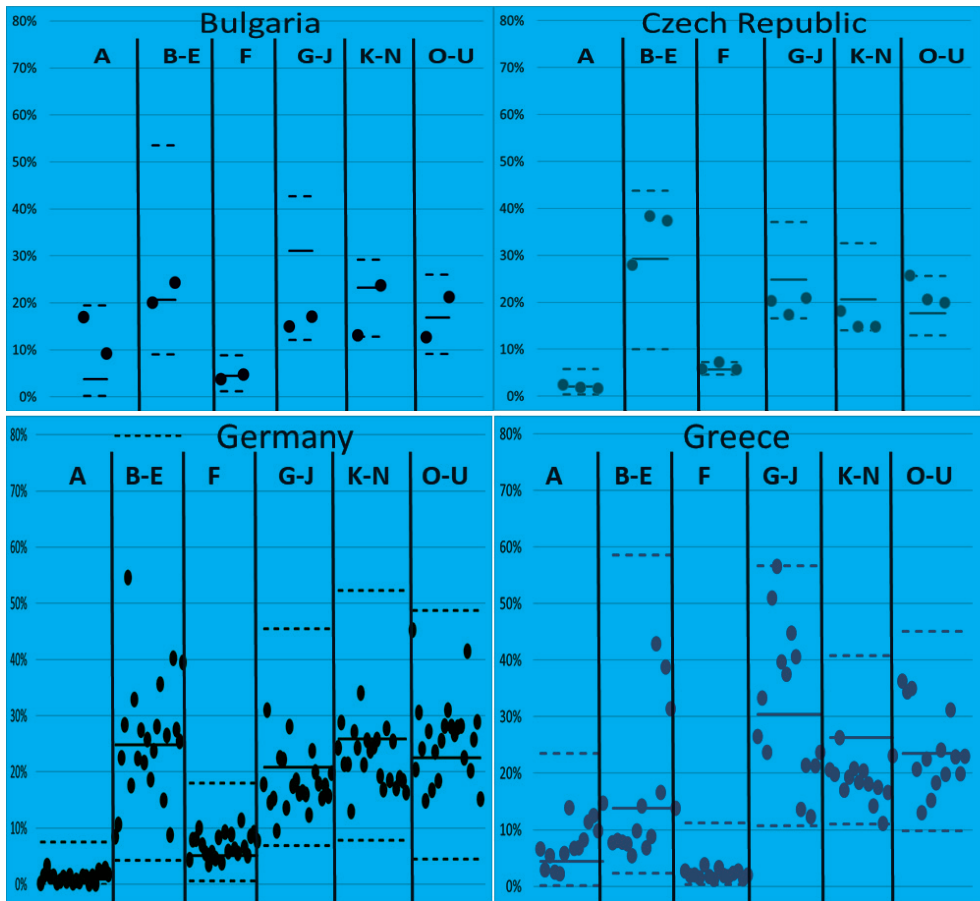


Figure 5: Share of Gross Value Added per TJTP areas in Germany, Greece, Bulgaria and Czech Republic (2019) compared to national characteristics.

The examination of the ratio of employment per GVA could provide a valuable indicator for further analysis of growth potential at the national and regional level. Figure 6 illustrates the respective indicator for the four examined countries.

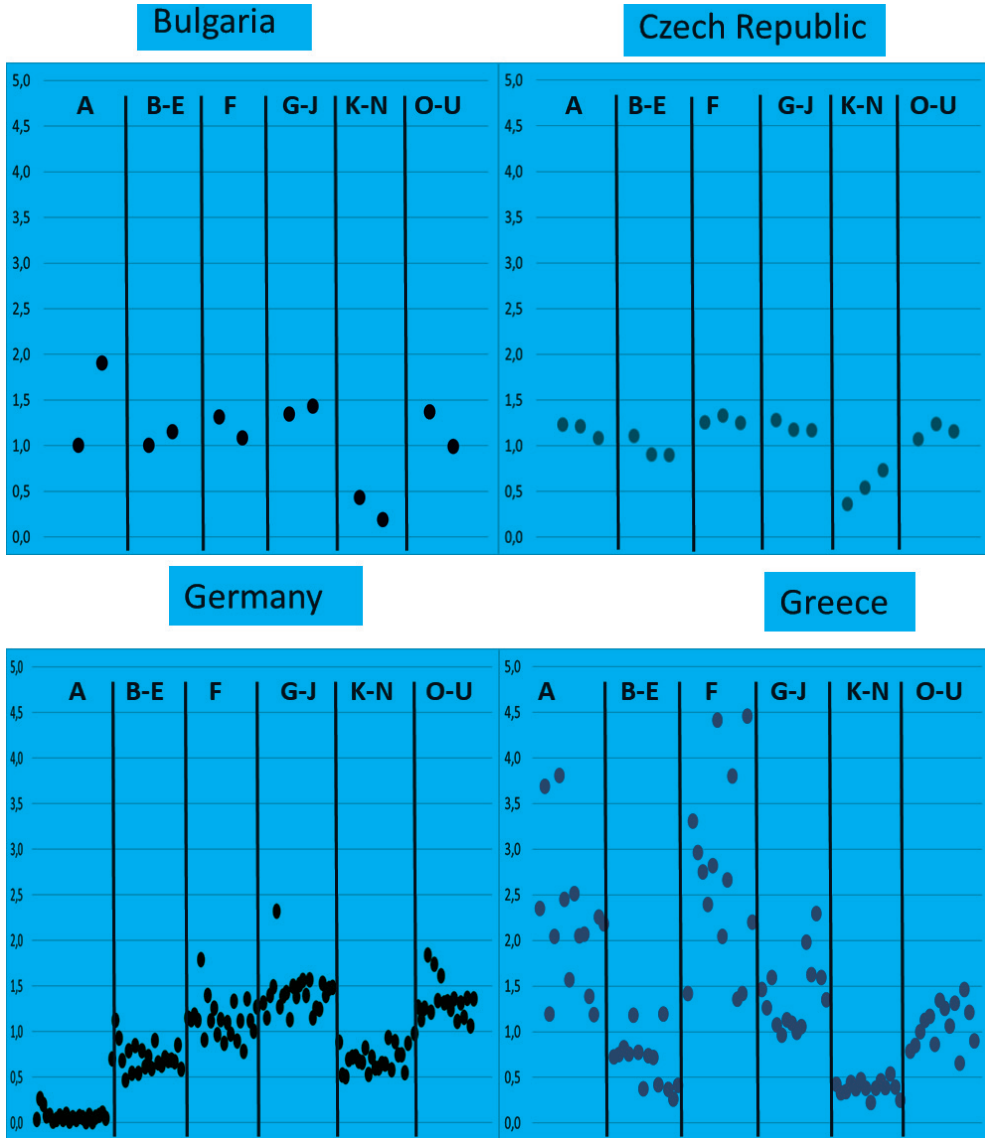
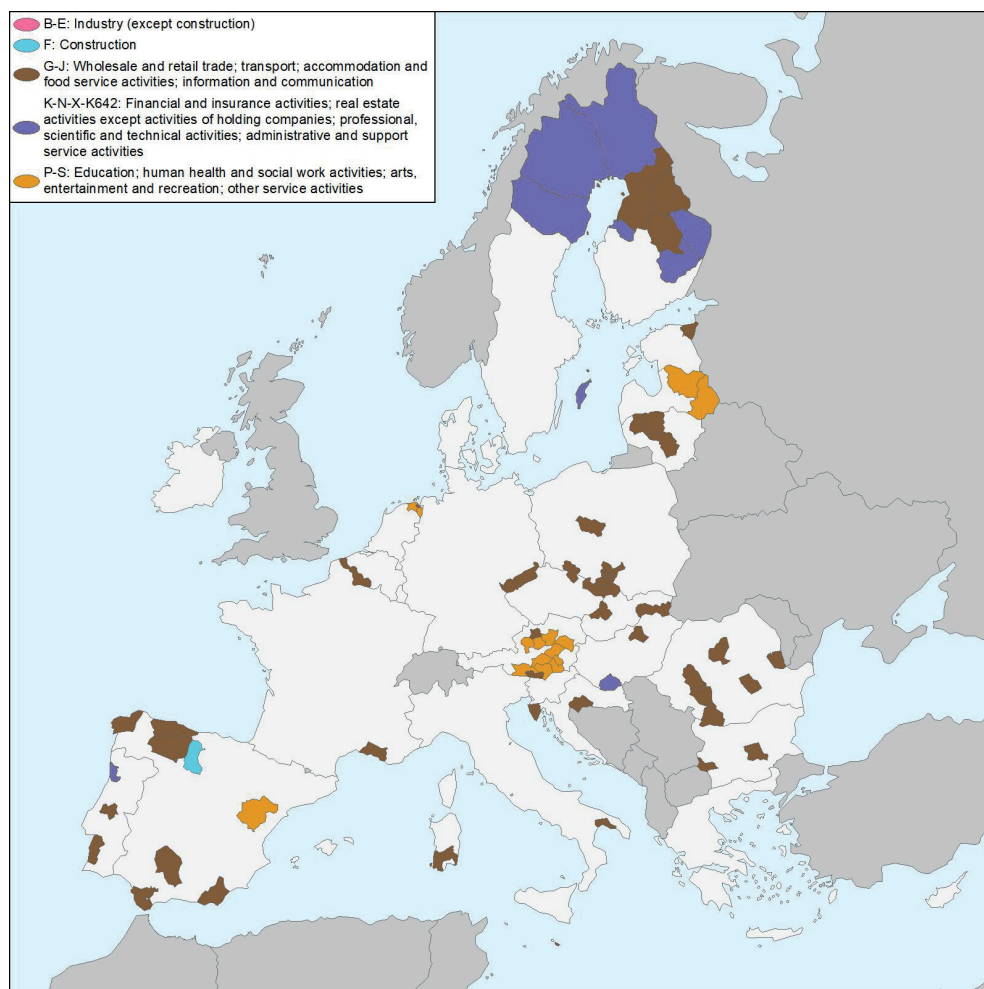


Figure 6: Ratio of employment / GVA per TJTP areas in Germany, Greece, Bulgaria and the Czech Republic (2019) compared to national characteristics.



Map 3: Business demography: Dominant sector per TJTP area (2019). Data source: Eurostat.

The examination of Business demography amongst TJTP areas, Map 3, results in the requirement for further data availability, since published data are only available for 73 of the 119 areas examined. From this arises a further work and usefulness of proposed Observatory to act as an intermediate stakeholder amongst regional, national and EU authorities to identify information needed, data gaps and contribute to further actions for common EU indicators development.

In terms of the Business demography analysis, [G-J] sector is dominant in 48 cases, followed by 15 of [P-S], while [K-N-X-K642] is related to only 9 areas and [F] to one.

The analysis of the newly-born businesses in the last 3 years achieving the continuation of their activities as a share of total business activities in the examined area is proposed as an economic growth indicator to be used in the Observatory, as illustrated in the Figure 7. It must be noted that TJTF areas achieved a higher score than 90% of the examined cases areas in Austria, Bel-

gium, Latvia, Lithuania, Malta and Romania. Specific analysis of these may provide useful results for replication, as well as Best Practices that could then be developed and disseminated.

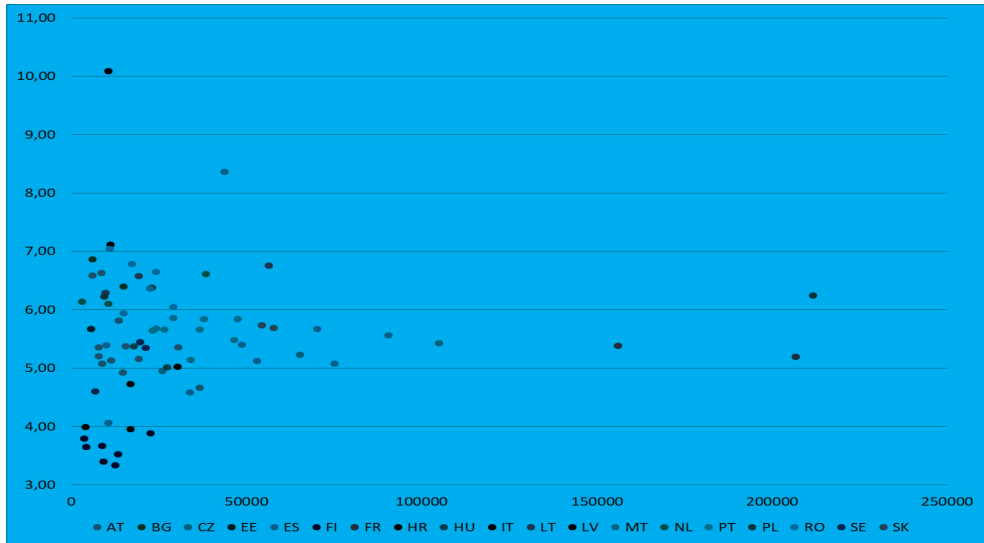


Figure 7: Percentage of newly-born active enterprises in the last 3 years per TJTP area (2019, Eurostat).

6 CONCLUSIONS

Given the longitudinal nature of green transition and climate change, the theme of establishing an objective monitoring mechanism of just transition policies per each affected region across the EU is challenging and necessary, particularly at this time, in view of the Just Transition Fund's unfolding. Considering that climate neutral goals will remain in place over the next few decades, comprehensive and inclusive policies, as well as efficient means, instruments and valid indicators, are indispensable.

Hence, a consensus on both mechanisms and a set of common indicators for measuring these indicators requires stakeholder engagement and agreement to inform and validate the indicator selection process. By selecting, through consultation processes, 'what' exactly to measure, monitor and use as indicators for performance, stakeholders can develop a shared understanding and responsibility for developing and updating indicators. In turn, this has the potential to create a local platform for co-operation amongst institutions based on different and multi-layered responsibilities and expertise.

This paper addresses the need of establishing an Observatory, aiming to monitor and assess the just transition endeavour in each coal-dependent area in Europe, based on co-created and pre-defined indicators and criteria. For the sake of the discussion, three pilot indicators have been selected to be analysed in a comparative perspective at a European, national and regional level. In particular, the critical parameters of employment, gross value added, and business en-

vironment growth have been explored and evaluated per economic sector in Germany, Greece, Bulgaria and the Czech Republic.

The preceding analysis has shown that establishing a comprehensive local transition monitoring mechanism and developing collectively-agreed indicators in a participatory way, could essentially assist the Just Transition Goals of local policies. Multi-level governance practices and co-ordination between multi-layered stakeholders in these planning, implementation, and monitoring processes within and amongst regions could prove crucial. The truth is that institutional and regional boundaries do not often match up in real life. As a result, a tailor-made approach that ensures a process of stakeholder engagement must be developed per each involved area.

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ANNEX

Table 1: NUTS3 territories proposed or included in TJTPs

NUTS3 Territory	Status	Area (%)
AT121–Mostviertel-Eisenwurzen	Included in approved TJTP	100%
AT122–Niederösterreich-Süd	Included in approved TJTP	100%
AT211–Klagenfurt-Villach	Included in approved TJTP	50%
AT212–Oberkärnten	Included in approved TJTP	13%
AT213–Unterkärnten	Included in approved TJTP	100%
AT221–Graz	Included in approved TJTP	89%
AT223–Östliche Obersteiermark	Proposed by EC and included in approved TJTP	100%
AT225–West- und Südsteiermark	Included in approved TJTP	38%
AT226–Westliche Obersteiermark	Included in approved TJTP	100%
AT312–Linz-Wels	Included in approved TJTP	29%
AT314–Steyr-Kirchdorf	Included in approved TJTP	55%
AT315–Traunviertel	Proposed by EC and included in approved TJTP	100%
BE323–Arr. Mons	Proposed by EC	100%
BE328–Arr. Tournai-Mouscron	Proposed by EC	86%
BE32B–Arr. Charleroi	Proposed by EC	100%
BE32C–Arr. Soignies	Proposed by EC	23%
BG344–Stara Zagora	Proposed by EC	100%
BG415–Kyustendil	Proposed by EC	100%
CY000–Kýpros	Proposed by EC and included in approved TJTP	100%
CZ041–Karlovarský kraj	Proposed by EC	100%
CZ042–Ústecký kraj	Proposed by EC	100%

NUTS3 Territory	Status	Area (%)
CZ080–Moravskoslezský kraj	Proposed by EC	100%
DE402–Cottbus, Kreisfreie Stadt	Proposed by EC	100%
DE406–Dahme-Spreewald	Proposed by EC	100%
DE407–Elbe-Elster	Proposed by EC	100%
DE40B–Oberspreewald-Lausitz	Proposed by EC	100%
DE40G–Spree-Neiße	Proposed by EC	100%
DEA15–Mönchengladbach, Kreisfreie Stadt	Included in approved TJTP	100%
DEA1D–Rhein-Kreis Neuss	Proposed by EC and included in approved TJTP	100%
DEA26–Düren	Proposed by EC and included in approved TJTP	100%
DEA27–Rhein-Erft-Kreis	Proposed by EC and included in approved TJTP	100%
DEA29–Heinsberg	Included in approved TJTP	100%
DEA2D–Städteregion Aachen	Included in approved TJTP	100%
DEA31–Bottrop, Kreisfreie Stadt	Included in approved TJTP	100%
DEA36–Recklinghausen	Included in approved TJTP	39%
DED2C–Bautzen	Proposed by EC	100%
DED2D–Görlitz	Proposed by EC	100%
DED51–Leipzig, Kreisfreie Stadt	Proposed by EC	100%
DED52–Leipzig	Proposed by EC	100%
DEE02–Halle (Saale), Kreisfreie Stadt	Proposed by EC	100%
DEE05–Anhalt-Bitterfeld	Proposed by EC	100%
DEE08–Burgenlandkreis	Proposed by EC	100%
DEE0A–Mansfeld-Südharz	Proposed by EC	100%
DEE0B–Saalekreis	Proposed by EC	100%
DK050–Nordjylland	Proposed by EC	100%
EE00A–Kõrde-Eesti	Proposed by EC	100%
EL411–Lesvos, Limnos	Proposed by EC and included in approved TJTP	100%
EL412–Ikaria, Samos	Proposed by EC and included in approved TJTP	100%
EL413–Chios	Proposed by EC and included in approved TJTP	100%
EL421–Kalymnos, Karpathos, Kasos, Kos, Rodos	Proposed by EC and included in approved TJTP	100%
EL422–Andros, Thira, Kea, Milos, Mykonos, Naxos, Paros, Syros, Tinos	Proposed by EC and included in approved TJTP	100%
EL431–Irakleio	Proposed by EC and included in approved TJTP	100%
EL432–Lasithi	Proposed by EC and included in approved TJTP	100%
EL433–Rethymni	Proposed by EC and included in approved TJTP	100%
EL434–Chania	Proposed by EC and included in approved TJTP	100%
EL531–Grevena, Kozani	Proposed by EC and included in approved TJTP	100%
EL532–Kastoria	Proposed by EC and included in approved TJTP	100%
EL533–Florina	Proposed by EC and included in approved TJTP	100%
EL651–Argolida, Arkadia	Proposed by EC and included in approved TJTP	49%
EL653–Lakonia, Messinia	Included in approved TJTP	6%
ES111–A Coruña	Proposed by EC	100%
ES120–Asturias	Proposed by EC	100%
ES242–Teruel	Proposed by EC	100%
ES413–León	Proposed by EC	100%
ES414–Palencia	Proposed by EC	100%

NUTS3 Territory	Status	Area (%)
ES611–Almería	Proposed by EC	100%
ES612–Cádiz	Proposed by EC	100%
ES613–Córdoba	Proposed by EC	100%
FI1D1–Etelä-Savo	Proposed by EC	100%
FI1D2–Pohjois-Savo	Proposed by EC	100%
FI1D3–Pohjois-Karjala	Proposed by EC	100%
FI1D5–Keski-Pohjanmaa	Proposed by EC	100%
FI1D7–Lappi	Proposed by EC	100%
FI1D8–Kainuu	Proposed by EC	100%
FI1D9–Pohjois-Pohjanmaa	Proposed by EC	100%
FRE11–Nord	Proposed by EC	100%
FRL04–Bouches-du-Rhône	Proposed by EC	100%
HR028–Sisačko-moslavačka županija	Proposed by EC	100%
HR036–Istarska županija	Proposed by EC	100%
HU231–Baranya	Proposed by EC	100%
HU312–Heves	Proposed by EC	100%
IE063–Midland	Proposed by EC	100%
ITF43–Taranto	Proposed by EC	100%
ITG2H–Sud Sardegna	Proposed by EC	23%
LT022–Kauno apskritis	Proposed by EC	100%
LT026–Šiaulių apskritis	Proposed by EC	100%
LT028–Telšių apskritis	Proposed by EC	100%
LU000–Luxembourg	Proposed by EC	1%
LV005–Latgale	Proposed by EC	100%
LV008–Vidzeme	Proposed by EC	100%
MT001–Malta	Proposed by EC	11%
NL111–Oost-Groningen	Proposed by EC	100%
NL112–Delfzijl en omgeving	Proposed by EC	100%
NL113–Overig Groningen	Proposed by EC	100%
PL225–Bielski	Proposed by EC	100%
PL227–Rybnicki	Proposed by EC	100%
PL228–Bytomski	Proposed by EC	100%
PL229–Gliwicki	Proposed by EC	100%
PL22A–Katowicki	Proposed by EC	100%
PL22B–Sosnowiecki	Proposed by EC	100%
PL22C–Tyski	Proposed by EC	100%
PL414–Koniński	Proposed by EC	100%
PL517–Wałbrzyski	Proposed by EC	100%
PT11A–Área Metropolitana do Porto	Proposed by EC	3%
PT16I–Médio Tejo	Proposed by EC	100%
PT181–Alentejo Litoral	Proposed by EC	100%
RO125–Mureș	Proposed by EC	100%
RO224–Galați	Proposed by EC	100%
RO316–Prahova	Proposed by EC	100%
RO411–Dolj	Proposed by EC	100%

NUTS3 Territory	Status	Area (%)
RO412–Gorj	Proposed by EC	100%
RO423–Hunedoara	Proposed by EC	100%
SE214–Gotlands län	Included in approved TJTP	100%
SE331–Västerbottens län	Proposed by EC and included in approved TJTP	100%
SE332–Norrbottens län	Proposed by EC and included in approved TJTP	100%
SI034–Savinjska	Proposed by EC	100%
SI035–Zasavska	Proposed by EC	100%
SK022–Trenčiansky kraj	Proposed by EC	100%
SK042–Košícký kraj	Proposed by EC	100%

ENERGY SOURCE REPLACEMENT IN A THERMAL POWER PLANT

ZAMENJAVA ENERGENTA V TERMOELEKTRARNI

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Keywords: wood biomass, thermal power plant, electricity production

Abstract

In Slovenia, approximately one third of electricity is produced in thermal power plants. Electricity prices have risen sharply recently. There are several reasons for this. One of them is the large increase in the price of CO₂ coupons that thermal power plants have to buy, since they emit large amounts of greenhouse gas into the environment during the production of electricity. Emissions of the greenhouse gas CO₂ are the result of burning fossil fuels, in this case coal. We want to use renewable energy sources to replace fossil fuels and reduce greenhouse gas emissions. More than half of Slovenia is covered with forest, and as a result, wood biomass energy represents a great energy potential. One possibility is the use of wood biomass in a classic thermal power plant for the production of electricity. This contribution presents the energy potential of Slovenian forests, before evaluating the replacement of the energy source in the existing coal-based thermal power plant with wood biomass. It has been discovered that there is enough wood biomass in Slovenia, and that all the electricity that is currently produced from coal can be produced from wood biomass. The cost of wood biomass is higher than the cost of coal. By changing the energy source, we save on the purchase of CO₂ coupons. Therefore, the use of wood biomass represents an economically justified energy source for the production of electricity.

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Povzetek

V Sloveniji približno eno tretjino električne energije proizvedemo v termoelektrarnah. Električna energija se je v zadnjem času močno podražila – razlogov za to je več. Eden izmed njih je veliko povišanje cene emisijskih kuponov, ki jih morajo kupovati termoelektrarne, saj pri proizvodnji električne energije v okolje emitirajo izdatne količine toplogrednega plina. Emisije toplogrednega plina CO₂ so posledica zgorevanja fosilnih goriv, v tem primeru premoga. Z obnovljivimi viri energije želimo nadomestiti fosilna goriva in zmanjšati emisije toplogrednih plinov. Več kot polovica Slovenije je pokrita z gozdom, zato energija lesne biomase predstavlja velik energetski potencial. Ena od možnosti je uporaba lesne biomase v klasični termoelektrarni za proizvodnjo električne energije. V tem prispevku predstavimo energetski potencial slovenskih gozdov in ovrednotimo zamenjavo energenta v obstoječi termoelektrarni na premog z lesno biomaso. Ugotovitve kažejo, da je v Sloveniji dovolj lesne biomase, da lahko iz nje proizvedemo vso električno energijo, ki jo sedaj pridobivamo iz premoga. Strošek lesne biomase je višji od stroška premoga, vendar z zamenjavo energenta prihranimo pri nakupu emisijskih kuponov. Tako je uporaba lesne biomase ekonomsko upravičen energent za proizvodnjo električne energije.

1 INTRODUCTION

Renewable energy sources include all energy sources that are captured from constantly repeating natural processes. Renewable energy sources (RES) include solar radiation, wind, water flow in rivers, photosynthesis, ground heat flows and sea currents. Renewable energy sources locally reduce import dependence and increase energy security. The industry related to RES promotes greater employment and rural development. The most important renewable energy source in Slovenia is wood biomass, followed by water energy, while the use of solar energy has also been increasing recently. Slovenia had set a national goal of achieving at least a 25% share of RES in the final gross energy consumption by 2020. However, Slovenia itself did not reach this target. The achieved share of energy use from renewable sources was 24.1%. In order to fulfil the set goal, Slovenia concluded an agreement with the Czech Republic and, with the help of the mechanism of statistical transfer of renewable energy, transferred 465 GWh of energy from another EU member state and thus avoided sanctions. By 2030, Slovenia has set an overarching national goal of achieving at least a 27% share of RES in the final gross energy consumption. In accordance with the National Energy and Climate Plan (NECN), the sectoral target shares of RES in the gross final use of energy are also set for 2030. In the heating and cooling sector, the share of RES is 41.4%, in the electricity sector the share is 43.3% and in the transport sector 20.8%, with a projected share of biofuels of at least 11%. In 2020, the share of RES in the heating and cooling sector was 32.14%, in the electricity sector 35.09% and in the transport sector 10.91%. [1] It follows that we will have to significantly increase the share of RES in all sectors.

The aim of this research is to analyse the replacement of coal as an energy source with wood biomass in a thermal power plant.

2 DATA AND METHODS

2.1 Thermal power plant

For the analysis, we will use data from 2019. During this year, the Šoštanj thermal power plant (TEŠ) operated two blocks, block 5 and block 6. Block 5 produced 775,028 MWh and block 6 produced 3,397,672 MWh of electricity. [2] A total of 4,195,305 MWh and 3,720,821 MWh of electricity were produced on both generators. They used 3,040,612 tons of lignite coal from Velenje. The calorific value of coal was 11,874 GJ/t. Depending on the technology used in the individual blocks, the specific CO₂ emissions in block 5 are 1.090 kg/MWh and 0.869 kg/MWh in block 6. In total, CO₂ emissions amounted to 3,800 tons. Companies need emission coupons for greenhouse gas emissions. For each emission coupon, the company can release 1 ton of CO₂ into the atmosphere or an equivalent amount of another greenhouse gas that is equally or similarly harmful to the environment. Companies that need emission coupons buy them on the emissions market. The basic idea behind emission coupons is to encourage companies to focus on operations that are kinder to nature and the planet. Emission coupons are issued by the European Union, and the total number of issued coupons decreases every year. In doing this, the European Union seeks to reduce the amount of greenhouse gases in the atmosphere over time. In the period between 2021 and 2030, 2.2% fewer coupons are issued each year. Figure 1 shows the evolution of emission coupon prices over time. The diagram shows that the price of coupons was low until 2018 and was around €10 per ton of CO₂. This price then rose above €20 per ton, with a subsequent sharp jump in 2021. In August 2022, the maximum price was recorded at almost €100 per coupon. The current price is around €80.



Figure 1: Emission coupons prices on the stock exchange

The price of coal and the cost of emission coupons have the greatest influence on the own price of the electricity produced in the thermal power plant. In 2019, the Šoštanj thermal power plant

produced 3,721 GWh of electricity and recorded €217.8 million in revenues from the sale of electricity, or a total of €225.9 million in revenues from the sale of electricity and heat. 3,040,612 tons of coal were used for the production of electricity and heat. The price of coal is €2.75/GJ. The cost of coal amounted to €99.3 million. In Slovenia, we have 45 devices that require emission coupons for their operation. In the year under review, 6,253,595 emission coupons were handed over, of which 3,817,347 went to the Šoštanj thermal power plant, which represents 61% of all the coupons handed over. The average price of emission coupons in the year in question was €24.60 per coupon. [3] Based on this data, we can calculate that the cost of coal was €26.7/MWh and the cost of emission coupons, if we consider the average price of all submitted coupons, was €25.1/MWh. On average, electricity was sold at €58.5/MWh. Mainly due to the high cost of emission coupons, the company's profit was negative. As the prices of emission coupons increase, business is getting worse. One of the possibilities for improving operations is the transition from fossil fuels to renewable energy sources, or the replacement of the energy source coal with wood biomass, thereby avoiding the cost of emission coupons.

2.2 Wood biomass

Slovenia's natural wealth is the forest, which covers 58% of Slovenia's surface. The area of commercial forests measures 1,068,484 ha, protected forests 98,762 ha and forest reserves 9,508 ha. The total area of forests is 1,176,754 ha. Taking into account the forest cultivation plans (GGN) made in 2019, the wood stock is estimated at 356,756,000 m³ or 303 m³/ha. The annual increase is estimated at 8,827,600 m³ or 7.5 m³/ha. In 2019, 5,287,863 m³ of woody biomass were cut, of which 3,326,578 m³ were conifers and 1,961,285 m³ hardwoods (deciduous trees). The recorded logging in 2019 amounted to 87% of the possible logging according to GGN.

One of the main tasks of the Forestry Institute in the field of wood for energy is to provide data on the potential of wood suitable for energy. They spatially show the potential of wood suitable for energy use (supply), its use (demand) and the balance sheet for an arbitrarily selected area. When calculating supply, in addition to other parameters, data on forests and the potential of non-forest land, industrial resources and collected wood waste in collection centres are taken into account. When determining demand, they take into account the estimated use of wood for energy by households. Table 1 shows the energy potential of wood. [4]

Table 1: Potential of wood biomass for energy

Source	Parameter	Net quantity in tons of dry matter
forest	available logging quantity of lower quality assortments	1,603,000
	actual logging quantity of lower quality assortments	799,000
	logging residue in the forest upon the undertaken of a possible felling	455,000
	logging residue in the forest upon the actual realisation of the felling	294,000
	the amount of log bark when a possible felling is realised	59,000
	the amount of log bark when an actual felling is undertaken	59,000
agricultural areas	estimated possible permanent felling of trees on non-forested areas	151,000
	wood and non-wood residues from agricultural land usable for energy	197,000
industry	the amount of sawmill residues during the processing of logs upon realisation of a possible felling	530,000
	the amount of sawmill residues during the processing of logs during the current realisation of the felling	500,000
collection centres	collected wood residues	350,000
consumption	consumption of lower-quality assortments in households for heating and cooking	776,000
	consumption of lower quality assortments in district heating and cogeneration systems	94,000
	wood residues used in industry	32,000
	total consumption of wood for energy in all sectors	902,000
	the amount of competitive use of lower quality wood in the industry	255,000

3 RESULTS

One of the options for the extended operation of thermal power plants is the replacement of the energy source coal with wood biomass, which is carbon neutral. In 2019, TEŠ consumed 3,040,612 tons of coal with a calorific value of 11,874 GJ/t. If the consumed amount of coal is converted into energy, we get 36 PJ of energy. Taking into account the annual increase in Slovenia and the assumed average wood density of 550 kg/m³, as well as the average calorific value of 16.5 MJ/kg, we find that coal energy can be replaced with 45% of the annual increase. This value is also very close to the percentage of waste when processing logs into quality products with high added value. If we allocated the same amount of money for wood biomass as was spent in 2019 (before the drastic increase in the price of emission coupons) for the payment of coal and emission coupons, then the price of wood biomass delivered to the thermal power plant could be €48/m³.

Table 1 shows a more detailed analysis of the potential of wood biomass for energy production. The possible harvest of lower-quality assortments amounts to 1,603,000 tons. If we add to this the amount of log bark at the realisation of a possible felling (59,000 tons), the amount of sawmill residues from the processing of logs at the realisation of a possible felling (530,000 tons), and the collected wood residues in collection centres (350,000 tons), we get the sum of wood biomass resources at the realisation of a possible felling in the amount of 2,542,000 tons. From this sum, we can subtract the consumption of lower-quality assortments in households for heating

and cooking (776,000 tons) and the consumption of lower-quality assortments in district heating and cogeneration systems (94,000 tons), as well as wood residues used in industry. In doing this, we obtain a quantity of lower-quality wood when the possible harvest is realised in the amount of 1,640,000 tons. This is the amount of wood biomass that could be usefully used in a thermal power plant. Taking into account the calorific value of 16.5 MJ/kg, 75% of coal consumption and consequently 75% of CO₂ emissions could be replaced with the available amount of lower-quality wood, which corresponds to 2.8 million tons of CO₂.

4 CONCLUSION

The article analyses the replacement of coal as an energy source with wood biomass in a thermal power plant. The analysis was made on the basis of data for the year 2019. This year was chosen because the Covid situation broke out a year later, and it thus represents a normal, average year. The analysis of the data showed a sharp increase in the prices of emission coupons, which have a negative impact on the operation of the thermal power plant. It was found that the entire amount of coal used can be replaced by 45% of the annual increase in wood biomass. Furthermore, it was found that if the coal was replaced only by the consumption of lower quality wood when the possible felling was realised, then 75% of the coal consumption could be replaced.

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Nomenclature

<i>(Symbols)</i>	(Symbol meaning)
GGN	forestry cultivation plan
TEŠ	Thermal power plant Šoštanj
RES	Renewable energy sources

ENERGY ANALYSIS OF HYDROGEN USE IN ROAD TRANSPORT OF THE REPUBLIC OF CROATIA

ENERGETSKA ANALIZA UPORABE VODIKA V CESTNEM PROMETU REPUBLIKE HRVAŠKE

Franco Krog^{1✉}, Jurij Avsec¹

Key words: hydrogen, hydrogen technologies, hydrogen acquisition, transport

Abstract

In this paper, we will calculate the needs for hydrogen if all traffic in Croatia was driven by hydrogen. In the article, we will determine the required amount in several ways. First, we will briefly describe fuel cell cars and the extent to which the amount of exhaust gases would be reduced. We will then explain the ways of obtaining hydrogen, its transport and what the purchase costs would be. Finally, we will compare the results and draw some conclusions.

Povzetek

V članku bomo izračunali, kakšne bi bile potrebe po vodik, če bi ves promet na Hrvaškem potekal na vodik. V nalogi bomo na različne načine določili potrebno količino vodika, potrebnega za transport na Hrvaškem. Opredili bomo avtomobile na gorivne celice ter količino izpušnih plinov, ki bi se zmanjšala z uporabo vodikovih tehnologij. Pojasnili bomo tudi načine pridobivanja vodika, njegovega transporta in kolikšni bi bili stroški nakupa vozila. Na koncu bomo primerjali rezultate in zapisali ugotovitve.

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1 INTRODUCTION

Road traffic is an indispensable part of everyday life. About 30% of the total energy used and 25% of the total exhaust gas emissions emitted within the EU come from road transport. The European Commission has proposed several different directions for sustainable development, one of which involves the application of hydrogen technology. Regardless of the environmental protection aspect, the need for a new fuel has arisen due to the high prices of currently-available fuels and the dependence on fuel imports. Fuel cells were found as an alternative to internal combustion engines. Since Europe is at a low level of self-sufficiency, its own hydrogen production would help solve an additional problem. Fuel cells are already available on the market and are still under development. Production of fuel cell cars and this technology are also available for purchase, something which represent a very successful development.

2 HYDROGEN CAR

More and more companies are deciding to develop hydrogen cars. The most successful hydrogen car, developed in serial production, is the Toyota Mirai hydrogen car. In Table 1, we present the technical characteristics of the Toyota Mirai car, developed in December 2021. 17,940 units have already been sold, [1] a small number compared to sales of battery electric vehicles, but intense growth in hydrogen vehicle sales has nevertheless been predicted. In Table 1, you can see the technical data relating to the Toyota Mirai hydrogen car.

Table 1: Technical data of the car Toyota Mirai [2]

Motor power	113 kW / 335 Nm
Number of reservoirs	3
Maximum speed	178 km/h
Nominal working pressure	700 bar
Range	550 km (NEDC)
Tank volume	122,4 l
Maximum mass of stored hydrogen	5 kg
Refill time	3 min
Combined consumption	0,76 kg/100 km
Starting price in Germany	60 000 EUR

A fuel cell car has similar design as a battery electric car except instead of a battery it has fuel cells and a hydrogen tank.

The main components of a fuel cell car are:

1. The electric motor;
2. The high pressure hydrogen tank;
3. The battery;
4. The fuel cells;
5. The boost converter;
6. The control unit.

In these cars, hydrogen is stored at 700 bar in three polymer high-pressure tanks. They are made of three layers: an inner plastic layer, a middle carbon fibre plastic layer and an outer plastic layer with glass fibre to protect it against damage. The Toyota Mirai car uses PEMFC or polymer fuel cells where the electrodes are separated by a solid polymer electrolyte. The 650 V electrical installation allows for a smaller number of fuel cells. The battery in fuel cell cars is primarily intended to store excess energy generated during regenerative braking. This stored energy is then used by the car during re-acceleration, thus increasing the car's range. The battery is much smaller than that found in electric vehicles. The size or energy capacity of the Toyota Mirai lithium-ion battery is 1,2 kWh. [1]



Figure 1: Design of the Toyota Mirai II
(<https://www.toyota-europe.com/news/2020/new-mirai-concept>).

3 THE NEED FOR HYDROGEN

In this article, we have calculated the energy needs for hydrogen in road traffic of the Republic of Croatia. To determine the required amount of hydrogen for road traffic needs, we calculated the required amount of hydrogen with the help of the data presented in Table 2.

Table 2: Data required for calculation in Croatia

Number of registered vehicles	1 666 413 [3]
Energy consumed in traffic	5,34 * 10 ¹⁰ MJ [4]
Average mileage	15 000 km/year [5]

We calculated the need for hydrogen from the car's declared hydrogen consumption, which was 0.76 kg/100 km: [2]

$$(Consumption_{H_2})_{15000km} = P_{TM} * d = 0,76 \frac{kg}{100km} * 15000 km = 114 kg \quad (3.1)$$

Where:

- $(\text{Consumption}_{H_2})_{15000\text{km}} - \text{hydrogen consumption (EU average)} - 15\,000\text{ km (kg)}$;
- PG_{TM} – Toyota Mirai combined consumption (kg/100 km);
- d – distance (km).

$$m_{H_2} = N * m = 1\,666\,413 * 115\text{ kg} = 1,92 * 10^8\text{ kg} \quad (3.2)$$

The electricity required to produce one kilogram of hydrogen is 55 kWh/kg, which means that 6,270 kWh will need to be supplied for one car. It will also be necessary to obtain at least 10,448,409,510 kWh of electricity, which means that a 1,200 MW power plant would be required.

4 HYDROGEN PRODUCTION

As shown in the previous sections, hydrogen is required for a fuel cell car. We already solved the first problem, environmental pollution, by introducing green hydrogen, as opposed to grey and blue hydrogen, both of which are also available. Grey hydrogen, which is currently the most common form of hydrogen, is produced from natural gas or methane in the steam reforming process. Blue hydrogen, on the other hand, is the same as grey hydrogen, except that it captures greenhouse gases in the process. The gas capture process is cost prohibitive. Green hydrogen is created with the help of electricity from renewable sources.

Another problem with conventional fuels is their price. Since we want the lowest possible price and zero pollution, our own local production of hydrogen with the help of renewable sources would represent the most economical solution. Hydrogen can be obtained from fossil fuels and from water. The direction of obtaining hydrogen from fossil fuels is not sustainable from an ecological point of view. Extraction from water can take place via electrolysis, thermochemical and photochemical processes. Currently, only electrolysis devices can be purchased from the above on the market.

Obtaining hydrogen by means of electrolysis can be represented by formula 4.1



As seen in the previous section, a 1200 MW plant is not the best idea. Another option for green electricity is to use photovoltaic systems. The advantage of using photovoltaic panels is the production of DC electricity, which is necessary for electrolysis. In Figure 2, you can see the annual solar radiation.

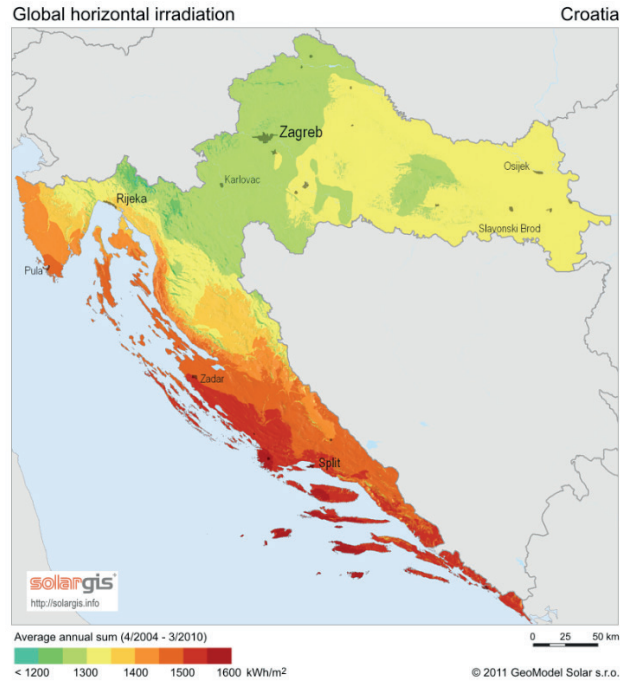


Figure 2: Annual solar radiation. [6]

On average, solar radiation in Croatia amounts to 1250 to 1500 kWh per square metre and 2000 hours of sunshine, [7] which means that our own production of hydrogen could well be something to consider. [6] Currently, the preferred way of producing hydrogen is self-production. If we needed 114 kilograms of hydrogen per car per year, then we would require 6270 kWh of electricity, as well as another 1.35 kWh [8] to compress a kilogram of hydrogen, giving us a total of 6425 kWh. If we, for example, installed 25 photovoltaic modules, each with a power of 300 W, on a roof of 50 m², we would theoretically obtain up to 12000 kWh of electricity per year, which means we would be able to meet these requirements.

$$W_{PV} = W_{modul} * t_{year} * N_{modul} * f = 300 \text{ W} * 2000 \text{ ur} * 25 * 0,8 = 12000 \text{ kWh} \quad (4.2)$$

Where:

- W_{PV} – production of photovoltaic modules [W];
- W_{modul} – power of each module [W];
- t_{year} – number of sunny hours per year;
- N_{modul} – number of modules;
- k – correction factor.

As we can see from this calculation, with 25 power modules of 300 W, we can produce enough energy for hydrogen production and compression, allowing us to install fewer modules.

5 REDUCTION OF EMISSIONS IN THE CASE OF SWITCHING TO HYDROGEN

We know from experience that an average car emits between 110 and 150 $\frac{gCO_2}{km}$. Every machine in which a certain fuel is burned produces emissions of certain gases. Car engines have different emissions, which depend mainly on which fuel is used and the engine's fuel consumption. To simplify the calculation, we will use the average consumption. Currently, the most prevalent exhaust gas is carbon dioxide. Data on the amount of CO_2 are as follows. [9]

- 1 litre of gasoline contains 652 g CO_2 ;
- 1 litre of diesel contains 720 g CO_2 .

When we calculate emissions for an average consumption of 5.2 l/100 km for diesel and 7 l/100 km for gasoline, we get:

$$CO_{2,D} = (Consumption_D * CO_{2,D}) / 100 km = (5,2 * 2640) / 100 = 137,3 g / 100 km \quad (5.1)$$

$$CO_{2,B} = (Consumption_B * CO_{2,B}) / 100 km = (7 * 2392) / 100 = 167,44 g / 100 km \quad (5.2)$$

$$CO_{2,D,15000} = CO_{2,D} * d = 137,3 \frac{g}{km} * 15000 km = 2059,5 kg \quad (5.3)$$

$$CO_{2,B,15000} = CO_{2,B} * d = 167,44 \frac{g}{km} * 15000 km = 2511,6 kg \quad (5.4)$$

If we add the average mileage and the average fuel consumption to the above data, with the help of a calculator to calculate the carbon footprint, we obtain the results shown in Table 3: [10]

Table 3: Total CO_2 emissions

Fuel	Annual consumption in litres	Annual emissions of CO_2 in kg per 15,000 km	Total annual emission in kg
Diesel	780	2060	$1,75 * 10^9 kg$
Gasoline	1005	2512	$2,05 * 10^9 kg$

If we calculate the average value of 130 $\frac{gCO_2}{km}$ to overall average 15000 kilometres per year, we get the following value:

$$CO_{2,15000} = CO_2 * d = 130 \frac{g}{km} * 15000 km = 1950 kg \quad (5.5)$$

We can also calculate this for all cars:

$$CO_2 = CO_{2,15000} * n = 1950 kg * 1666413 = 3\,249\,505\,350 kg \quad (5.6)$$

6 PURCHASE COSTS OF HYDROGEN TECHNOLOGIES

In Table 4, we present the price of the Toyota Mirai and its running costs:

Table 4: Data for Toyota Mirai. [2]

Car	Toyota Mirai
Propulsion type	Electric motor 113 kW
Fuel consumption	0.76 kg /100 km
CO ₂ emissions	0 g/100 km
New vehicle price	60 000 EUR
Annual fuel cost and CO ₂ emissions	1083 EUR and 0 kg CO ₂

In the Figure 3, we present the costs of several types of vehicles per 15,000 km and the dependence of annual costs on the distance travelled from 5,000 to 100,000 km depending on the type of fuel in Figure 3. [11, 12, 13, 14]

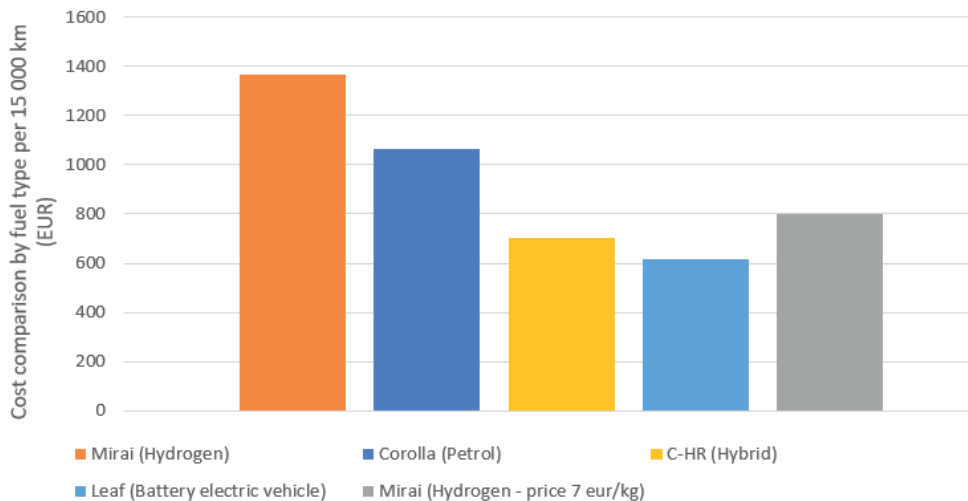


Figure 3: Annual cost per fuel type per 15,000 km.

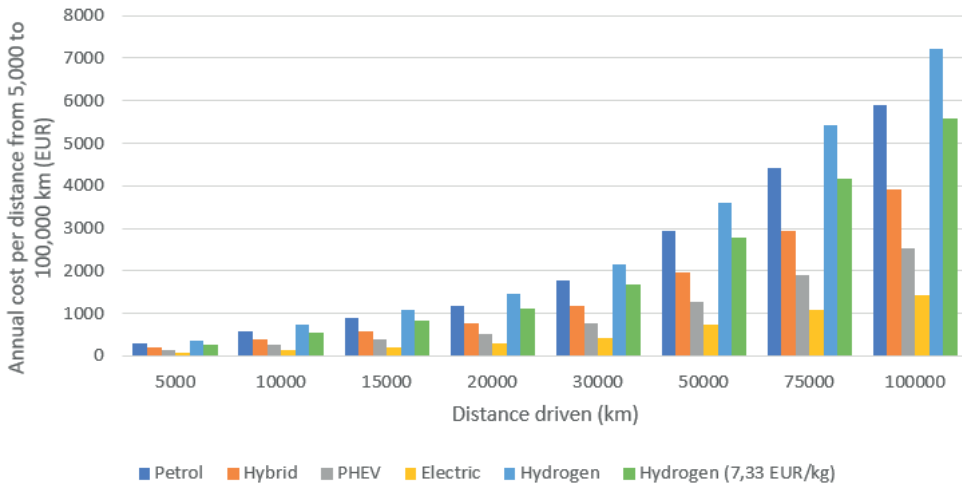


Figure 4: Annual cost per distance from 5,000 to 100,000 km.

Figure 4 shows the annual cost per distance from 5,000 to 100,000 km. In a comparison of hydrogen with today's most expensive energy source, gasoline, it can be seen that hydrogen is about 200 euros more expensive per 15,000 kilometres travelled. For every kilometre more, the difference is even greater.

In Figure 5, we can see the price difference depending on the fuel used in the car.

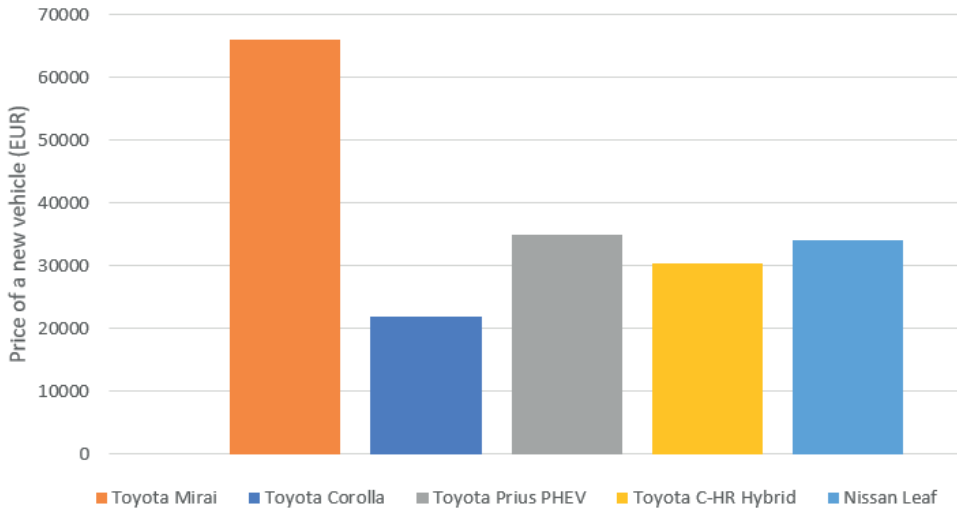


Figure 5: The price of buying a new vehicle.

The hydrogen car itself is expensive. The best option at the moment is a hybrid. Therefore, when introducing hydrogen technologies, it will first be necessary to reduce the purchase price of the

car. The competitiveness of the hydrogen car could be achieved through subsidies and reductions in car taxes

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Nomenclature

(Symbol)	(the meaning of the symbol)
CO_2	carbon dioxide
P_{TM}	combined consumption of Toyote Mirai
(Consumption H_2) _{15000km}	consumption (EU average) – 15 000 km
$CO_{2,D}$	CO ₂ emissions of diesel fuel
$CO_{2,B}$	CO ₂ emissions of petrol fuel
$CO_{2,D,15000}$	CO ₂ emissions for diesel fuel every 15000 kilometers

$CO_{2,B,15000}$	CO_2 emissions for gasoline fuel at 15000 kilometers
k	corection factor
d_T	distance
$CO_{2,D}^T$	emissions after burning a litre of diesel fuel
$CO_{2,D}$	emissions after burning a litre of gasoline
H_2	hydrogen
t_{leto}	insolation
W_{modul}	power of each module
N_{modul}	number of modules
O_2	oxygen
W_{PV}	energy production of PV modules

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References

- [1] **N. Surname:** *Title*, Journal Title, Vol., Iss., p.p., Year of Publication
- [2] **N. Surname:** *Title*, Publisher, Year of Publication
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Examples:

- [1] **J. Usenik:** *Mathematical model of the power supply system control*, Journal of Energy Technology, Vol. 2, Iss. 3, p.p. 29 – 46, 2009
- [2] **J. J. DiStefano, A.R. Stubberud, I. J. Williams:** *Theory and Problems of Feedback and Control Systems*, McGraw-Hill Book Company, 1987
- [3] **T. Žagar, L. Kegel:** *Preparation of National programme for SF and RW management taking into account the possible future evolution of ERDO* [online], Journal of Energy Technology, Vol. 9, Iss. 1, p.p. 39 – 50, 2016. Available: http://www.fe.um.si/images/jet/Volume_9_Issue1/03-JET_marec_2016-PREPARATION_OF_NATIONAL.pdf (7. 10. 2016)

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Nomenclature

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