Open Access Journal

Journal of Power Technologies 99 (2) (2019) 115–122

journal homepage:papers.itc.pw.edu.pl

Sensitivity analysis of main parameters of pressurized SOFC hybrid system

Jakub Kupecki*

Department of High Temperature Electrochemical Processes (HiTEP), Institute of Power Engineering
Augustowka 36, 02-981 Warsaw, Poland

Abstract

The paper presents a sensitivity analysis of a pressurized SOFC–HS system. The systems are divided into two groups: atmospheric and pressurized. The main parameter of such systems are indicated and commented. The comparison of various configurations is shown in a view of efficiency obtained. The ultra high efficiency (65% HHV, 72% LHV) of electricity production seems to be possible by systems like these.

Keywords: Solid Oxide Fuel Cell, Hybrid system, Structure, Configuration

1. Introduction

Solid Oxide Fuel Cells [1–10], next to the Molten Carbonate Fuel Cell [11–21] belong to the group of fuel cells that can be used for energy purposes. Currently, next to piston engines [22–24] and micro–turbines [25, 26], these types of fuel cells are installed as supply hospitals and larger facilities where power stability is more important than cost. One can imagine a future in which fuel cells will be used on a wider scale. Housing estates, cottages agglomerations or industrial sites will have their own mini-power plants based on fuel cells. In such applications, the criteria used in the selection of the energy is electric current generation efficiency. Consequently, there is a need to use as much of the waste heat from the fuel cell. Capacity, which should generate such fuel cells, are much larger than for fuel cells designed for other purposes (eg automotive).

Currently, the most common way to generate power is based on the circulation of the heat transfer fluid, usually water [27–30]. Improving the efficiency of power systems operating in these cycles mainly refers to raising the temperature of the upper heat source. The fuel cell so that it can be considered as the upper heat source should work in a fairly high temperature. SOFCs are characterized by a temperature suitable for this purpose: 1,000°C. The high temperature makes the SOFCs do not require the use of expensive platinum to catalyze the anode reaction which also results in an increased tolerance to contamination. Due to its high operating temperatures, and greater tolerance to pollution has become possible to apply internal conversion of hydrocarbon fuels to hydrogen. Fuel to be converted (reformed) to hydrogen [31], among other things: methane, methanol, crude oil and other hydrocarbons [32] such as biofuels [33–35]. This allows hydrogen supplied to the cell need not be in pure form, as it is in low–temperature cells such as the PEMFC [36, 37].

In the articles [38, 39] a complete, dynamic model for optimization of the elements (particularly including heat exchangers) of a hybrid SOFC-GT system was presented. a 0D model of the system was developed in Aspen Plus environment. All the elements of the model were introduced into Matlab Simulink. Necessary simulations were performed in order to obtain appropriate dimensions of the main elements what should ensure good inertia of the system and correct evaluation of its total performance (efficiency, reaction time). Additionally, interactions between elements of the system were analyzed. Particular focus was put on the effect of inertia of the gas turbine, heat exchangers and the fuel cell. The dynamic model that was developed may be used for operation analysis of a hybrid SOFC/GT system, optimization of its components as well as selection of control system.

The article [40] presents a research on a hybrid SOFC/GT system fired with liquid fuels. Two fuels were investigated: methanol and paraffin in four different configurations including different strategies for fuel processing. The analyzed system was a hybrid SOFC/GT of 500 kW. Own software was developed for thermodynamic and economic analyses. As the result it was obtained that methane-fired hybrid system has better thermodynamic and economic parameters. On the other hand, in paper [41], an efficiency analysis of electricity generation from biomass in a hybrid SOFC/GT sys-

*Corresponding author
Email address: jakub.kupecki@ien.com.pl (Jakub Kupecki*)

tem was presented. a reference system is a hybrid system in which pure methane is used as fuel. In all the analyzed compositions of biomass extracted fuel (BEF), the efficiency was lower than in case of the reference system fired with methane. This was valid for both sole SOFC as well as a hybrid system. This is mainly caused by low heating value of the BEF. Adding some steam to BEF to reach 40% of molar concentration causes significant performance drop both of the sole SOFC as well as of the hybrid system. Hence, when the hybrid system is supplied with BEF, it has to be larger to produce the same amount of electricity as the reference system. Further research was made for more fuel compositions taking into account different gasification types and different sorts of biomass. The influence of fuel composition may be accounted for mainly by the change of calorific value of the fuel and the delivered heat that was necessary for reforming. It was concluded that the effectiveness obtained for all three cases for different kinds of BEF is quite high, therefore, biomass as the fuel for hybrid SOFC/GT systems is promising.

In the article [42] an analysis of a hybrid system with a gas turbine and heat recovery steam generator for steam generation was presented. It was assumed that only hydrogen takes part in the electrochemical reaction. The system is composed of an internal reformer, SOFC stack, combustion chamber, gas turbine, power turbine running the electric generator, fuel and air compressors, two heat exchangers and a heat recovery steam generator. Modeling was performed on different levels, i.e. for operation of the fuel cell, of the stack and the hybrid system. The results of the simulation indicate that a hybrid system with internal reforming (IR-SOFC/GT) may achieve theoretical net electrical efficiency higher than 60% and total efficiency including heat recovery and steam generation higher than 80%.

In the article [43] an analysis of a 1 MW SOFC/GT hybrid system was presented. a significant notion is the fact that due to advanced development of gas turbines and their market readiness, a commercially available gas turbine was used for the analysis. The examination of results was made in order to find the total power of the hybrid system taking into account the maximum allowable fuel cell temperature. In order to keep high performance of the hybrid system during partial load, an optimal control strategy depending on the power loading was created. The result for partial load proved that the streams of supplied fuel and air must be altered simultaneously. Moreover, in order to prevent performance drop, the temperatures in the combustion chamber and on the inlet to the turbine must be kept possibly close to the design point. a potential expansion of the SOFC/GT system to several Megawatts was analyzed. The Mercury 50 turbine of power 4,6 MW manufactured by Solar Turbines was used as the reference device. The results showed that maximum allowable temperature of SOFC part is limited by the total energy of the hybrid system and this limitation constraints the asset of increased efficiency due to increase of SOFC power. For the selected gas turbine the total power was of 11,5 MW and the efficiency of 58,62 %.

In the work [44] simulation of work and exergy analysis of a hybrid SOFC/GT system with internal reforming are presented. In the SOFC model it was assumed that only hydrogen takes part in the electrochemical reaction. Gases which did not react are oxidized. Energy and exergy are calculated not only for the whole installation but also for each element in order to assess distribution of irreversibilities. Simulations were made for different values of working pressure and fuel utilization factor. The results proved that for a 1.5 MW unit, electrical efficiency equal to 60% may be achieved for proper design, i.e. operational pressure and current density. Losses are taken into account also during heat recovery and the total efficiency of 70% is possible. The results proved that sole SOFC is an element subject to largest losses due to irreversible processes. Even if it is a very efficient device, it houses chemical and electrochemical reactions (steam reforming and electrochemic oxidization) that are characterized by largest exergy losses. As in many other papers on hybrid systems, like [45] and [46], the exergy analysis was not only made for a fuel cell stack (such analysis may be found in [47]), but also for all elements of hybrid SOFC/GT system.

In [48], two different advanced control approaches for a pressurized solid oxide fuel cell (SOFC) hybrid system are investigated and compared against traditional proportional integral derivative (PID), retaining system stability and operator confidence. Experimental tests were carried out to compare Model Predictive Control (MPC) against classic PID method: load following tests were carried out. Similar investigation is done in [49], where an advanced control strategies based on MPC method are compared against a traditional PID controller in a Gas Turbine Pressurized SOFC hybrid system. Fuel cell temperature is regulated by manipulating the cell by–pass mass flow, while power is regulated by changing the fuel cell electrical current and fuel mass flow (the fuel utilization factor is kept constant). MPC demonstrated superior performance over the two distributed PID controls, thanks to the better setpoint tracking on the cell temperature, which is particularly evident when the ambient temperature deviates from the nominal condition.

2. The structures and parameters of SOFC Hybrid System

Systems incorporating fuel cells may be divided into many categories. The first classification of power systems containing solid oxide fuel cell is based on the level of outlet pressure of flue gases rejected from the fuel cell. Systems in which the flue gases leaving the fuel cell have the pressure comparably equal to the atmospheric one are called the atmospheric pressure systems. The second group are systems in which the pressure of rejected flue gases from the fuel cell is higher than the atmospheric one—they are named as the pressurized fuel cell systems.

The categorization above determines the location of the fuel cell in a power system. In general, a fuel cell may have the same systemic function as the combustion chamber, i.e.

oxidize the fuel fed to the system. An advantage of the solution is generation of quite significant amount of electrical energy from the sole fuel cell. As a result, less amount of fuel is fed to the combustion chamber located after the fuel cell, hence large air excess decreasing the temperature of gases directed to the turbine is not essential.

The complete analysis of the SOFC–HS structures is presented in [50]. A gas turbine system composed of an air compressor, combustion chamber and a gas turbine is depicted. a pressurized fuel cell can be located between the compressor and the turbine [51]. Two solutions are feasible. In the first the fuel cell substitutes the combustion chamber, in the other it is located directly before the combustion chamber. The system with pressurized fuel cell substituting the combustion chamber is considerably limited due to the fuel cell operation temperature. The temperature of gases supplying the turbine is determined by the fuel cell operation temperature. Hypothetically, it is possible to increase the temperature thereby decreasing the fuel utilization factor for the cell, but this results in much worse performance. Addition of combustion chamber gives higher independence of the gas turbine comparing to the system operating on the solitude fuel cell. An extreme situation may be presumed in this case, in which the fuel cell does not operate at all, and the whole power is generated by the gas turbine.

All the configurations itemized in [50] are characterized by quite large exhaust losses. Flue gas flows rejected from the system have much higher temperature than the ambient temperature (from 400°C to 1,000°C). In order to mitigate the exhaust loss regeneration a heat exchanger may be installed on the supplying flows that would recover some energy from the exhaust flow. Another way is to consider the flue gases as the upper heat source for next system—this solution is applied in combined cycle gas turbines.

Regeneration heat exchangers may be installed both on the air flow as well as on the fuel flow ducts. The compressor is the limiting device in this case as the temperature of compressed air is quite high. Therefore, the temperature of flue gases rejected from the gas turbine determine the effectiveness of installing a heat regenerator on the flow. The problem may be solved by adding an additional combustion chamber placed before the heat exchangers. This will allow to increase the temperature of the flue gases before the heat exchangers independently from the operation of the fuel cell. It should be also mentioned that the gas turbine shall have higher than atmospheric pressure at the outlet. This results from the necessity of taking into account the pressure drop on the heat exchangers.

The Fig. 1 presents an altered idea of heat regeneration in a pressurized system with fuel cell, in which the gas turbine decompresses the gas to the atmospheric pressure. In systems incorporating atmospheric fuel cell additional devices have to be used to recover some of the lost heat. Analogically, they are necessary in pressurized systems independently on chosen regeneration system. The highest efficiency is obtained for the system P–III but for very high temperatures and pressures present in the system. Thus, this configuration has been chosen for further analysis. As shown in Fig. 1, there are following main elements of the system:

1. Air Compressor
2. Gas Turbine
3. Combustion Chamber
4. Fuel Pre-heater
5. Air Pre-heater

The main parameters of these five elements are investigated from the system efficiency point of view.

Table 1: Nominal parameters of the system

Parameter	Value	Point on the chart
System efficiency, HHV, %	73	
Air Compressor mass flow rate, kg/s	20	(1)
Air Compressor pressure outlet, bar	29	(2)
Air Compressor polytropic efficiency, %	80	
Gas Turbine polytropic efficiency, %	90	
Combustion Chamber fuel flow rate, kg/s	0	(3)

3. Sensitivity analysis of the main parameters

Fig. 2 presents the influence of an air compressor mass flow rate with keeping the rest parameters on theirs unchanged values. Increasing the amount of air means increasing air excess factor (λ). Increasing the amount of air decreases the total system efficiency.

The high value of system efficiency is obtained by rapid increase of temperatures in a few points: SOFC, combustion chamber and gas turbine outlet. The temperature of SOFC is raised even up to 1,400°C, what can be difficult to manage from material point of view.

Fig. 4 presents the influence of an air compressor outlet pressure with keeping the rest parameters on theirs unchanged values. Increasing the air compressor outlet pressure means increasing system pressure ratio (π). The pressure ratio has an optimal value from system efficiency point of view around 29. The trend is similar to a gas turbine system, it should be noted that increase with pressure ratio makes all machines more difficult to operate whereas the profits with efficiency increase are relatively small.

Figs 5 and 6 present the influence of adiabatic efficiency of air compressor and turbine, respectively. Increase in the both efficiencies translates into increase the total system efficiency with linear trends. The impact of turbine adiabatic efficiency is slightly higher than air compressor efficiency.

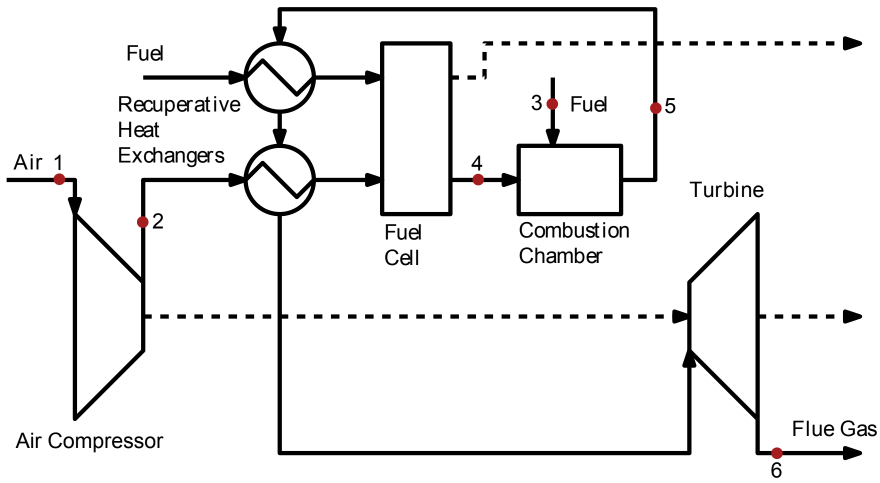

Figure 1: Diagram of the system with heat regeneration and gas turbine working to atmospheric pressure (P-III)

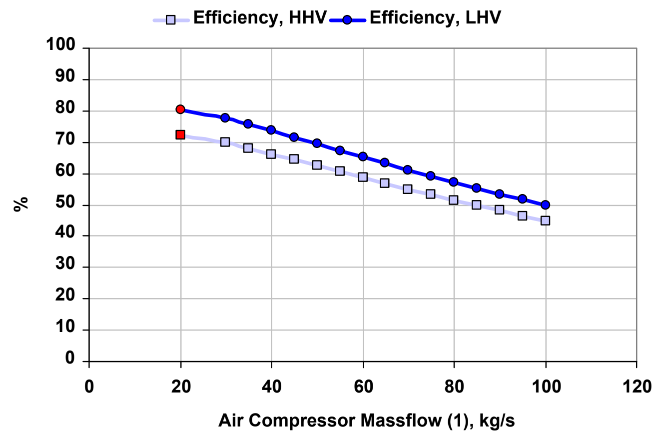

Figure 2: The influence of air compressor mass flow rate

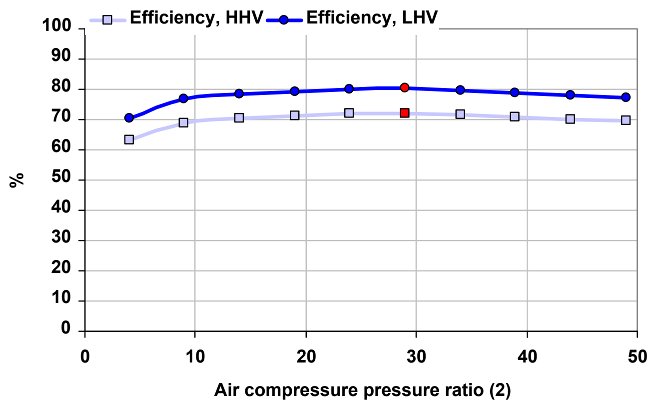

Figure 4: The influence of air compressor pressure ratio

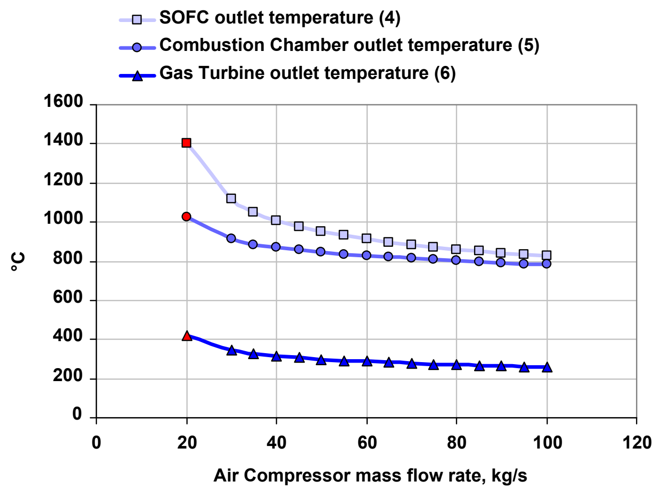

Figure 3: The influence of air compressor mass flow rate on temperatures in chosen system points

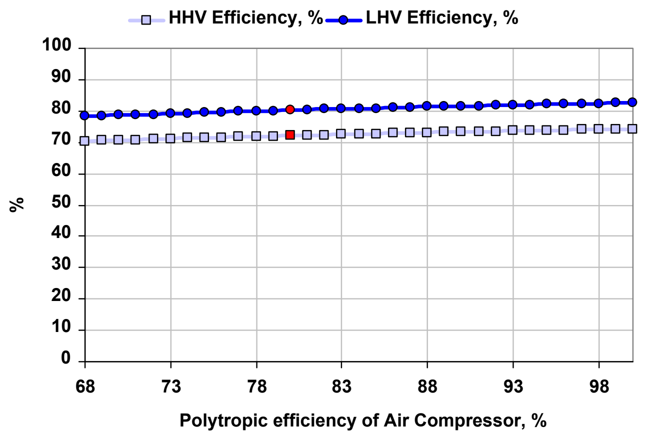

Figure 5: The influence of Air Compressor polytropic efficiency

Fig. 7 presents the influence of amount of fuel supplied to external combustion chamber for rising temperature of gases before the gas turbine. The influence is slightly negative, but the fuel flow can be used for forcing system power.

The influence of two heat exchangers area is shown in Figs 8 and 9. In fact, the figures include a multiplication

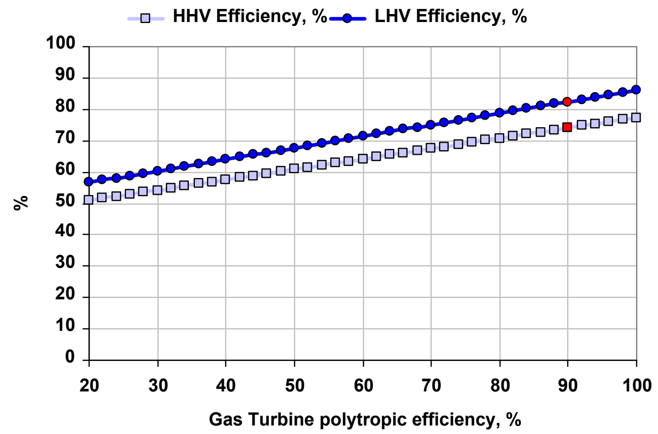

Figure 6: The influence of Gas Turbine polytropic efficiency, %

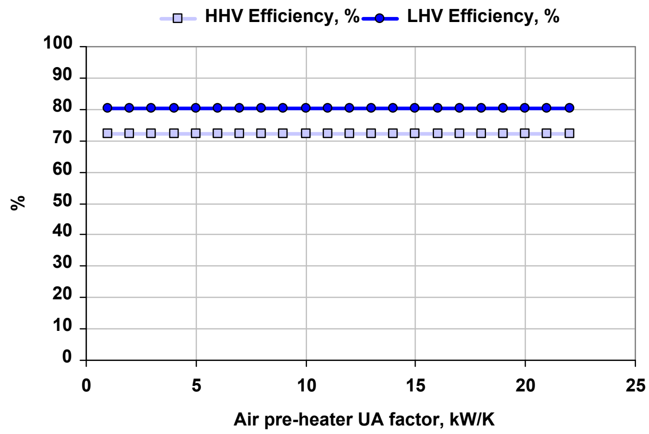

Figure 9: The influence of air pre-heater heat exchanger UA factor

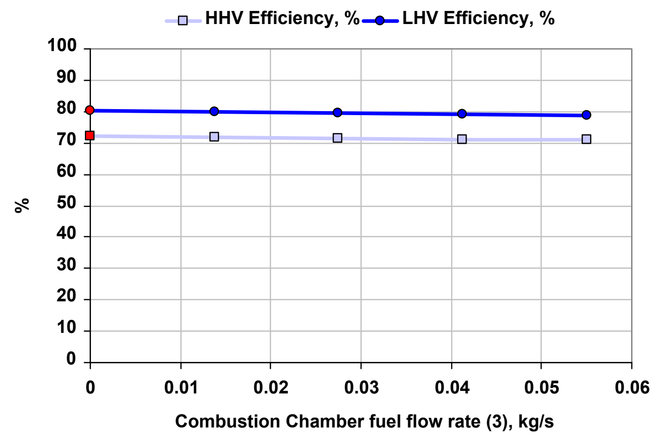

Figure 7: The influence of Combustion Chamber fuel flow rate

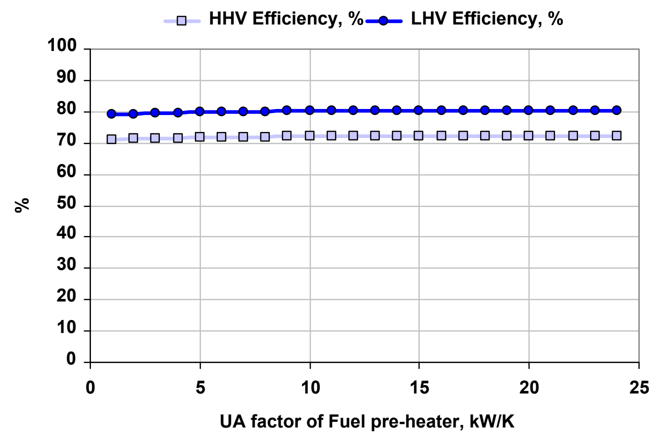

Figure 8: The influence of fuel pre-heater heat exchanger UA factor

of an area (A) and heat transfer coefficient (U) aggregated in a single factor (UA). The both heat exchangers have a marginal impact on system efficiency, because SOFC itself acts as heat recuperator.

4. Discussion

Based on the calculations done, the highest impact on the system efficiency related to air compressor mass flow rate, what is directly translated into operating temperature of SOFC. In fact, the chosen design point seems to be unrealistic (1,400°C), and resulting in very high total system efficiency (>70% HHV-based).

Pressure ratio of the gas turbine subsystem has definite maximum point similarly to the gas turbine stand alone. The optimal value requires very high operating pressure (29 bar) but the curve is relatively flat, thus considerably pressure ratio reduction can be proposed with still quite high total system efficiency. The influence of the rotary machinery (compressor and expander) is visible but not pivotal, as far as gas turbine is responsible for only 10% of the total power generated. The influences of additional heat exchangers (for air and fuel) are negligible because the SOFC stack plays the same role of heat recuperation.

5. Conclusions

A structural analysis of SOFC-HS variants by a possibility of installing a solid oxide fuel cell in a power system was presented in the article. The most rational configuration of a power system with the fuel cell is a system in which it is located in a simple gas turbine cycle before the combustion chamber. For the chosen system, the sensitivity analysis is made. Some of the investigated parameters has negligible influence on system efficiency (this mainly regards area of the heat exchangers), but other can be carefully chosen to keep the system in the most optimal point. Turbomoachinery should be designed or chose very accurately, due to the big impact on the efficiency can be reached.

It should be noted, that the absolute efficiency of the system depends on the assumptions made and the way in which the mathematical model was developed, thus the presented analysis is rather qualitative than quantitative.

References

[1] M. Afrand, A. A. Nadooshan, M. Hassani, H. Yarmand, M. Dahari, Predicting the viscosity of multi-walled carbon nanotubes/water nanofluid by developing an optimal artificial neural network based on experimental data, INTERNATIONAL COMMUNICATIONS IN HEAT AND MASS TRANSFER 77 (2016) 49–53. doi:10.1016/j.icheatmasstransfer.2016.07.008.

[2] M. A. Ansari, S. M. A. Rizvi, S. Khan, Optimization of Electrochemical Performance of a Solid Oxide Fuel Cell using Artificial Neural Network, in: 2016 INTERNATIONAL CONFERENCE ON ELECTRICAL, ELECTRONICS, AND OPTIMIZATION TECHNIQUES (ICEEOT), DMI Coll Engn; IEEE DMI Coll Student Branch, 2016, pp. 4230–4234, International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT), Palnchur, INDIA, MAR 03-05, 2016.

[3] M. Kamvar, M. Ghassemi, M. Rezaei, Effect of catalyst layer configuration on single chamber solid oxide fuel cell performance, APPLIED THERMAL ENGINEERING 100 (2016) 98–104. doi:10.1016/j.applthermaleng.2016.01.128.

[4] X. Lv, C. Gu, X. Liu, Y. Weng, Effect of gasified biomass fuel on load characteristics of an intermediate-temperature solid oxide fuel cell and gas turbine hybrid system, INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 41 (22) (2016) 9563–9576. doi:10.1016/j.ijhydene.2016.04.104.

[5] A. Majedi, A. Abbasi, F. Davar, Green synthesis of zirconia nanoparticles using the modified Pechini method and characterization of its optical and electrical properties, JOURNAL OF SOL-GEL SCIENCE AND TECHNOLOGY 77 (3) (2016) 542–552. doi:10.1007/s10971-015-3881-3.

[6] D. Marra, C. Pianese, P. Polverino, M. Sorrentino, Models for Solid Oxide Fuel Cell Systems Exploitation of Models Hierarchy for Industrial Design of Control and Diagnosis Strategies Introduction, in: MODELS FOR SOLID OXIDE FUEL CELL SYSTEMS: EXPLOITATION OF MODELS HIERARCHY FOR INDUSTRIAL DESIGN OF CONTROL AND DIAGNOSIS STRATEGIES, Green Energy and Technology, 2016, pp. 1–26. doi:10.1007/978-1-4471-5658-1_1.

[7] M. Mehrpooya, H. Dehghani, S. M. A. Moosavian, Optimal design of solid oxide fuel cell, ammonia-water single effect absorption cycle and Rankine steam cycle hybrid system, JOURNAL OF POWER SOURCES 306 (2016) 107–123. doi:10.1016/j.jpowsour.2015.11.103.

[8] R. Peters, R. Deja, M. Engelbracht, M. Frank, V. N. Nguyen, L. Blum, D. Stolten, Efficiency analysis of a hydrogen-fueled solid oxide fuel cell system with anode off-gas recirculation, JOURNAL OF POWER SOURCES 328 (2016) 105–113. doi:10.1016/j.jpowsour.2016.08.002.

[9] M. Skrzypkiewicz, M. Wierzbicki, M. Stepien, Solid Oxide Fuel Cells coupled with a biomass gasification unit, in: Filipowicz, M and Dudek, M and Olkuski, T and Styszko, K (Ed.), 1ST INTERNATIONAL CONFERENCE ON THE SUSTAINABLE ENERGY AND ENVIRONMENT DEVELOPMENT (SEED 2016), Vol. 10 of E3S Web of Conferences, Head Minist Sci & Higher Educ; Minist Energy; Minist Environm; Natl Fund Environm Protect & Water Management; Energy Regulatory Off; Natl Ctr Res & Dev; Head Malopolska Prov Off; Marshal Malopolska Reg; Municipality Krakow; Natl Contact Point; AGH UST Rector; EDFPolska; Cieplo Krakowa; CC Poland Plus; MetalERG; RWE Polska; Fdn Inst Sustainable Energy; AGH UST, Fac Energy & Fuels, 2016, 1st International Conference on the Sustainable Energy and Environment Development (SEED), Krakow, POLAND, MAY 17-19, 2016. doi:10.1051/e3sconf/20161000115.

[10] K. Zouhri, S.-Y. Lee, Tubular SOFC air electrode ohmic overpotential: Parametric and exergy study, ENERGY CONVERSION AND MANAGEMENT 121 (2016) 1–12. doi:10.1016/j.enconman.2016.04.098.

[11] H. Jeong, S. Cho, D. Kim, H. Pyun, D. Ha, C. Han, M. Kang, M. Jeong, S. Lee, A heuristic method of variable selection based on principal component analysis and factor analysis for monitoring in a 300 kw mcfc power plant, International Journal of Hydrogen Energy 37 (15) (2012) 11394–11400.

[12] E. Arato, E. Audasso, L. Barelli, B. Bosio, G. Discepoli, Kinetic modelling of molten carbonate fuel cells: Effects of cathode water and electrode materials, JOURNAL OF POWER SOURCES 330 (2016) 18–27. doi:10.1016/j.jpowsour.2016.08.123.

[13] M. Della Pietra, G. Discepoli, B. Bosio, S. J. McPhail, L. Barelli, G. Bidini, A. Ribes-Greus, Experimental investigation of SO2 poisoning in a Molten Carbonate Fuel Cell operating in CCS configuration, INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 41 (41) (2016) 18822–18836, 3rd International Workshop on Molten Carbonates and Related Topics (IWMC), NE Univ, Shenyang, PEOPLES R CHINA, JUN 11-13, 2015. doi:10.1016/j.ijhydene.2016.05.147.

[14] L. Duan, L. Yue, T. Feng, H. Lu, J. Bian, Study on a novel pressurized MCFC hybrid system with CO2 capture, ENERGY 109 (2016) 737–750. doi:10.1016/j.energy.2016.05.074.

[15] S. Frangini, A. Masi, Molten carbonates for advanced and sustainable energy applications: Part II. Review of recent literature, INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 41 (42) (2016) 18971–18994. doi:10.1016/j.ijhydene.2016.08.076.

[16] F. Golzar, M. Astaneh, R. Roshandel, A. B. Forough, Reducing CO2 emission from exhaust gases using molten carbonate fuel cells: a new approach, INTERNATIONAL JOURNAL OF AMBIENT ENERGY 37 (4) (2016) 331–340. doi:10.1080/01430750.2014.963206.

[17] C. Huang, Y. Pan, Y. Wang, G. Su, J. Chen, An efficient hybrid system using a thermionic generator to harvest waste heat from a reforming molten carbonate fuel cell, ENERGY CONVERSION AND MANAGEMENT 121 (2016) 186–193. doi:10.1016/j.enconman.2016.05.028.

[18] P. Jienkulsawad, A. Arpornwichanop, Investigating the performance of a solid oxide fuel cell and a molten carbonate fuel cell combined system, ENERGY 107 (2016) 843–853. doi:10.1016/j.energy.2016.04.072.

[19] S. Samanta, S. Ghosh, A thermo-economic analysis of repowering of a 250 MW coal fired power plant through integration of Molten Carbonate Fuel Cell with carbon capture, INTERNATIONAL JOURNAL OF GREENHOUSE GAS CONTROL 51 (2016) 48–55. doi:10.1016/j.ijggc.2016.04.021.

[20] E. Audasso, B. Bosio, S. Nam, Extension of an effective MCFC kinetic model to a wider range of operating conditions, INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 41 (12) (2016) 5571–5581. doi:10.1016/j.ijhydene.2015.10.152.

[21] J. Milewski, M. Wołowicz, A. Miller, R. Bernat, A reduced order model of molten carbonate fuel cell: A proposal, International Journal of Hydrogen Energy 38 (26) (2013) 11565–11575.

[22] G. Rey, C. Ulloa, J. Luis Miguez, E. Arce, Development of an ICE-Based Micro-CHP System Based on a Stirling Engine; Methodology for a Comparative Study of its Performance and Sensitivity Analysis in Recreational Sailing Boats in Different European Climates, ENERGIES 9 (4). doi:10.3390/en9040239.

[23] A. Chmielewski, R. Guminski, J. Maczak, S. Radkowski, P. Szulim, Aspects of balanced development of RES and distributed microcogeneration use in Poland: Case study of a mu CHP with Stirling engine, RENEWABLE & SUSTAINABLE ENERGY REVIEWS 60 (2016) 930–952. doi:10.1016/j.rser.2016.01.131.

[24] L. Szablowski, J. Milewski, J. Kuta, K. Badyda, Control strategy of a natural gas fuelled piston engine working in distributed generation system, Rynek Energii (3) (2011) 33–40.

[25] D. McLarty, J. Brouwer, C. Ainscough, Economic analysis of fuel cell installations at commercial buildings including regional pricing and complementary technologies, ENERGY AND BUILDINGS 113 (2016) 112–122. doi:10.1016/j.enbuild.2015.12.029.

[26] L. Romero Rodriguez, J. M. Salmeron Lissen, J. Sanchez Ramos, E. A. Rodriguez Jara, S. Alvarez Dominguez, Analysis of the economic feasibility and reduction of a building's energy consumption and emissions when integrating hybrid solar thermal/PV/micro-CHP systems, APPLIED ENERGY 165 (2016) 828–838. doi:10.1016/j.apenergy.2015.12.080.

[27] H. Wu, L.-j. Yang, J.-p. Yan, G.-x. Hong, B. Yang, Improving the removal of fine particles by heterogeneous condensation during WFGD processes, FUEL PROCESSING TECHNOLOGY 145 (2016) 116–122. doi:10.1016/j.fuproc.2016.01.033.

[28] . Bartela, A. Skorek-Osikowska, J. Kotowicz, Integration of a supercritical coal-fired heat and power plant with carbon capture installation and gas turbine, Rynek Energii 100 (3) (2012) 56–62.

[29] R. Laskowski, A. Smyk, A. Rusowicz, A. Grzebielec, Determining the Optimum Inner Diameter of Condenser Tubes Based on Thermodynamic Objective Functions and an Economic Analysis, ENTROPY

18 (12). doi:10.3390/e18120444.
[30] M. Wołowicz, J. Milewski, K. Futyma, W. Bujalski, Boosting the efficiency of an 800 mw-class power plant through utilization of low temperature heat of flue gases, in: Applied Mechanics and Materials, Vol. 483, Trans Tech Publ, 2014, pp. 315–321.
[31] J. Kotowicz, M. Jurczyk, D. Wecel, W. Ogulewicz, Analysis of Hydrogen Production in Alkaline Electrolyzers, JOURNAL OF POWER TECHNOLOGIES 96 (3) (2016) 149–156.
[32] J. Kupecki, J. Jewulski, K. Badyda, Comparative study of biogas and dme fed micro-chp system with solid oxide fuel cell, Applied Mechanics and Materials 267 (2013) 53–56.
[33] W. Budzianowski, Sustainable biogas energy in poland: Prospects and challenges, Renewable and Sustainable Energy Reviews 16 (1) (2012) 342–349.
[34] P. Krawczyk, Control strategy for ventilation system of sewage sludge solar dryer, JOURNAL OF POWER TECHNOLOGIES 96 (2) (2016) 145–148.
[35] A. Skorek-Osikowska, L. Bartela, J. Kotowicz, K. Dubiel, Use of a gas turbine in a hybrid power plant integrated with an electrolyser, biomass gasification generator and methanation reactor, JOURNAL OF POWER TECHNOLOGIES 96 (2) (2016) 73–80.
[36] I.-S. Han, C.-B. Chung, Performance prediction and analysis of a PEM fuel cell operating on pure oxygen using data-driven models: A comparison of artificial neural network and support vector machine, INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 41 (24) (2016) 10202–10211. doi:10.1016/j.ijhydene.2016.04.247.
[37] M. Beltran-Gastelum, M. I. Salazar-Gastelum, R. M. Felix-Navarro, S. Perez-Sicairos, E. A. Reynoso-Soto, S. W. Lin, J. R. Flores-Hernandez, T. Romero-Castanon, I. L. Albarran-Sanchez, F. Paraguay-Delgado, Evaluation of Pt-Au/MWCNT (Multiwalled Carbon Nanotubes) electrocatalyst performance as cathode of a proton exchange membrane fuel cell, ENERGY 109 (2016) 446–455. doi:10.1016/j.energy.2016.04.132.
[38] L. Barelli, G. Bidini, A. Ottaviano, Part load operation of a sofc/gt hybrid system: Dynamic analysis, Applied Energy 110 (0) (2013) 173 – 189.
[39] J. Kupecki, J. Milewski, A. Szczesniak, R. Bernat, K. Motylinski, Dynamic numerical analysis of cross-, co-, and counter-current flow configuration of a 1 kw-class solid oxide fuel cell stack, International Journal of Hydrogen Energy 40 (45) (2015) 15834–15844.
[40] M. Santin, A. Traverso, L. Magistri, A. Massardo, Thermoeconomic analysis of sofc-gt hybrid systems fed by liquid fuels, Energy 35 (2) (2010) 1077 – 1083, <ce:title>ECOS 2008</ce:title> <xocs:full-name>21st International Conference, on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems</xocs:full-name>.
[41] M. Sucipta, S. Kimijima, K. Suzuki, Performance analysis of the SOFC–MGT hybrid system with gasified biomass fuel, Journal of Power Sources 174 (1) (2007) 124 – 135, <ce:title>Hybrid Electric Vehicles</ce:title>.
[42] S. Chan, H. Ho, Y. Tian, Multi-level modeling of sofc–gas turbine hybrid system, International Journal of Hydrogen Energy 28 (8) (2003) 889 – 900.
[43] T. W. Song, J. L. Sohn, T. S. Kim, S. T. Ro, Performance characteristics of a mw-class sofc/gt hybrid system based on a commercially available gas turbine, Journal of Power Sources 158 (1) (2006) 361 – 367.
[44] F. Calise, M. D. d Accadia, A. Palombo, L. Vanoli, Simulation and exergy analysis of a hybrid solid oxide fuel cell (sofc)–gas turbine system, Energy 31 (15) (2006) 3278 – 3299, <ce:title>ECOS 2004 - 17th International Conference on Efficiency, Costs, Optimization, Simulation, and Environmental Impact of Energy on Process Systems</ce:title> <xocs:full-name>17th International Conference on Efficiency, Costs, Optimization, Simulation, and Environmental Impact of Energy on Process Systems</xocs:full-name>.
[45] W. R. Dunbar, N. Lior, R. A. Gaggioli, Combining fuel cells with fuel-fired power plants for improved exergy efficiency, Energy 16 (10) (1991) 1259 – 1274.
[46] W. Dunbar, N. Lior, R. Gaggioli, Effect of the fuel-cell unit size on the efficiency of a fuel-cell-topped rankine power cycle, Journal of Energy Resources Technology, Transactions of the ASME 115 (2) (1993) 105–107, cited By (since 1996)8.
[47] S. Chan, C. Low, O. Ding, Energy and exergy analysis of simple solid-oxide fuel-cell power systems, Journal of Power Sources 103 (2) (2002) 188 – 200.
[48] L. Larosa, A. Traverso, M. L. Ferrari, V. Zaccaria, Pressurized sofc hybrid systems: Control system study and experimental verification, Journal of Engineering for Gas Turbines and Power 137 (3) (2015) 031602.
[49] L. Larosa, A. Traverso, V. Zaccaria, AMBIENT TEMPERATURE IMPACT ON PRESSURIZED SOFC HYBRID SYSTEMS, in: ASME TURBO EXPO: TURBINE TECHNICAL CONFERENCE AND EXPOSITION, 2015, VOL 3, Int Gas Turbine Inst, 2015, ASME Turbo Expo: Turbine Technical Conference and Exposition, Montreal, CANADA, JUN 15-19, 2015.
[50] J. Milewski, M. Wołowicz, R. Bernat, L. Szablowski, J. Lewandowski, Variant analysis of the structure and parameters of sofc hybrid systems, in: Applied Mechanics and Materials, Vol. 437, Trans Tech Publ, 2013, pp. 306–312.
[51] D. Bakalis, A. Stamatis, Incorporating available micro gas turbines and fuel cell: Matching considerations and performance evaluation, Applied Energy 103 (2013) 607–617.
[52] M. Amirinejad, N. Tavajohi-Hasankiadeh, S. Madaeni, M. Navarra, E. Rafiee, B. Scrosati, Adaptive neuro-fuzzy inference system and artificial neural network modeling of proton exchange membrane fuel cells based on nanocomposite and recast nafion membranes, International Journal of Energy Research 37 (4) (2013) 347–357.
[53] L. Barelli, G. Bidini, S. Campanari, G. Discepoli, M. Spinelli, Performance assessment of natural gas and biogas fueled molten carbonate fuel cells in carbon capture configuration, JOURNAL OF POWER SOURCES 320 (2016) 332–342. doi:10.1016/j.jpowsour.2016.04.071.
[54] L. Bartela, J. Kotowicz, K. Dubiel, Technical - economic comparative analysis of energy storage systems equipped with a hydrogen generation installation, JOURNAL OF POWER TECHNOLOGIES 96 (2) (2016) 92–100.
[55] S. Bozorgmehri, M. Hamedi, Modeling and optimization of anode-supported solid oxide fuel cells on cell parameters via artificial neural network and genetic algorithm, Fuel Cells 12 (1) (2012) 11–23.
[56] D. A. Brunner, S. Marcks, M. Bajpai, A. K. Prasad, S. G. Advani, Design and characterization of an electronically controlled variable flow rate ejector for fuel cell applications, International Journal of Hydrogen Energy 37 (5) (2012) 4457 – 4466.
[57] W. M. Budzianowski, A review of potential innovations for production, conditioning and utilization of biogas with multiple-criteria assessment, RENEWABLE & SUSTAINABLE ENERGY REVIEWS 54 (2016) 1148–1171. doi:10.1016/j.rser.2015.10.054.
[58] W. M. Budzianowski, K. J. Budzianowska, D. S. Budzianowska, Analysis of solutions alleviating CO2 emissions intensity of biogas technology, INTERNATIONAL JOURNAL OF GLOBAL WARMING 9 (4) (2016) 507–528.
[59] K. Chaichana, Y. Patcharavorachot, B. Chutichai, D. Saebea, S. Assabumrungrat, A. Arpornwichanop, Neural network hybrid model of a direct internal reforming solid oxide fuel cell, International Journal of Hydrogen Energy 37 (3) (2012) 2498–2508.
[60] S. H. Chan, J. P. Stempien, O. L. Ding, P.-C. Su, H. K. Ho, Fuel cell and hydrogen technologies research, development and demonstration activities in Singapore - An update, INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 41 (32) (2016) 13869–13878. doi:10.1016/j.ijhydene.2016.05.192.
[61] A. Chmielewski, R. Guminski, J. Maczak, Selected properties of the adiabatic model of the Stirling engine combined with the model of the piston-crankshaft system, in: 2016 21ST INTERNATIONAL CONFERENCE ON METHODS AND MODELS IN AUTOMATION AND ROBOTICS (MMAR), 2016, pp. 543–548, 21st International Conference on Methods and Models in Automation and Robotics (MMAR), Miedzyzdroje, POLAND, AUG 29-SEP 01, 2016.
[62] A. Chmielewski, R. Guminski, J. Maczak, Dynamic model of a free-piston Stirling engine with four degrees of freedom combined with the thermodynamic submodel, in: 2016 21ST INTERNATIONAL CONFERENCE ON METHODS AND MODELS IN AUTOMATION AND ROBOTICS (MMAR), 2016, pp. 583–588, 21st International Conference on Methods and Models in Automation and Robotics (MMAR), Miedzyzdroje, POLAND, AUG 29-SEP 01, 2016.
[63] A. Chmielewski, R. Guminski, J. Maczak, P. Szulim, Model-based re-

search on a micro cogeneration system with Stirling engine, JOURNAL OF POWER TECHNOLOGIES 96 (4) (2016) 295–305.

[64] C. Churiaque, M. R. Amaya-Vazquez, F. J. Botana, J. M. Sanchez-Amaya, FEM Simulation and Experimental Validation of LBW Under Conduction Regime of Ti6Al4V Alloy, JOURNAL OF MATERIALS ENGINEERING AND PERFORMANCE 25 (8, SI) (2016) 3260–3269, International Symposium on Metal-Matrix Composites as part of the European Congress on Advanced Materials and Processes (EUROMAT), Warsaw, POLAND, SEP 20-24, 2015. doi:10.1007/s11665-016-2214-1.

[65] G. De Lorenzo, P. Fragiacomo, A methodology for improving the performance of molten carbonate fuel cell/gas turbine hybrid systems, International Journal of Energy Research 36 (1) (2012) 96–110.

[66] G. Discepoli, G. Cinti, U. Desideri, D. Penchini, S. Proietti, Carbon capture with molten carbonate fuel cells: Experimental tests and fuel cell performance assessment, International Journal of Greenhouse Gas Control 9 (2012) 372–384.

[67] D. Grondin, J. Deseure, P. Ozil, J.-P. Chabriat, B. Grondin-Perez, A. Brisse, Solid oxide electrolysis cell 3d simulation using artificial neural network for cathodic process description, Chemical Engineering Research and Design 91 (1) (2013) 134–140.

[68] E. Jannelli, M. Minutillo, A. Perna, Analyzing microcogeneration systems based on lt-pemfc and ht-pemfc by energy balances, Applied Energy 108 (2013) 82–91.

[69] K. Janusz-Szymańska, Economic efficiency of an igcc system integreted with ccs installation [efektywność ekonomiczna układu gazowo-parowego zintegrowanego ze zgazowaniem węgla oraz z instalacją CCS], Rynek Energii 102 (5) (2012) 24–30.

[70] H. Jeong, K. Park, J. Cho, Numerical analysis of variable polarity arc weld pool, JOURNAL OF MECHANICAL SCIENCE AND TECHNOLOGY 30 (9) (2016) 4307–4313. doi:10.1007/s12206-016-0845-7.

[71] P. Krawczyk, L. Szablowski, K. Badyda, S. Karellas, E. Kakaras, Impact of selected parameters on performance of the Adiabatic Liquid Air Energy Storage system, JOURNAL OF POWER TECHNOLOGIES 96 (4) (2016) 238–244.

[72] J. Kupecki, K. Motylinski, M. Ferraro, F. Sergi, N. Zanon, Use of NaNiCl battery for mitigation of SOFC stack cycling in base-load telecommunication power system-a preliminary evaluation, JOURNAL OF POWER TECHNOLOGIES 96 (1) (2016) 63–71.

[73] C.-G. Lee, D.-H. Kim, H.-C. Lim, Electrode reaction characteristics under pressurized conditions in a molten carbonate fuel cell, Journal of the Electrochemical Society 154 (4) (2007) B396–B404.

[74] X. Lv, X. Liu, C. Gu, Y. Weng, Determination of safe operation zone for an intermediate-temperature solid oxide fuel cell and gas turbine hybrid system, ENERGY 99 (2016) 91–102. doi:10.1016/j.energy.2016.01.047.

[75] H. Marzooghi, M. Raoofat, M. Dehghani, G. Elahi, Dynamic modeling of solid oxide fuel cell stack based on local linear model tree algorithm, International Journal of Hydrogen Energy 37 (5) (2012) 4367–4376.

[76] J. Milewski, A mathematical model of sofc: A proposal, Fuel Cells 12 (5) (2012) 709–721.

[77] P. Pianko-Oprych, Z. Jaworski, Numerical modelling of the micro-tubular solid oxide fuel cell stacks [przeglad metod modelowania numerycznego mikrorurowych stał otlenkowych stosów ognhw paliwowych], Przemysl Chemiczny 91 (9) (2012) 1813–1815.

[78] J. Qian, Z. Tao, J. Xiao, G. Jiang, W. Liu, Performance improvement of ceria-based solid oxide fuel cells with yttria-stabilized zirconia as an electronic blocking layer by pulsed laser deposition, International Journal of Hydrogen Energy 38 (5) (2013) 2407–2412.

[79] D. Sánchez, B. Monje, R. Chacartegui, S. Campanari, Potential of molten carbonate fuel cells to enhance the performance of chp plants in sewage treatment facilities, International Journal of Hydrogen Energy 38 (1) (2013) 394–405.

[80] A. Sobolewski, . Bartela, A. Skorek-Osikowska, T. Iluk, Comparison of the economic efficiency of chp plants integrated with gazela generator [porównanie efektywności ekonomicznej układów kogeneracyjnych z generatorem gazu procesowego gazela], Rynek Energii 102 (5) (2012) 31–37.

[81] A. Zamaniyan, F. Joda, A. Behroozsarand, H. Ebrahimi, Application of artificial neural networks (ann) for modeling of industrial hydrogen plant, International Journal of Hydrogen Energy 38 (15) (2013) 6289–6297.