Influence of the CO_2 emission factor value on the result of the load distribution analysis between the hybrid PV/WT/FC system and the electric power system

Bartosz Ceran[1,*]

[1]Poznań University of Technology, Faculty of Electrical Engineering, Institute of Electrical Power Engineering, Poland

Abstract. This article presents the results of the multicriteria analysis of loads distribution between hybrid power generation system consisting of PV/WT/FC and the electricity system. The simulations were performed for power systems with different structures of the manufacturing sector, and so with different values of the factor of CO_2 emission. A decision-making criteria, which were used to compare the relevant scenarios, have been defined.

1 Introduction

One of the indicators characterizing the electricity system of the country is the unit rate of carbon dioxide emissions that tells how much CO_2 accompanies the production of 1 MWh of electricity. This indicator characterizes the structure of the manufacturing sector of the electricity system. In the Polish power supply system, which is based on the carbon sources, carbon dioxide emission ranges from 700 to 800 kgCO_2/MWh, depending on the usage degree of wind power for the energy production process. For comparison, the annual average rate in Germany is 560, however, its instantaneous value fluctuates within the limits from 300 kgCO_2/MWh to 700 kgCO_2/MWh depending on the use of renewable sources installed in German system in accordance with the Energiewende policy [1]. Czech electricity system, where two nuclear power plants are installed is characterized by the value at 450 kg/MWh. Systems based on renewable sources, for example, Swedish and those nuclear - French, are characterized by the indicator at the level of 40 kgCO_2/MWh and 70 kg/MWh. An indisputable is the fact that the emissivity factor values should be minimized. Therefore, countries with systems based on conventional sources, must develop strategies to transform the manufacturing sector.

In publications concerning CO_2 emissions related with electricity generation authors calculate the values of emission indicators for the system of specific manufacturing structure [2,3,4]. In case of distributed generation, the CO_2 emission indicator for hybrid power generation system is formulated [5,6,7].

* Corresponding author: bartosz.ceran@put.poznan.pl

The purpose of this paper is to present the results of studies on the effects of the emission of CO_2 on multi-option analysis of load distribution between the electricity system and PV/WT/FC hybrid power generation system - HPGS. The aim of presented research is to define the optimal exploitation strategy for hybrid power generation system in the power system of certain manufacturing structure.

2 A DESCRIPTION OF THE PROBLEM

Flowchart of analyzed system is shown in Figure 1.

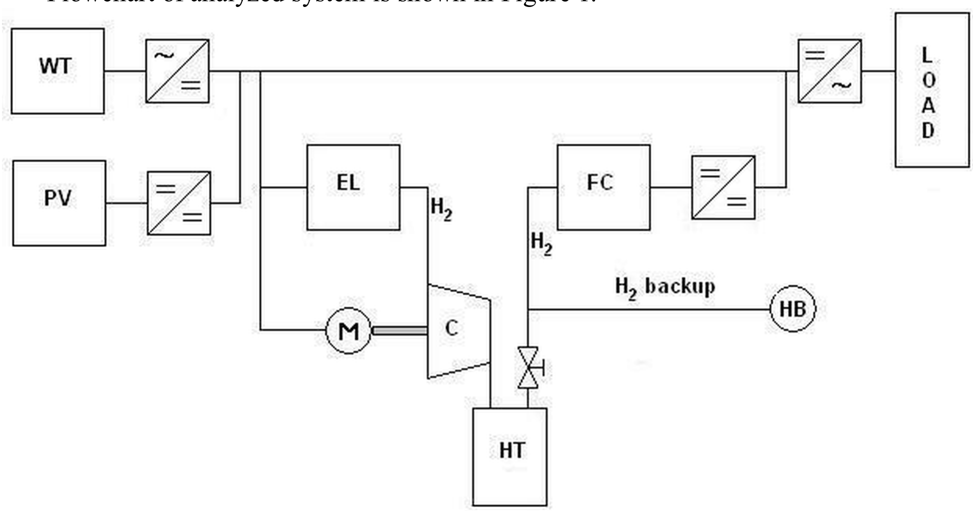

Fig. 1. The flowchart of the hybrid power generation system: FC – fuel cell, PV – photovoltaic cell, WT – wind turbine, El – electrolyzer, HT – hydrogen tank, HB – hydrogen back-up, M – motor, C – compressor, PS – power system.

The balance of power in the system, depends on the ratio of power generated by renewable energy sources to the demand of the recipient. In the case where the demand is less than the power generated balance sheet equation takes the form [6].

$$P_{load} = P_{PV} + P_{WT} - P_{elek} - P_{comp} + P_{sys} \tag{1}$$

where: P_{load}– power consumed by the recipient, P_{PV} – power generated by the photovoltaic installation, P_{WT} – power generated by the wind plants, P_{elek} – power consumed by electrolyzer, P_{comp} – power consumed to drive the compressor, P_{sys} – power drawn from the power system.

If the demand exceeds the power produced by sources the receiver power describes the formula:

$$P_{load} = P_{PV} + P_{WT} + P_{FC} + P_{sys} \tag{2}$$

where: P_{FC} – power generated by the fuel cell stack.

The analysis assumes the profile of municipal customer with a maximum power consumption of 80 kW and an annual electricity demand in the amount of 478 MWh. Simulated scenarios of covering the load are shown in Figure 2. In the S-I scenario, the basic load is covered by the electricity system while the remaining part of the demand is covered by hybrid power generation system. In the S-II scenario, the ordered power from the power system is 20 kW, in the S-III scenario - 30 kW and in the S-IV scenario - 40 kW.

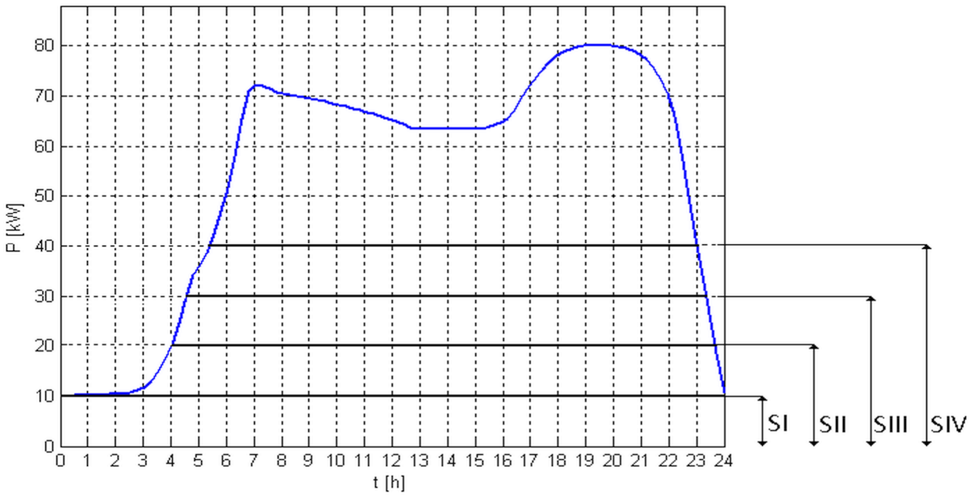

Fig. 2. The load profile of the recipient - work scenarios (own study).

As the decision criteria for the multi-criteria analysis the following indicators has been adopted:
k_1 – unit usage of additional hydrogen by the hybrid system,
k_2 – unit cost of energy production by the hybrid system,
k_3 – the indicator of carbon dioxide emission by hybrid power system and electric power system,
k_4 – the capacity of utilization of power ordered from the electric power system.

$$k_1 = \frac{V_{H_2}}{E_{load}}\left[\frac{m^3 H_2}{kWh}\right] \tag{3}$$

where: V_{H2} – the amount of utilized additional hydrogen for backup purpose, E_{load} – the demand for energy by the recipient.

$$k_2 = \frac{K_e}{E_{HPGS}}\left[\frac{PLN}{kWh}\right] \tag{4}$$

where: K_e – operating costs of hybrid system, E_{HPGS} – the amount of energy produced by hybrid power generation system

$$k_3 = \frac{E_{sys} \cdot WE_{CO_2} + V_{H_2} \cdot \rho_{H_2} \cdot \dfrac{M_{CO_2}}{M_{H_2}}}{E_{load}}\left[\frac{kg_{CO_2}}{kWh}\right] \tag{5}$$

where: E_{sys} – energy input from the electricity system, WE_{CO2} – indicator of carbodioxide emission in electricity system, ρ_{H2} – hydrogen density, M_{CO2}/M_{H2} – the amount of carbon dioxide formed in the production of 1 kg of hydrogen in the steam reforming process of hydrocarbons

$$k_4 = \frac{P_{ord} \cdot t}{E_{sys}}\left[\frac{kWh}{kWh}\right] \tag{6}$$

where: P_{ord} – maximum input power from the power system by the consumer at time $t = 8760$ h.

Multi-criteria analysis is a mathematical method which allows to select the most favorable solution, the so-called. scenario, in the light of adopted criteria. One of the methods of multi-criteria analysis is “a compromise programming method” [8]. It allows to rank examined scenarios in order from the shortest distance from the socalled X’ destination. The destination coordinates are equal to the maximum value of the adopted standardization scale, i.e. always takes the best value. The method of “compromising programming” allows to assign weights to each decision-making criteria, i.e. the decision - maker has the ability to take into account in the calculations validity of some parameters, especially important for him.

In order to bring the values of all the criteria for a unified scale, the normalization criteria has been used in accordance with the equation (7).

$$x'_{nm} = 1 - \frac{x_{nm}}{\sqrt{\sum_{j=1}^{m} x_{nm}^2}} \tag{7}$$

A mathematical record of distance measure of considered variant from the ideal point describes the formula:

$$L_\alpha(S_n) = \sum_{m=1}^{M} w_m^\alpha (x'_m - x'_{nm})^\alpha \tag{8}$$

where: L_α – a measure of divergence of considered scenario S_n from the ideal point, w_m – weight factor m of this criterion, α – exponent measuring the deviation strategy from the ideal point, x_m '- mth coordinate of the ideal point, x_{nm}' - normalized value of the evaluation criterion.

The most favorable scenario in the light of the adopted criteria complies with the relation:

$$S_j = S \Leftrightarrow L_\alpha(S_j) = \min L_\alpha(S_n), \quad \text{dla} \quad n = 1, 2.....N; \ \alpha = 1,2...\infty \tag{9}$$

where: S* - selected scenario.

Based on the equations and the proprietary code implemented in the Maltab environment, for any of the considered scenarios have been designated powers of devices of hybrid power generation system – table 1, values of decision-making criteria – table 2 and normalized values of decision-making criteria – table 3.

Table 1. Equipment forming a hybrid power system for scenarios S-I…S-IV.

Devices in hybrid system	Scenarios of power system loads.			
	S-I	**S-II**	**S-III**	**S-IV**
Wind turbines [kW]	2x80	2x80	2x80	1x80
Panels PV-250 [Wp]	576x290	351x290	183x290	279x290
Fuel cell [kW]	70	60	50	40
Electrolyzer [kW]	180	160	130	90

Table 2. Payment matrix of decision problem for scenarios S-I...S-IV.

Decision criteria	Scenarios of power system loads.			
	S-I	**S-II**	**S-III**	**S-IV**
k_1 [m^3H_2/kWh]	0.117	0.089	0.071	0.052
k_2 [PLN/kWh]	1.251	1.259	1.261	1.263
k_3 [$kgCO_2$/kWh]	0.295	0.390	0.465	0.561
k_4 [kWh/kWh]	1.000	1.084	1.212	1.227

Table 3. The normalized payment matrix for the scenarios S-I...S-IV.

Normalized decision criteria	Scenarios of power system loads.			
	S-I	**S-II**	**S-III**	**S-IV**
k_1(min)	0.320	0.480	0.583	0.695
k_2(min)	0.503	0.500	0.499	0.498
k_3(min)	0.664	0.555	0.470	0.361
k_4(min)	0.559	0.522	0.466	0.459

The simulations were conducted for the equal weight value of decision-making criteria and for double overweighting of the given decision - making criteria relative in terms of the others. The calculations were performed for the following values of CO_2 emission indicators: accordingly 800 $kgCO_2$/MWh, 600 $kgCO_2$/MWh, 400 $kgCO_2$/MWh, 200 $kgCO_2$/MWh, 70 $kgCO_2$/MWh. The research assumes that the value of the pointer of the CO_2 emissions associated with the hydrogen production in steam reforming process to HPGS is at the level of 13.7 kg.

4 Analysis results

The table shows the results of the multi-variant analysis of loads distribution between hybrid power generation system and electricity system which are shown in the tables 4-8.

Table 4. Multi – criteria analysis results.

Ratio of weight of criteria	CO_2 emission factor - 800 $kgCO_2/MWh$	
$w_1:w_2:w_3:w_4$	$\alpha = 1$	$\alpha = 2$
1:1:1:1	**SII***→ SIV↔SIII→SI	**SII***→ SIII↔SI→SIV
2:1:1:1	**SIV***→ SIII↔SII→SI	**SIV***→ SIII↔SII→SI
1:2:1:1	**SII***→ SI↔SIII→SIV	**SII***→ SI↔SIII→SIV
1:1:2:1	**SI***→ SII↔SIII→SIV	**SI***→ SII↔SIII→SIV
1:1:1:2	**SI***→ SII↔SIII→SIV	**SI***→ SII↔SIII→SIV

Table 5. Multi – criteria analysis results.

Ratio of weight of criteria	CO_2 emission factor - 600 $kgCO_2/MWh$	
$w_1:w_2:w_3:w_4$	$\alpha = 1$	$\alpha = 2$
1:1:1:1	**SIV***→ SIII↔SII→SI	**SII***↔ **SIII***→SI→SIV
2:1:1:1	**SIV***→ SIII↔SII→SI	**SIV***→ SIII↔SII→SI
1:2:1:1	**SII***→ SIII↔SIV→SI	**SII***→ SIII↔SI→SIV
1:1:2:1	**SI***→ SII↔SIII→SIV	**SI***→ SII↔SIII→SIV
1:1:1:2	**SII***→ SI↔SIV→SIII	**SI***→ SII↔SIII→SIV

Table 6. Multi – criteria analysis results.

Ratio of weight of criteria	CO_2 emission factor - 400 $kgCO_2/MWh$	
$w_1:w_2:w_3:w_4$	α = 1	α = 2
1:1:1:1	**SIV***→ SIII→SII→SI	**SIV***→ SIII→SII→SI
2:1:1:1	**SIV***→ SIII→SII→SI	**SIV***→ SIII→SII→SI
1:2:1:1	**SIV***→ SIII→SII→SI	**SII***↔ **SIII***→SI→SIV
1:1:2:1	**SIV***→ SIII→SII→SI	**SII***→ SIII→SI→SIV
1:1:1:2	**SIV***→ SIII→SII→SI	**SI***↔ SII→SIII→SIV

Table 7. Multi – criteria analysis results.

Ratio of weight of criteria	CO_2 emission factor - 200 $kgCO_2/MWh$	
$w_1:w_2:w_3:w_4$	α = 1	α = 2
1:1:1:1	**SIV***→ SIII→SII→SI	**SIV***→ SIII→SII→SI
2:1:1:1	**SIV***→ SIII→SII→SI	**SIV***→ SIII→SII→SI
1:2:1:1	**SIV***→ SIII→SII→SI	**SIII***→ SII→SIV→SI
1:1:2:1	**SIV***→ SIII→SII→SI	**SIV***→ SIII→SII→SI
1:1:1:2	**SIV***→ SIII→SII→SI	**SIV***→ SIII↔SII→SI

Table 8. Multi – criteria analysis results.

Ratio of weight of criteria	CO_2 emission factor - 70 $kgCO_2/MWh$	
$w_1:w_2:w_3:w_4$	α = 1	α = 2
1:1:1:1	**SIV***→ SIII→SII→SI	**SIV***→ SIII→SII→SI
2:1:1:1	**SIV***→ SIII→SII→SI	**SIV***→ SIII→SII→SI
1:2:1:1	**SIV***→ SIII→SII→SI	**SIV***↔ **SIII***→SII→SI
1:1:2:1	**SIV***→ SIII→SII→SI	**SIV***→ SIII→SII→SI
1:1:1:2	**SIV***→ SIII→SII→SI	**SIV***→ SIII→SII→SI

In case of balanced weights distribution of decision-making criteria, scenario S - IV is indicated for value α equal to 1 and 2, as accepted for CO_2 at 400 $kgCO_2/MWh$.

Doubling the overweighting of energy criterion k_1, which is the unit fuel consumption (hydrogen) by hybrid power generation system, the 4th scenario is chosen for all the considered values of the indicator of CO_2 emissions equal to 800 kg/MWh. It is due to the fact that the k1 criterion prefers S-IV scenario, in which the hybrid power generation system will generate the least energy.

At overweighting of k_2 cost criteria, the unit cost of electricity generation, S-IV scenario, is chosen for both values of an aggregate criterion α = 1 and α = 2, for values of the CO_2 indicator at 70 $kgCO_2/MWh$. This is related to the fact that for such a low value of the indicator of CO_2 emissions in the electricity system, HPGS work with the use of additional hydrogen emits more CO_2. Therefore, despite the largest unit costs of work of HPGS, the preferred scenario is S-IV.

The environmental criterion k_3, prefers the S-I scenario, in which during the process of electricity production total carbon dioxide emissions should be as low as possible. The research has shown that the scenario S-IV is chosen for both values of an aggregate criterion α = 1 and α = 2, for values of the CO_2 indicator at 200 $kgCO_2/MWh$, however, it is worth mentioning that for the factor at 400 $kgCO_2/MWh$ the S-I scenario is not pointed as the best variant of loads distribution.

The system criterion of k_4 prefers the S-I scenario, in which the electricity system is working at the base load. A reduction in the value of emission factor in the system to 600 $kgCO_2/MWh$ causes that for α = 1 is pointed S-II scenario. Further reducing of the value of the emission factor causes that the best variant, despite the double overweighting of k_4 criterion to the others, the S - IV scenario is chosen.

5 Conclusion

The performed research allow for the formulation of the following conclusions:

- factor value of CO_2 emission significantly affects the result of the multi-variant analysis of loads distribution between hybrid power generation system and electricity system. Reducing the value of factor emission in power generation system causes as acceptable scenarios are indicated those where the power system has a larger part in covering the load profile of the recipient,
- in the Polish power generation system, characterized by the index of carbon dioxide emission at the level of approximately 800 $kgCO_2/MWh$, the load distribution between the HPGS and power generation system needs to be carried out according to S-I or S-II scenario. In electricity systems at the value of a pointer at the level of the 600 $kgCO_2/MWh$ this distribution should be carried out according to the S-II scenario, however in systems with the value of indicator at 400 $kgCO_2/MWh$ and lower, the load distribution is recommended according to the S-IV scenario,
- the proposed analysis model can be a starting point to optimize the work of hybrid power generation systems based on sources of stochastic nature of work in the electricity system at varying structure of the manufacturing sector.

References

1. R. Szczerbowski, B. Ceran, Acta Energetica **3,** 32, 201–208 (2017)
2. Jia-Jun Ma, Gang Du, Bai-Chen Xie, Energy Policy **124,** 1-12 (2019)
3. T. Inoue, K. Yamada, Energy Procedia, **142,** 2761-2766 (2017)
4. J. I. Mikayilov, M. Galeotti, F. J. Hasanov, Journal of Cleaner Production, **197**, 1558-1572 (2018)
5. M. D. A. Al-Falahi, K. S. Nimma, S. D. G. Jayasinghe, H. Enshaei, J. M. Guerrero, Energy Convers Manage, **172,** 50-66 (2018).
6. M. Usmana, M. T. Khanb, A. S. Ranab, S. Alic, Journal of Electrical Systems and Information Technology, **5**, 653–662 (2018)
7. S. Paraschiv Spiru, L.S. Paraschiv, Energy Procedia, **147,** 343-350 (2018)
8. W. Wójcik, Z. Mucha, A. Generowicz, Acta Sci. Pol.**13**,3, 101–114 (2014)