# Utilisation of a set of distributed generation sources controlled by artificial neural network to meet electricity demand of public utility buildings

***Lukasz Szablowski[a], Jaroslaw Milewski[b] and Krzysztof Badyda[c]***

[a,b,c] *Institute of heat engineering, Warsaw University of Technology, Warsaw, Poland,*
[a] *lukasz.szablowski@itc.pw.edu.pl*
[b] *milewski@itc.pw.edu.pl*
[c] *krzysztof.badyda@itc.pw.edu.pl*

**Abstract:**

The paper presents a way of using artificial neural networks to develop operation strategies for a set of distributed energy sources. The considered system consists of: LHM80 piston engine, two SD4-E Stirling engines supplied with fine coal, Capstone C65 micro gas turbine, SOFC fuel cell, ORC unit, three Mistral 3K wind turbines and forty six HIP-215NKHE1 SANYO photovoltaic cells. To simulate the control process of system of distributed sources artificial neural network (consisted of three layers) was constructed. At the input of the network the following information have been given: actual demand for electric power of customers supplied with the system, wind speed, solar power and ambient temperature. At the outputs were obtained: information on the suggested values of load (power) of the piston engine, Stirling engine, micro gas turbine, SOFC fuel cell and ORC unit. The demand for electric power of customers supplied with the system was obtained by rescaling the demand of Institute of Heat Engineering and Central Canteen of Warsaw University of Technology (the time period from October 8, 2011 to October 23, 2011 inclusive), so that the maximum value of the demand was equal to the total capacity of the conventional energy sources of the considered DG system.

**Keywords:**

Distributed generation, Artificial neural networks, Control strategy, Virtual power plants.

# 1. Introduction

The current problems in the energy sector force us to develop more and more sophisticated and technologically advanced systems [1–10]. One of the alternative ways of development is distributed generation.

Until now research on operation of sources in a distributed generation system concerned mainly on electrical issues [11–17] – synchronization with the network, the impact of disturbances generation, etc. Problems related to the long-term way of exploitation of DG sources were virtually recognized and unexplored.

Studies on the specificity of work of distributed sources and their impact on the power system are carried out around the world. According to [18] the development of this technology is essential in the prevalence of many so-called clean technologies and this development has to force the transition from procedures of forecasting to scenario techniques. Influence of the development of distributed generation on the reliability of the power system is presented in [11] together with stating the conditions that must be met. It was also found that decentralized production makes it possible to realize the personalized requirements of users and their active participation in the game of market supply and demand.

In [11, 12, 18, 19] sources that can operate as a distributed were classified:

- piston engines;
- gas turbines;
- Stirling engines;
- CHP systems based on gas turbines and reciprocating engines;

- small hydroelectric plants; wind power plants;
- photovoltaic systems (direct method); geothermal plants;
- fuel cells;
- solar thermal systems (indirect method);
- systems using biomass and waste, tides, marine currents, wave energy and heat.

The studies [12, 19] also discuss various aspects of operation of such sources (technical, economic, operational, environmental). Also influence of distributed generation on the national power system has been analyzed. Those studies also pointed out that it is necessary to prepare the IT systems for managing distributed generation, basing on new communication equipment and technologies.

The distributed power generation has been quite comprehensively discussed in [20]. This work describes issues such as technical integration with the power system, economic conditions, impact of legal framework on distributed power generation development and SWOT analysis.

The study [21] discusses potential of distributed power generation in Poland, along with technologies which in its author’s opinion [21] should be developed in Poland. The study also highlighted a possibility of developing energy agriculture in this country.

Most published studies focus almost exclusively on electrical and electronic aspects of the cooperation between a distributed source and a power system [12, 13]. Investigated time frames are below 1 second. A number of solutions ensuring safe interconnection between a source and the grid ensuring safe operation are proposed (e.g. through intermediate DC link).

Micro grids (small energy systems) are discussed in [22, 23], which discuss mutual covering of each other’s needs by prosumers (producers-consumers) using local heating and power networks. The study [24] covers the topics related to island operation of generators within a power micro grid.

There is also ongoing investigation on operation of the power grid itself [13, 14] including transmission issues. Another issue which has been analysed is behaviour of the power grid with connected distributed generation in emergency situations [15] – this also focused on electrical questions.

The study [25] presented operation of a CHP system with a gas micro turbine and a heat storage system installed at a university in Sapporo.

Influence of replacing the parallel connection with a series one in a local hot water supply system supplied from a distributed CHP source has been presented in [26]. It has been proposed to replace heat exchanger in each building with a heat storage tank in order to reduce required nominal output of the energy source supplying the analysed system. Similar issues have been dealt with by the authors of the study [27].

The use of heat pumps in virtual power plants (composed of many distributed sources) was discussed in [28].

Possibilities of using biomass gasification process in CHP systems are presented in [29–32], which used – among others – experimental data obtained during tests of a small output (60 kWth) gas generator GazEla.

Controlling multiple distributed sources using the Internet was a subject of the study [33], which also discussed economic aspects of joint operation of such sources. A real-time simulator of a distributed source connection has been developed for analytical purposes [16], however it has only been used to analyse electrical aspects of cooperation between source and the grid. Analysed time frames were below 100 μs. Other analysed aspects were: operation of the sources alone in the context of their efficiency and output, as well as possibility of CHP operation [34, 35].

Presently available publications do not contain information concerning long-term operation of a distributed source or a operational strategy to be followed depending on the changing market environment.

## 2. Methods and Materials

In this section the way of use of artificial neural networks to develop operation strategies for a set of distributed energy sources was shown. Using the artificial neural networks the whole system has been modeled.
The considered system consists of: LHM80 piston engine, two SD4-E Stirling engines supplied with fine coal, Capstone C65 micro gas turbine, SOFC fuel cell, ORC unit, three Mistral 3K wind turbines and forty six HIP-215NKHE1 SANYO photovoltaic cells.
Power ranges of these machines and devices are discussed in subsection 2.1, while the types of fuel used, the price of fuel and the cost of purchasing electricity – in subsection 2.2.
The number of renewable energy sources was chosen in such a way that the powers of a particular type of renewable devices were close to 10 kW (9 kW for wind turbines and 9.936 kW for photovoltaic). Thus, the impact of these sources on the operation of the entire system was no longer negligible.
To simulate the control process of system of distributed sources artificial neural network (theory of artificial neural networks is described in subsection 2.3) was constructed. The network consisted of three layers: input, hidden and output layer. In this case, the network has a 4 inputs and 5 outputs. At the input of the network the following information have been given: actual demand for electric power of customers supplied with the system, wind speed, solar power and ambient temperature. At the outputs were obtained: information on the suggested values of load (power) of the piston engine, Stirling engine, micro gas turbine, SOFC fuel cell and ORC unit.
The neural network was designed to simulate a load optimizer for the five listed above, machines and devices belonging to the system under consideration.
Power values of wind turbines and photovoltaic cells were only the result of wind speed, solar radiation and air temperature, therefore they was not considered as a output of described above artificial neural network. These values, however, had a significant impact on the data that were used for network training, since they have reducing the total demand for electric power and constituted an additional income (negative expense) as a certificate of origin for electricity (green certificates).
The selection of neural network structure was to determine the number of neurons in the hidden layer. For this purpose, 20 variants of artificial neural network architectures were tested (from 4-1-5 to 4-20-5).
To obtain data for training and testing artificial neural network considered in this section, the system was also modelled in a classical way – using MS Excel spreadsheet.
"Classical" system was optimized using the add-in called Solver so that the variable cost of obtaining electrical energy ((1) and (2)) was the lowest.

$$K_{el\ en\ i} \rightarrow \min \ , \qquad (1)$$

$$K_{el\ en\ i} = -\left(E_{el\ en\ w\ i} + E_{el\ en\ phot\ i}\right) \cdot pr_{cert} + K_{fuel\ mgt\ i} + K_{fuel\ SOFC\ i} + K_{fuel\ ORC\ i} + K_{fuel\ Stirling i} + K_{fuel\ pistoneng\ i} + K_{el\ en\ grid\ i} - P_{sel\ el\ en\ i} , \qquad (2)$$

where: $K_{el\ en\ i}$ – the cost of electricity for the $i$-th time period, $E_{el\ en\ w\ i}$ – electrical energy generated by wind turbines for the i-th time period, $E_{el\ en\ phot\ i}$ – electrical energy generated by photovoltaics for the $i$-th time period, $pr_{cert}$ – green certificate price per unit of energy, $K_{fuel\ mgt\ i}$, $K_{fuel\ SOFC\ i}$, $K_{fuel\ ORC\ i}$, $K_{fuel\ Stirling\ i}$, $K_{fuel\ piston\ eng\ i}$ – the cost of fuel consumed respectively by: micro gas turbine, SOFC fuel cell, ORC unit, Stirling engine and piston engine for the $i$-th time period, $K_{el\ en\ grid\ i}$ – the cost of purchasing electricity from the grid for the $i$-th time period, $P_{sel\ el\ en\ i}$ – the revenue from selling electricity for the $i$-th time period.
The demand for electric power of customers supplied with the system was obtained by rescaling the demand of Institute of Heat Engineering and Central Canteen of Warsaw University of Technology (the time period from October 8, 2011 to October 23, 2011 inclusive), so that the maximum value of

the demand was equal to the total capacity of the conventional energy sources of the considered DG system. For the same time period the archival data on wind speed, solar radiation and air temperature was collected from the weather service [36]. These data, together with the demand for electric power has been used in a classical model of the system, thereby suggested loads of five conventional DG sources was obtained. In this way, a full set of information for testing artificial neural network was achieved.

Set of data for training of artificial neural network was obtained using the random number generator in MS Excel. At the rescaled electric power demand of the IHE WUT building and Central Canteen of WUT random filter (±20%) was applied. The speed of the wind, solar irradiance, and the air temperature were generated randomly from the ranges respectively: from 0 to 17 m/s, from 0 to 1000 W/m$^2$ (maximum value for the applied photovoltaic cell) and from -20 to 36°C. Suggested loads of conventional sources of the considered system were obtained in the same manner as the data set to test of artificial neural network.

## 2.1. Distributed generation sources

### 2.1.1. Piston engine

Stationary piston engine LHM80 made by the Chinese company LVHUAN was one of analyzed sources. Rated power of that unit was 64/80 kW (prime/standby) and its heat consumption was equal or smaller than 9.8 MJ/kWh ($\eta \geq 0.367$).

The engine efficiency graph (Fig. 1) was based on actual data from the operation of Mephisto engines ([37]) after they were first normalized and generalized.

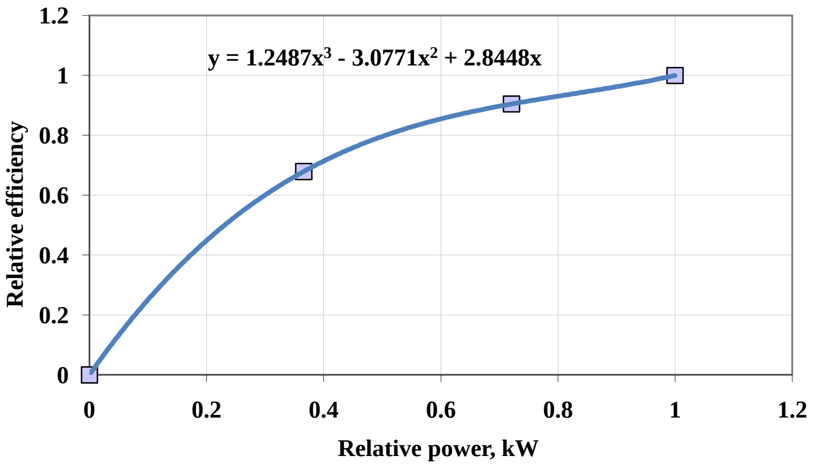


*Fig. 1. Relative engine efficiency (based on [37]).*

Changes in the efficiency of the engine during load changes can be approximated by the following relationship:

$$\eta_{rel} = 1.2487 \cdot P_{rel}^3 - 3.0771 \cdot P_{rel}^2 + 2.8448 \cdot P_{rel}, \qquad (3)$$

where: $\eta_{rel}$ – relative engine efficiency, $P_{rel}$ – relative power.

Engine efficiency at the actual load is obtained by multiplying nominal electrical efficiency by relative efficiency.

The power supplied to the engine through the fuel ($P_{fuel}$) was determined by (4).

$$P_{fuel} = P_{el} \cdot \eta_{nom} \cdot \eta_{rel}, \qquad (4)$$

where: $\eta_{nom}$ – nominal engine efficiency, $P_{el}$ – electrical power.
Fuel chemical energy consumption can be calculated by the trapezoidal rule or by dividing the demand for electric power by the actual efficiency of engine.
Knowing the lower heating value of the fuel (in this case natural gas) its consumption can be calculated in units in which a fee is charged ($Nm^3$ in this case).
The quantity of electricity obtained by using the motor was calculated using the trapezoidal rule (like for other machines and devices).

### 2.1.2. Stirling engine

Stationary Stirling engines SD4-E made by the Stirling DK was an analyzed source.
Therefore, the considered demand is nearly twice as the SD4-E nominal power it was assumed that this demand can be meet with two such engines. It is quite widely used solution (are found even a combination of four engines) because the SD4-E engine is the largest commercially available device of this type.
The elecrical power output of that unit is 35 kW, electrical efficiency (LHV) of engine – 28 % and electrical efficiency (LHV) of system (including boiler) – 17.5 %.
The characteristics of efficiency of Stirling engine was reconstructed from data describing changes of power and efficiency of solar system consisted of solar dishes and Stirling engines during the day [38]. Changes in the efficiency of the Stirling engine during load changes can be approximated (similarly as in case of piston engine) by the following relationship:

$$\eta_{rel} = 1.5947 \cdot P_{rel}^3 - 4.0547 \cdot P_{rel}^2 + 3.5229 \cdot P_{rel} - 0.0624\,, \qquad (5)$$

where: $\eta_{rel}$ – relative engine efficiency, $P_{rel}$ – relative power.
Stirling engine efficiency at the actual load is obtained by multiplying nominal electrical efficiency by relative efficiency.

### 2.1.3. *μ*-turbine

Third analized source was stationary microturbine C65 made by the Capstone Turbine Corporation. In order to improve the electrical efficiency the device is equipped with a recuperation system. The elecric power of that unit is 65 kW and its electrical efficiency (LHV) – 29 %.
The micro-turbine efficiency characteristics was based on actual data from [39]. Changes in the efficiency of the μ-turbine during load changes can be approximated by the following relationship:

$$\eta_{rel} = 0.3907 \cdot P_{rel}^3 - 1.1877 \cdot P_{rel}^2 + 1.7942 \cdot P_{rel}\,, \qquad (6)$$

where: $\eta_{rel}$ – relative engine efficiency, $P_{rel}$ – relative power.
Micro-turbine efficiency at the actual load is obtained the same way as for piston engine.

### 2.1.4. Fuel cell

The fuel cell must run on the maximum lifetime, what we get as a result of continuous operation (without unnecessary shutdowns and start-ups). To get a decent profit (or minimize losses) in this case, the fuel cell cannot be oversized. This means that for a large demand electrical energy must be purchased from the grid or produced by other sources. Rated output of the cell has been adopted at approx. 25.7 kW. Technical minimum of cell operation was set at the level of 60%. However, if encountered a situation that the demand would be lower, excess of electricity produced by the SOFC fuel cell must be sold in order to avoid shutdowns and start-ups of the cell.

As a result of approximation of efficiency characteristic of SOFC the following relationship were obtained (similarly as in case of piston engine):

$$\eta = -0.3711 \cdot P_{rel}^2 + 0.8421 \cdot P_{rel}, \qquad (7)$$

where: $\eta$ – actual (momentary) electrical efficiency of the fuel cell, $P_{rel}$ – relative power.

### 2.1.5. ORC unit

Characteristics of ORC efficiency of electricity production as a function of load were taken from [40] and then normalized (like in case of other machines/devices mentioned above) and approximated by formula 8.

$$\eta_{ORC} = \left(-57.6 \cdot P_{rel}^3 + 159 \cdot P_{rel}^2 - 167 \cdot P_{rel} + 84.2\right) \cdot P_{rel}, \qquad (8)$$

ORC system can operate in the range of load between 30 and 105% of the nominal power. This means that the production of electricity must be carried out continuously.

The smallest commercially available ORC system has a power of 200 kW. It was assumed that the system operates in the range of 30 to 100% load, without unnecessary start-ups and shut-downs. In case of lower demand than 60 kW (30% of the nominal power of the unit) excess of electricity should be sold to the grid (at a price of 0.2 zł/kWh) to avoid shut-down of the unit.

### 2.1.6. Micro wind turbine

One of the elements of the system discussed in the article was a wind turbine of the horizontal axis and three blades – Carlo Gavazzi Mistral 3K with a maximum power of 3 kW.

According to [41] nominal output power of the unit, its maximal output power, wind speed at which energy is supplied by turbine, wind speed which activate “Furl” security system were respectively: 2.0 kW (for 11.0 m/s), 3 kW, 3 m/s and 13.5 m/s.

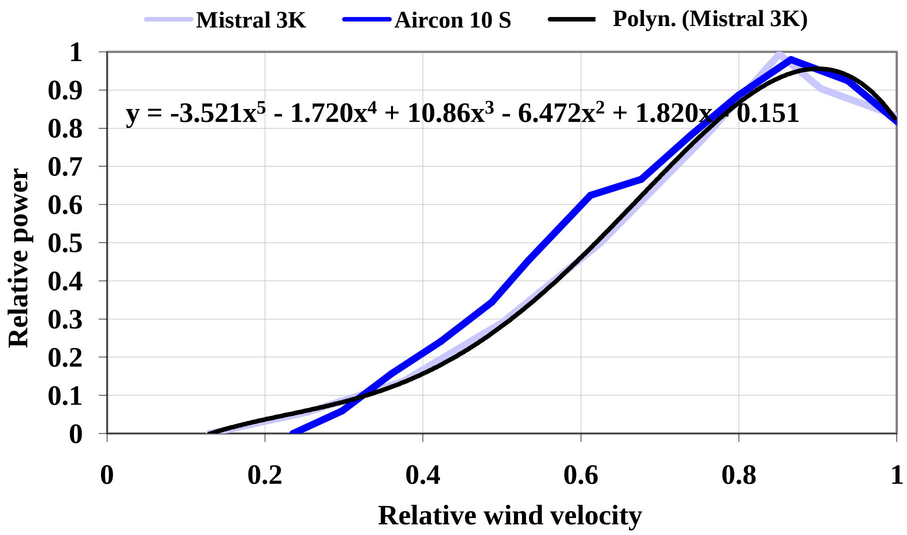


*Fig. 2. Relative power of the wind turbine depending on the relative wind speed for two different devices with a nominal power of 3 kW (based on [42]) and 12.5 kW (based on [43]).*

The characteristics of power of the Mistral 3K (Fig. 2) wind turbine was approximated by the following formula:

$$P_{rel} = -3.5216 \cdot V_{rel\,w}^5 - 1.7209 \cdot V_{rel\,w}^4 + 10.863 \cdot V_{rel\,w}^3 - 6.4723 \cdot V_{rel\,w}^2 + 1.8209 \cdot V_{rel\,w} - 0.1513, \quad (9)$$

where: $P_{rel}$ – relative power, $V_{rel\,w}$ – relative wind velocity.
Equation (9) is correct for the range of wind speed of 3 – 16 m/s.

### 2.1.7. Solar cell

According to [44] maximum power of SANYO HIP-215NKHE1 module, its guaranteed nominal power, cell efficiency, efficiency of the module and its nominal operating temperature were respectively: 215 W, 204.3 W, 19.3 %, 15.1 % and 25°C.
The characteristics of this cell for the case of working with maximum power and device temperature equal to 25°C is described using the following formula:

$$P = 0.2193 \cdot \varphi - 2.7812, \quad (10)$$

where: $P$ – power of the cell (W), $\varphi$ – solar radiation power (W/m$^2$).
This relationship is the result of the approximation of a curve created by connecting points corresponding to the maximum power of the cell for different values of solar radiation power (created using characteristic from [44]).
In order to use (10) to calculate the cell's power for other operating temperatures the result should be multiplied by the correction factor described the (11).

$$Ct = -0.003 \cdot t - 1.075, \quad (11)$$

where: $Ct$ – correction factor due to the cell operating temperature, $t$ – cell operating temperature (°C).
Equation (11) was formed in a similar way as (10), but using characteristic of power density generated by solar cell for different temperatures of operation and solar power of 1000 W/m2 (from [44]).
To simplify the calculations it was assumed that the operating temperature of the cell is equal to the ambient temperature.

## 2.2. Costs

To cooperate with the analyzed system a single-zone tariff (G11 [45, 46]) of electricity was used. Variable costs for electricity and its transmission in 2012 according to tariffs [45,46] (in sequence: trading and distribution) were respectively 0.35 and 0.26 zł/kWh.
In the event of over-production it was assumed that excess of electricity would be sold to the grid at a price of 0.2 zł/kWh.
The price of natural gas needed to power a piston engine, gas microturbine and fuel cells are the result of tariff [47] for 2012. In accordance with the tariff w-5 for the fuel (1.334 zł/Nm$^3$), while for the transmission – tariff E-1A (0.034 zł/Nm$^3$).
The cheapest possible fuel for the ORC unit and for the system with Stirling engines is fine coal. In order to avoid the cost of transporting fuel the chosen supplier has to be the one whose headquarters

is located near Warsaw – offer [48]. According to this offer [48] per tonne of coal dust of LHV of 21 – 23 GJ/t (the average value was assumed to calculations) a 500 zł have to be paid.

## 2.3. Artificial Neural Networks

An ANN is a black-box model which produces certain output data as a response to a specific combination of input data. The ANN can be trained to learn the internal relationships and predict system behavior without any physical equations. The ANN consists of neurons gathered into layers. Information is delivered to the neurons by dendrites and the activation function is realized (by the nucleus). Then, modified information is transferred forward by the axon and synapses (see Fig. 3) to other neurons.

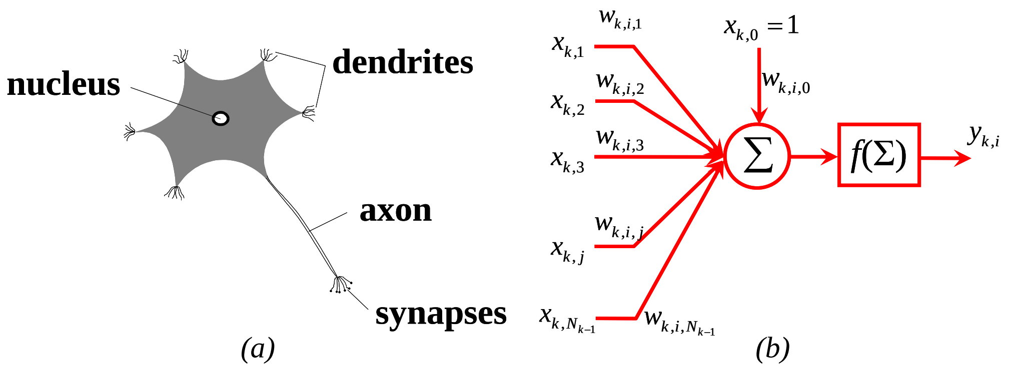


*Fig. 3. Neuron scheme (a) and its mathematical model (b) [49].*

Each neuron in the first layer takes the input values, multiplies them by the corresponding weights ($w_{k,i,1}$) and summarizes all these multiplications. Bias ($x_{k,0}$) is added to the sum ($s_{k,i}$). The sum ($s_{k,i}$) is recalculated by the neuron activation function (see Fig. 3) which gives the neuron answer: $y_{k,i}$.
In this study, a hyperbolic tangent sigmoid transfer function was used as the neuron activation function in the first layer, whereas a linear transfer function was used in the output layer.
During the model calculations, information proceeds step by step from the first layer to the last one. The answers of the neurons in the last layer are the output parameters of the ANN model (see Fig. 4).

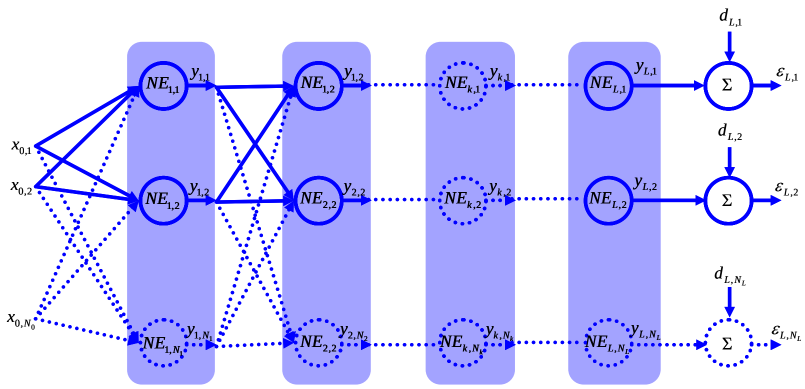

*Fig. 4. Artificial Neural Network model.*

Backpropagation was chosen as the learning process of the ANN. Backpropagation is the generalization of the Widrow-Hoff learning rule to multiple-layer networks and nonlinear differentiable transfer functions. A detailed description of backpropagation can be found in [49].
The network architecture is indicated in the following way: “number of inputs – number of neurons in the first layer – number of neurons in the second layer”; e.g. 9-7-1 means that the two-layer

network consists of nine inputs, seven neurons in the first layer and one neuron in the second layer (the number of neurons in the last layer equals the number of outputs).

# 3. Results

The results obtained were compared using the average relative error. Therefore, it was possible to temporarily shut down some machines/devices of concerned system (power equal to 0), in order to avoid division by 0 the following relationship was used:

$$\delta = \frac{\sum_{i=1}^{n} \left| x_{data\,i} - x_{sym\,i} \right|}{\sum_{i=1}^{n} x_{data\,i}}, \qquad (12)$$

where: $\delta$ – average relative error, $x_{data}$ – value obtained by optimization using the Solver, $x_{sym}$ – the value obtained by simulation using ANN, $n$ – number of values resulting from the optimization using Solver or as a result of the simulation (in the present case – the number of hours in the considered period of time).

Table 1 compares the average relative errors for the data used for network teaching and test data for various configurations of artificial neural network. In the case of the data used for network training simulation accuracy increased with the increase in the number of neurons in the hidden layer, whereas for the test data set the best results were obtained for the 4-4-5 configuration ($\delta$ = 11.69%). This means that the network with the number of neurons in the hidden layer above 4 were able to better learn "by heart", but fared worse with conditions that were new to them.

*Table 1. Average relative error ( $\delta$ ) for various configurations of artificial neural networks (for controlling the set of sources) for data used to network teaching and for test data set*

| Architecture of ANN | Average relative error, % | |
|---|---|---|
| | Teaching data | Test data |
| 4-1-5 | 13.85 | 14.96 |
| 4-2-5 | 10.64 | 11.70 |
| 4-3-5 | 10.49 | 11.75 |
| 4-4-5 | 10.13 | 11.69 |
| 4-5-5 | 10.89 | 12.78 |
| 4-6-5 | 10.45 | 11.99 |
| 4-7-5 | 10.06 | 12.85 |
| 4-8-5 | 9.86 | 12.37 |
| 4-9-5 | 9.78 | 16.42 |
| 4-10-5 | 9.92 | 13.45 |
| 4-11-5 | 9.86 | 12.65 |
| 4-12-5 | 9.00 | 13.26 |
| 4-13-5 | 8.07 | 14.51 |
| 4-14-5 | 8.82 | 17.44 |
| 4-15-5 | 8.56 | 14.43 |
| 4-16-5 | 7.90 | 14.30 |
| 4-17-5 | 8.25 | 17.54 |
| 4-18-5 | 7.59 | 17.46 |
| 4-19-5 | 7.41 | 14.44 |
| 4-20-5 | 7.91 | 15.46 |

## 4. Conclusions

A method of using artificial neural networks as a load optimizer of a set of distributed energy sources working for the public utility buildings needs was presented. The considered system consists of: LHM80 piston engine, two SD4-E Stirling engines supplied with fine coal, Capstone C65 micro gas turbine, SOFC fuel cell, ORC unit, three Mistral 3K wind turbines and 46 HIP-215NKHE1 SANYO photovoltaic cells. A method of construction of the ANN and the selection of their structure was presented. The best network architecture turned out to be 4-4-5 with an average relative error of 11.69% for the test data set.
Comparison of costs of obtaining electricity for considered period of time is as follows: 37565.74 PLN for purchasing electricity only from the grid, 36018.61 PLN for considered system controlled by ANN and 34052.67 for considered system optimized by solver.
Benefits of the application of considered system of machines and devices would be greater if the analysis also took into consideration possibilities of meeting heating needs by the system.

## Acknowledgments

The project was funded by the National Science Centre allocated on the basis of decision number PRO-2013/09/N/ST8/02055.

## References

[1] Bartela Ł., Skorek-Osikowska A., Kotowicz J., Economic analysis of a supercritical coal-fired CHP plant integrated with an absorption carbon capture installation. Energy 2014;64:513-523.

[2] Bartela Ł., Skorek-Osikowska A., Kotowicz J., Thermodynamic, ecological and economic aspects of the use of the gas turbine for heat supply to the stripping process in a supercritical CHP plant integrated with a carbon capture installation. Energy Conversion and Management 2014;85:750-763.

[3] Skorek-Osikowska A., Bartela Ł., Kotowicz J., A comparative thermodynamic, economic and risk analysis concerning implementation of oxy-combustion power plants integrated with cryogenic and hybrid air separation units. Energy Conversion and Management 2015;92:421-430.

[4] Wee J.-H., Carbon dioxide emission reduction using molten carbonate fuel cell systems. Renewable and Sustainable Energy Reviews 2014;32:178-191.

[5] Liu A.-G., Weng Y.-W., Chen L., Ma H.-A., Performance analysis of fuel cell for pressured MCFC/MGT hybrid system. Shanghai Jiaotong Daxue Xuebao/Journal of Shanghai Jiaotong University 2014;48(9):1239-1245.

[6] De Lorenzo G., Fragiacomo P., Energy analysis of an SOFC system fed by syngas, Energy Conversion and Management 2015;93:175-186.

[7] Bakalis D., Stamatis A., Improving hybrid SOFC-GT systems performance through turbomachinery design. International Journal of Energy Research 2014;38(15):1975-1986.

[8] Stanek W., Technical-economical evaluation of CHP plant fed with methane from hard coal bed. Journal of Power Technologies 2014;94(3):211-218.

[9] Hanuszkiewicz-Drapała M. J., Składzień J., Two-seasonal thermal analyses of systems with a vapour compressor heat pump and horizontal ground heat exchangers. Journal of Power Technologies 2014;94(2):135-143.

[10] Shahinfard S., Beyene A., Regression comparison of organic working mediums for low grade heat recovery operating on rankine cycle. Journal of Power Technologies 2013;93(4):257-270.

[11] Malko J., Generacja rozproszona jako czynnik zwiększenia niezawodności dostaw energii elektrycznej do odbiorców. Energetyka 2004.

[12] Wang J., Kang L., Chang L., Cao B., Xu D., Energy complementary control of a distributed power generation system based on renewable energy. In: Power Engineering, 2004. LESCOPE-04. 2004 Large Engineering systems Conference on; 2004 July 28-30:136-140.

[13] Dai M., Marwali M., Jung J., Keyhani A., Power flow control of a single distributed generation unit with nonlinear local load. In: Power Systems Conference and Exposition, 2004. IEEE PES; 2004 October:398-403.

[14] Paatero J., Sevon T., Lehtolainen A., Lund P., Distributed power system topology and control studies by numerical simulation. In: Second International Symposium on Distributed Generation: Power System and Market Aspects; 2002 October; Stockholm, Sweden.

[15] Rodriguez P., Timbus A., Teodorescu R., Liserre M., Blaabjerg F., Flexible active power control of distributed power generation systems during grid faults. Industrial Electronics, IEEE Transactions on 2007;54(5):2583-2592.

[16] Ocnasu D., Gombert C., Bacha S., Roye D., Blache F., Mekhtoub S., Real-time hybrid facility for the study of distributed power generation systems. Revue des Energies Renouvelables 2008;11(3):343-356.

[17] Kojima H., Katsuno T., Nakanishi Y., Fukuyama Y., Matsuda H., Kanazawa Y., An introduction effect evaluation tool for distributed generators. In: Proceedings of the International Conference on Power Engineering-09; 2009 November 16-20; Kobe, Japan.

[18] Malko J., Generacja rozproszona w europejskiej polityce energetycznej. In: Elektroenergetyczne sieci rozdzielcze – SIECI 2004 V Konferencja Naukowo-Techniczna; 2004 September 15-17; Wroclaw, Poland.

[19] Mokrzycki E., Idea generacji rozproszonej. Nowe spojrzenie na środowisko. Nafta & Gaz Biznes 2003; październik.

[20] Kowalska A., Wilczynski A., Zródła rozproszone w systemie elektroenergetycznym. Lublin, Poland: Wydawnictwo KAPRINT; 2007.

[21] Popczyk J., Energetyka rozproszona. Warszawa, Poland: Polski Klub Ekologiczny Okręg Mazowiecki; 2011.

[22] Amano H., Seki H., Saito A., Senda J., Assessment of optimal energy device application for residence town. In: Proceedings of the International Conference on Power Engineering-09; 2009 November 16-20; Kobe, Japan.

[23] Ishida T., Evaluatted model of the distributed energy network system of an urban district. In: Proceedings of the International Conference on Power Engineering-09; 2009 November 16-20; Kobe, Japan.

[24] Shimoda E., Numata S., Yamane T., Morino K., Baba J., Masada E., Islanding operation control method of micro-grid including seamless transition from grid-connecting operation. In: Proceedings of the International Conference on Power Engineering-09; 2009 November 16-20; Kobe, Japan.

[25] Kurata O., Kadoguchi K., Iki N., Matsunuma T., Yoshida H., Maeda T., Takeuchi H., Micro gas turbine co-generation system at Sapporo city university under service conditions. In: Proceedings of the International Conference on Power Engineering-09; 2009 November 16-20; Kobe, Japan.

[26] Morita H., Hisazumi Y., Kiuchi Y., Yamaguchi H., A cogeneration system for an apartment building based on distributed heat storage technology. In: Proceedings of the International Conference on Power Engineering-09; 2009 November 16-20; Kobe, Japan.

[27] Tanabe A., Baba Y., Asano H., Hisazumi Y., Yamaguchi H., Morita H., Dynamic simulation of new central hot water supply system for residential building. In: Proceedings of the International Conference on Power Engineering-09; 2009 November 16-20; Kobe, Japan.

[28] Grzebielec A., Rusowicz A., Kuta J., Role of installations based on heat pumps cycles in virtual power plants [rola urządzeń i instalacji realizujących obiegi lewobieżne w wirtualnych elektrowniach]. Rynek Energii 2014;110(1):40-45.

[29] Kotowicz J., Iluk T., Instalacja zgazowania biomasy zintegrowana z silnikiem spalinowym. Rynek Energii 2011;94(3):47-52.

[30] Kotowicz J., Sobolewski A., Iluk T., Energetic analysis of a system integrated with biomass gasification. Energy 2013;52:265-278.

[31] Sobolewski A., Kotowicz J., Iluk T., Matuszek K., Badania eksperymentalne zgazowania biomasy pod katem wykorzystania gazu procesowego w układzie Kogeneracji. Przemysł Chemiczny 2010;89(6):794-798.

[32] Sobolewski A., Bartela Ł., Skorek-Osikowska A., Iluk T., Porównanie efektywności ekonomicznej układów kogeneracyjnych z generatorem gazu procesowego GazEla. Rynek Energii 2012;102(5):31-37.

[33] Sonderegger R. C., Distributed generation architecture and control. In: E-VISION 2000 CONFERENCE; 2000 October 11-13; Washington, D.C.:292-301.

[34] Badyda K., Lewandowski J., Możliwości skojarzonej produkcji energii elektrycznej oraz ciepła z wykorzystaniem gazu sieciowego. In: Materiały V Krajowej Konferencji GAZTERM 2002; 2002 May 27-29; Międzyzdroje, Poland.

[35] Milewski J., Miller A., Sałaciński J., The conception of high temperature fuel cell exhaust gas heat utilization. Prace Naukowe Politechniki Warszawskiej z. Mechanika 2005;211.

[36] Lab-el – Available at:<www.meteo.waw.pl> [accessed 20.11.2011]

[37] Kraftwerk – Available at:<www.kwk.info> [accessed 10.06.2011]

[38] Schiel W., Dish Stirling Activities at Schlaich Bergermann und Partner. – Available at:< http://www.nrel.gov/csp/troughnet/pdfs/2007/geyer_sbp_dish_stirling.pdf> [accessed 10.01.2015]

[39] Wang W., Cai R., Zhang N., General characteristics of single shaft microturbine set at variable speed operation and its optimization. Applied Thermal Engineering 2004;24(13): 1851-1863.

[40] Obernberger I., Thonhofer P., Reisenhofer E., Description and evaluation of new 1,000 kWel Organic Rankine Cycle process integrated in the biomass CHP plant in Lienz, Austria. Euroheat & Power 2002;10:1-17.

[41] fotoOGNIWA – Available at:<www.fotoogniwa-sklep.pl> [accessed 10.06.2011]

[42] ELTRON – Available at:<www.eltron.pl> [accessed 10.06.2011]

[43] Sunny Life Technologies – Available at:<www.sunnylifetechnologies.com> [accessed 09.06.2011]

[44] SANYO – Available at:<www.sanyo.com/solar> [accessed 10.06.2011]

[45] Stawka taryfowa ENERGA – OBRÓT S.A. dla energii elektrycznej na rok 2012 dla Odbiorców z grup taryfowych G [Tariff rate ENERGA – OBRÓT S.A. electricity for the year 2012 for customers of tariff group G].

[46] Stawka taryfowa dla dystrybucji energii elektrycznej Energa Operator S.A. (Oddział w Płocku) na rok 2012 dla Odbiorców z grup taryfowych G [Tariff rate for electricity distribution Energa Operator S.A. (Branch in Plock) for the year 2012 for customers of tariff groups G].

[47] Taryfy dla paliw gazowych [Tariffs for gaseous fuels]. Polskie Górnictwo Naftowe i Gazownictwo SA; 2012.

[48] KWK Hubertówka – Available at:<www.wkw-hubertowka.pl> [accessed 15.07.2012]

[49] Demuth H., Beale M., Hagan M., Neural network toolbox™ 6 user's guide matlab®.: The MathWorks, Inc.; 2009.