Integrated Cost-Benefit Assessment of Customer-Driven Distributed Generation

Čedomir Zeljković and Nikola Rajaković

Abstract—**Distributed generation (DG) has the potential to bring respectable benefits to electricity customers, distribution utilities and community in general. Among the customer benefits, the most important are the electricity bill reduction, reliability improvement, use of recovered heat, and qualifying for financial incentives. In this paper, an integrated cost-benefit methodology for assessment of customer-driven DG is presented. Target customers are the industrial and commercial end-users that are critically dependent on electricity supply, due to high consumption, high power peak demand or high electricity supply reliability requirements. Stochastic inputs are represented by the appropriate probability models and then the Monte Carlo simulation is employed for each investment alternative. The obtained probability distributions for the prospective profit are used to assess the risk, compare the alternatives and make decisions.**

Index Terms—**Distributed generation (DG), customer-perspective approach, integrated cost-benefit assessment, Monte Carlo simulation, long-term planning, uncertainty analysis.**

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I. Introduction

IN a few recent decades, distributed generation (DG) draws an increasing attention due to its numerous techno-economic and environmental potentials [1]. Primarily, the community may be interested in introducing such a small-scale generation connected close to end-users in order to improve the overall efficiency and security of the nation's energy supply. Second-ly, distributed generation may bring significant benefits to distribution power utilities through upgrade investment defer-ral, avoided electricity purchase, and loss reduction. Finally, the single electricity customers may also achieve remarkable benefits from the use of distribution generation especially through electricity bill reduction, improvement of supply reliability and combined production of heat and power (CHP).

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By the most authors, the concept of optimal investment in distributed generation is considered from the perspective of distribution power utility. This problem principally comes down to determination of rated powers and installation locations for prospective DG units and is usually referred to as optimal DG sizing and sitting. The optimality criteria are mainly loss minimization, improvement of reliability and power quality, network upgrade deferral or voltage profile improvement [2]-[4]. There are also multi-objective approaches with a combination of two or more optimization goals [5]-[7].

Several papers emphasize “a customer approach”, although the term customers does not refer to electricity end-users, but to the independent DG developers which consider the investments in DG units that would be connected at the appropriate locations in the distribution network being optimal for investor's profit maximization. For example, Ref. [8] has presented a methodology based on the Monte Carlo simulation where DG units of random size were placed on random locations in the distribution network searching for the solution which would offer the maximum overall network benefits. In the paper is then highlighted that the total achieved benefits must be accordingly translated to the deserving parties, among them the DG owners.

On the contrary to the network-perspective approaches, this paper focuses on the significantly less studied problem of the benefits achievable by the single electricity customers. In particular, we deal with the industrial and commercial customers that are billed by the world's most common time-of-use (TOU) electricity tariff, consisted of both volumetric and demand cost elements. Our target customers observe the problem exclusively from their point of view and are not in possession of any data about the structure and operation of the distribution network they are connected to.

The problem of customer adoption of distributed generation and optimal operation of installed DG units has been illustrated in [9]. The optimization task, written in a form of mixed-integer linear program, has been solved by using commercial software and, in its original form, has taken into account only the benefits of electricity bill reduction. This approach is a pure customer-perspective, though through using the more general concept of a microgrid, where a group of related customers are observed together as a low voltage network. The original model has been extended in [10], where combined generation of heat as well as the use of local energy storage devices have been considered, but still without taking into account the DG reliability benefits. It is not the only approach where the potentials of CHP systems to provide savings to the customers have been analyzed [11][12]. Finally, in this short literature review, the study of very important issue of stochastic change of fuel and electricity prices must necessarily be mentioned [13].

In our previous efforts we have also discussed about the customer electricity bill reduction by means of the optimal scheduling of distributed generation. We have introduced a method based on a search procedure capable of dealing with non-linear, non-convex and discontinuous DG cost functions [14]. We have also analyzed the impact of financial incentives on customer DG investments [15], as well as the potentials of DG to provide the reliability improvements [16].

In this paper, the results of recent studies have been utilized in order to establish a new integral DG installation assessment methodology that would include a majority of influential factors. The main goal of the methodology is to provide an answer to the customer is it profitable or not to invest in distributed generation and which is the best possible solution from the investment options available on the market. The approach considers the overall life time of the DG investment and, due to uncertainties in input parameters, involves not only deterministic but also stochastic elements. Since the life times of DG technologies are typically a couple of decades long, the change in worth of money over time must also be respected and thus all money amounts must be converted into their present values. Like in the other long-term planning methodologies, the employed models and procedures are kept as simple as possible, but tending to involve all the essential principles. The main benefits taken into account are the customer's bill reduction, reliability improvement, combined heat and power savings as well as financial incentives. On the opposite side of the scales lie the DG investment costs. The probability distributions of net profit calculated from the benefits and costs are used for declaring the best solution. They may also be used for the assessment of customer investment risk. It should be noted that the proposed methodology is modular and, in case of presence of additional facts not covered in this study, the new costs/benefits can be easily attached to the basic framework.

II. Problem Formulation and Solution Methodology

A. Overview of the System under Consideration

The target customer is a medium or large industrial or commercial company whose business is significantly dependent on electricity supply, due to high electricity consumption, high power peak demand or high electricity supply reliability requirements. The traditional way for customer energy supply is purchasing electricity from the distribution utility company. The alternative is buying fuel from the market and generating electricity locally, by using own generating units. The customer considers an investment in on-site dispatchable generating units such as reciprocating engines, gas turbines, microturbines, and fuel cells. The dispatchable units may also be combined with some renewable energy technologies like solar and wind power devices. Depending on their rated powers, DG units may partially or completely satisfy the customer load. A potential deficit can be compensated by purchasing electricity from the utility. The purchasing may also be preferred in the case of electricity prices being more attractive then fuel prices. On the other hand, it is assumed that the surplus electricity is not sold back to the grid. The opposite class of problems, assuming the two-way flow of energy and net-metering, deserves its own approach. Finally, since our research is focused on the application of distributed generation, the other customer cost-saving techniques like demand-side management or local energy storage are not considered in the paper. The concept of the system is illustrated in Fig. 1.

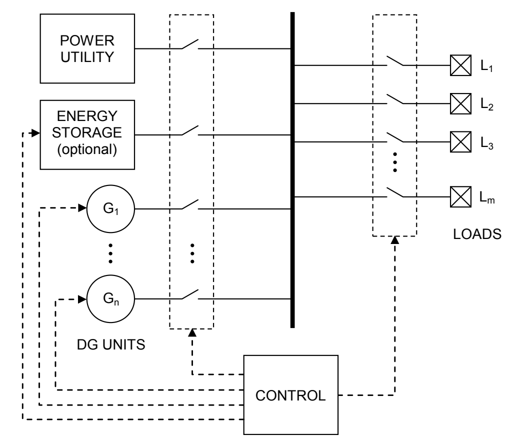

Fig. 1. The concept of the system under consideration

B. Stochastic vs. Deterministic Methodology

In case when all inputs are known with complete certainty, the economic cost-benefit assessment may be performed using the traditional discounted cash flow (DCF) method [17]. For each considered investment alternative, the net present value (NPV) is calculated using the following manner

$$NPV_j = \sum_{k \in L} \frac{B_{j,k} - C_{j,k}}{(1+d)^k} \tag{1}$$

where $B_{j,k}$ is the benefit obtained by the use of DG investment alternative j during the year k, $C_{j,k}$ is the corresponding annualized cost, d is the discount rate and L is the life time of the investment. The usual decision-making approach is choosing the alternative having the highest positive NPV.

On the contrary, in cases when several input variables exhibit stochastic changes, the conventional approach should be extended. One of the most comprehensive methods for analyzing problems that involve uncertainty is Monte Carlo simulation (MCS) [18]. In the MCS method, the main stochastic variables are assigned probabilistic models, a sufficient number of random scenarios is generated and, for each scenario, the behavior of the system is simulated. The output of MCS procedure is a probability distribution of NPV, which represents a full spectrum of possible outcomes of the investment. By analyzing the obtained distributions for considered investment alternatives, risk is assessed and the best solution is selected.

The example of decision making is shown in Fig. 2. Scenario 1 is the situation where cumulative density functions (CDF) of the profit do not intersect. For the same probability, the profit of project B is always higher than the profit of project A. Or alternatively, given one particular profit, the probability that it will be achieved or exceeded is always higher by project B than it is by project A. Hence, the project B should be unambiguously selected for realization. In scenario 2 the decision may go into two opposite directions. Risk-loving investors will be attracted by the possibility of higher profit and therefore will choose project A. Risk-averse investors will be attracted by the possibility of low loss and will therefore choose project B.

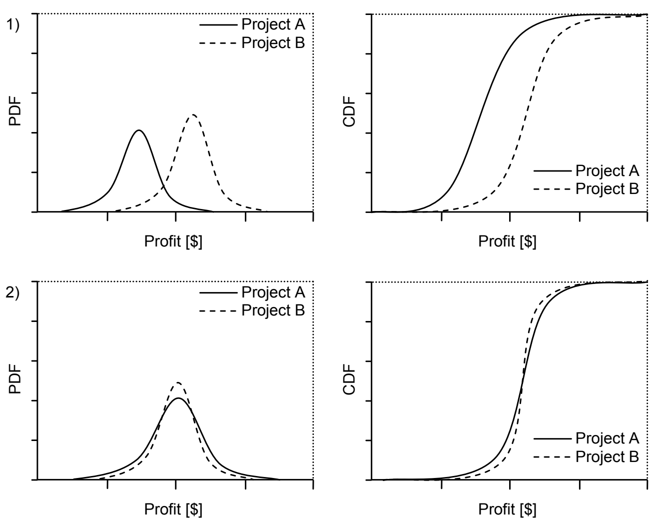

Fig. 2. Using the probability density functions (PDF) and cumulative density functions (CDF) for case comparisons: 1) unambiguous advantage of case B; 2) indeterminate situation - decision between low loss and high profit.

C. *The Principle of Existence of Optimum Rated Power*

The existence of the optimal investment solution may be demonstrated on a single DG unit example (Fig. 3). The investment costs grow linearly with the increase in rated power of the unit or, due to the economy of scale, their slope may have a slight decrease. The benefits are also getting higher when greater units are chosen, but the finite energy requirements of the customer are the reason for the growth saturation. Therefore, there exists the optimal rated power which guarantees the maximum difference between the benefits and costs.

III. Models and Methods

A. *Modeling of Inputs*

In procedures for quantification of achievable benefits, the following inputs are considered as crucial:

- Customer load diagram;
- Long term retail prices of electricity;

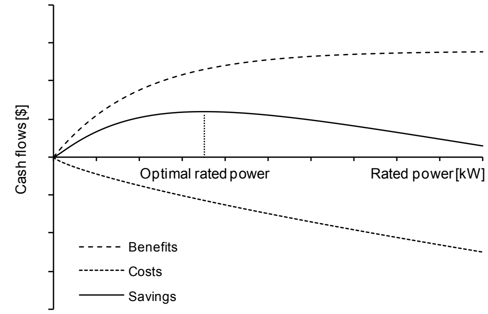

Fig. 3. The principle of finding the optimal rated power

- Long term retail prices of fuel for distributed generating units (such as natural gas, diesel, gasoline or hydrogen);
- Meteorological inputs such as wind speed and insolation (for renewable energy sources, if existent);
- Reliability of distributed generation;
- Reliability of the grid at the customer connection point;
- Start-up costs of distributed generation;
- Customer damage costs incurred by interruptions in power supply.

More details about the stochastic modeling of listed inputs can be found, for instance, in [16],[19]-[26],[28],[29].

B. *Quantification of Benefits and Costs*

1) *Reduction in Customer Electricity Bill*

The cost savings achievable by the customer are highly influenced by the way how the generating units are scheduled to run. The most simple but the less economical dispatch procedure is a continuous operation of DG. A quite better solution is dispatching the units at certain periods of day or year, during the hours of peak demand or high price of electricity [12]. A further improvement represents the threshold control, where DG is run whenever the customer load is greater than the predefined threshold value [12][30]. The best results are achievable by employing the heuristic dispatch methods which take into account the probabilistic nature of the input variables [19][31].

In this study, we employ our dispatch strategy which is presented and discussed in [19]. The so called *Enhanced threshold control algorithm* (ETC) is a quality solution which is capable of dispatching an arbitrary number of DG units. The algorithm is designed to successfully cope with realistic issues such as non-linearity in DG efficiency curves, stochastic nature of input variables and existence of peak demand charges in the customer electricity bill.

2) *Reliability Benefits*

Many industrial and commercial customers, that are sensitive on power interruptions, may also significantly benefit from DG in the role of a backup source. Evaluation of benefits of improved reliability are based on Monte Carlo simulation methodology that we described in [16]. Basically, we determine the customer damage costs incurred due to interruptions in power supply and comparing the cases without and with distributed generation. Avoided interruption costs are equivalent to achieved benefit of improved reliability (B_{REL}).

Since the crucial inputs such as number of failures per year or times of occurrences of particular failures are not deterministic but stochastic variables, the amount of reliability benefits is also obtained in a form of a probability distribution rather than as single value.

3) Benefits of Combined Generation of Heat and Power

For customers who have a substantial need for thermal energy, it could be thought about the investment in DG units that have the option of waste heat recovery (CHP). It is then necessary to assess whether the benefits of recovered heat from the CHP unit is greater than the cost of investment in such an upgrade.

The effectiveness of CHP system is primarily determined by a heat-to-power ratio of the customer [11]. The customers with high heat-to-power ratio, i.e. with heat load dominant over electrical load, utilize the CHP systems in heat-tracking (HT) mode of operation. HT means that the heat output of the CHP system follows the heat demand of the customer. Electricity generation has the second level of priority and the possible deficit of electrical energy is compensated by purchasing from the utility. Most of the savings is achieved on the basis of production of heat energy, while production of electricity, the peak shaving and reliability improvement are not of noticeable importance. Therefore, such kind of customers is not of interest for the methodology proposed in this paper.

Since the target for this study are the customers considerably dependent on supply of electric energy, the remainder of the analysis concentrates on the customers with low heat-to-power ratio. Considering this limitation, it only makes sense to analyze the electricity tracking mode for the operation of the CHP system. In electricity-tracking (ET) mode the primary goal is electricity production. The power output of the CHP system is adjusted to follow the electrical demand of the customer. Deficit of heat energy is compensated by the customer's auxiliary boiler or provided by an external heat supplier, while possible surplus of heat is dissipated into the atmosphere. By working in this regime, it is possible to operate DG units strictly according to previously calculated optimal schedules and thus to achieve maximum self-generation and peak-shaving benefits. The worth of CHP benefit is equivalent to the worth of heat energy which is avoided to be purchased or locally generated by customer boilers.

4) Incentives and Grants

Financial incentives are another important factor which can significantly improve the quality of the considered project and stimulate the customer to invest in distributed generation. DG technologies that are favored and predominantly financially supported by governments or other entities are renewable energy sources, environmentally improved fossil-fuel generation, as well as modern high-efficiency and cogeneration facilities. The diversity of possible types of incentives is practically unlimited and therefore it is hard to derive a universal approach. Instead, every available incentive program deserves its own separate analysis. However, despite of type diversity, every analysis should result in the stream of the present values of expected annual benefits which would the customer achieve from the incentive program.

5) Investment Costs

Analogously to the treatment of benefits, for the use in discounted cash flow, the investment costs are to be displayed in a form of stream of annual cash outflows. Due to a wide variety of options for financing the DG projects, the outflow stream formation procedure is not unambiguously defined. For example, for upfront paid investment, the cash flow comes down just to one outflow - the whole investment cost paid in the year zero. On the other hand, if the investment is loan based, the outflow stream contain values for the overall loan repayment period.

6) Other Benefits and Costs

Depending on regional, economical and regulatory occasions as well as the nature of the customer, it is possible to encounter other specific costs or earn some additional benefits related to the usage of distributed generation. New costs and benefits have also to be properly quantified in a form of annual cash flow streams and included in the evaluation model.

IV. Illustrative Example

A. Input Parameters

The algorithm is tested on a hypothetical customer which weekly diagram of expected load (L_m) and standard deviation (σ) are given in Fig. 4. It is assumed that precise load history is not available so as the random load time series is generated by using the following expression

$$L(h) = L_m(h) + \sigma(h) \cdot N_h(0,1) \tag{2}$$

where $N_h(0,1)$ are independent values drawn from the normal distribution.

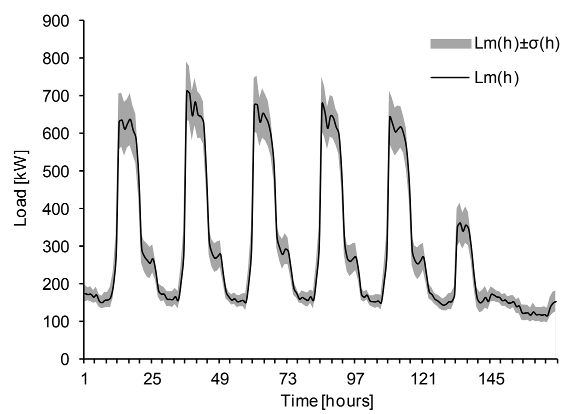

Fig. 4. Stochastic model of the customer load

The customer considers an investment in a natural gas fueled microturbine facility. The equipment manufacturer offers six alternatives (G1 to G6), with power outputs ranging from 65 to 1000 kW. The main characteristics are shown in Table I. The facilities G1 and G2 are made of a single turbine, while the others represent multiturbine configurations built by using 200kW units. The additional important parameters are listed in Table II. The example of extremely non-linear efficiency curve of a microturbine facility (alternative G4) is shown in Fig. 5.

The life time is 15 years, for all six investment options. The investments costs are covered by a subsidized loan with 5,56% interest rate. The discount rate is set at 7%.

TABLE I
BASIC PARAMETERS FOR CONSIDERED INVESTMENT OPTIONS

Parameter	G1	G2	G3	G4	G5	G6
Technology	Microturbine					
Type	C65	C200	C400	C600	C800	C1000
Configuration	1×65	1×200	2×200	3×200	4×200	5×200
Max. output (kW)	65	200	400	600	800	1000
Min. output (kW)	20	50	50	50	50	50
Invest. cost (M$)	0,15	0,40	0,75	1	1,2	1,4
CHP module (M$)	0,026	0,06	0,12	0,18	0,24	0,3

TABLE II
ADDITIONAL PARAMETERS FOR CONSIDERED INVESTMENT OPTIONS

Parameter	G1-G6
Mean time to failure - MTTF (h)	14000
Mean time to repair - MTTR (h)	3,1
Start-up time (min)	3
Start-up cost ($/start-up)	Start-up time×Full load cost
Non-fuel variable cost ($/kWh)	0,005

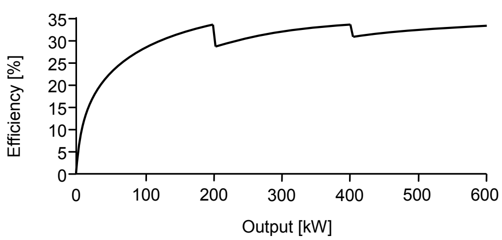

Fig. 5. Efficiency curve of a 3×200kW microturbine facility (alternative G4).

Wholesale prices of natural gas and electricity are simulated by using the Ornstein-Uhlenbeck (OU) correlated stochastic process with mean reverting drift, in accordance with the following equations:

$$dx = \kappa_x(\bar{x} - x)dt + \sigma_x dW_x \tag{2}$$

$$dy = \kappa_y(\bar{y} - y)dt + \rho\sigma_y dW_x + \sqrt{1-\rho^2}\sigma_y dW_y \tag{3}$$

where x and y are the logarithms of the electricity and natural gas prices, κ_x and κ_y are the corresponding mean-reversion rates, $\bar{x}$ and $\bar{y}$ are the mean reversion levels, σ_x and σ_y are the corresponding price volatility rates, W_x and W_y and are the standard Wiener processes.

The wholesale prices are transferred to the retail level by averaging on a monthly horizon and by adding the costs of distribution. The retail price of natural gas is assumed to be flat all the month long. The electricity prices are assumed different for both on-peak and off-peak volumetric consumption as well as the monthly peak demand, which is adjusted by appropriate factors. The most important parameters are summarized in Table III, while more detailed explanations can be found in [29].

The average number of grid outages is 1 failure/year, while the expected repair time is 2,3 hours. The outages are simulated using the failure pattern recorded at the customer connection point - the distributions of the moment of occurrence and repair time in terms of time of the day, day of the week, and season of the year. More details on reliability parameters are given in [16].

TABLE III
BASIC ENERGY PRICING PARAMETERS

Parameter	Value	Unit
Electricity mean level	3,61	ln($/MWh)
Electricity start price	3,73	ln($/MWh)
Electricity reversion rate	3,13	1/year
Electricity price volatility	0,41	1/year
Natural gas mean level	1,35	ln($/MWh)
Natural gas start price	1,31	ln($/MWh)
Natural gas reversion rate	1,69	1/year
Natural gas price volatility	0,39	1/year
Natural gas-electricity price correlation	0,82	-

B. *Base Case*

A Monte Carlo simulation is run for each investment alternative. The simulations contain 100 runs each, which is chosen as a compromise between computation time and the resolution of obtained results. The first conclusion for the base case can be drawn from distributions of profit NPV shown in Fig. 6. Since the cumulative probability functions do not intersect, it is possible to make unambiguous order of investments by the quality: (1) C800, (2) C600, (3) C1000, (4) C400, (5) C200 i (6) C65. Fig. 7 shows that the maximum expected value of the profit NPV corresponds to the rated power of 800kW. Expected profit for C65 is even negative, which makes the alternative G1 absolutely inappropriate for further analysis.

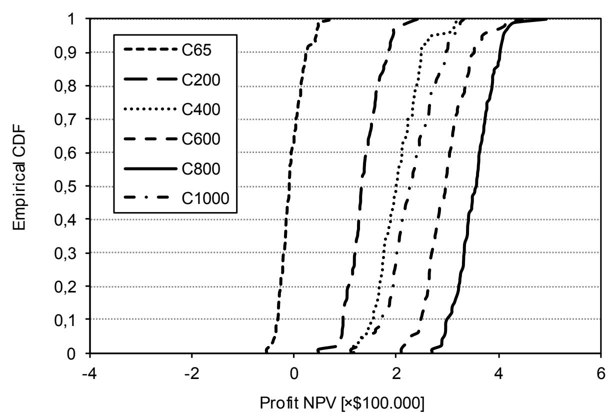

Fig. 6. Base case: Empirical CDFs for considered investment alternatives

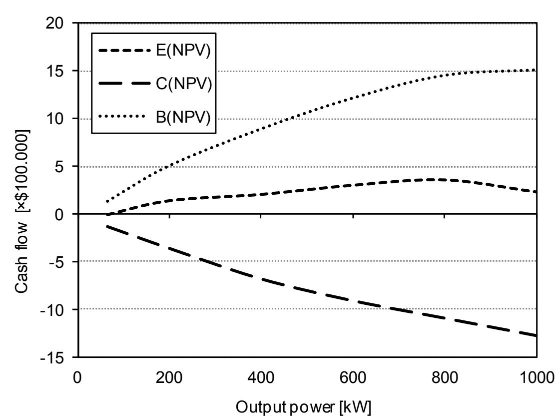

Fig. 7. Base case: Cash flows in terms of microturbine output power

C. Sensitivity Analysis

Errors in the input parameters may lead to erroneous results and conclusions. Therefore, the analysis is performed in order to determine how the results are influenced by the change in particular inputs. In this paper we show some representative results of our comprehensive sensitivity analysis. The investigation is limited to three most promising alternatives, namely G4-G6.

1) Case A: Electricity Price Volatility

Case A covers the impact of electricity price volatility. Fig. 8 shows that the increase in volatility of approximately 50% leads to a just slight increase in profit NPV, for each investment alternative. The increase is logical since the greater deviation in electricity price provides room for distributed generation to participate more effectively both in peak shaving and energy generation. Fig. 9 shows that the increase in deviation of the electricity price also leads to the larger deviation of the profit NPV. Obviously, C800 remains the best alternative for the customer.

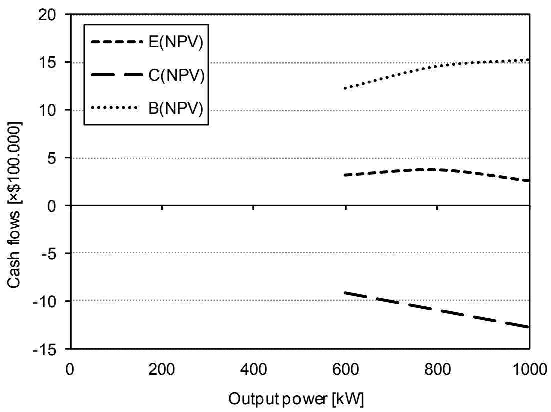

Fig. 8. Case A: Cash flows in terms of microturbine output power

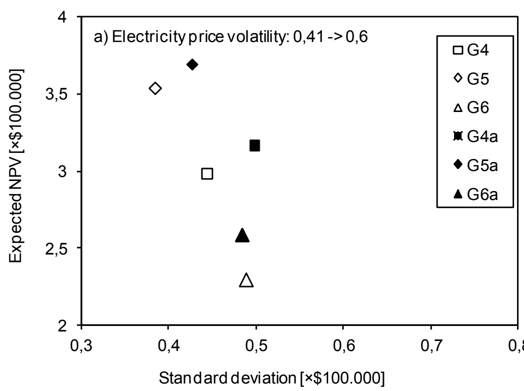

Fig. 9. Case A: Changes in expected value and standard deviation of profit NPV due to increase in electricity price volatility.

2) Case B: Natural Gas to Electricity Price Correlation

In the base case, the correlation between the prices of natural gas and electricity is assumed to be high, which is appropriate for the markets where a large portion of electricity is produced by gas power plants. The adopted value of the correlation coefficient ρ in the formula (3) is 0,82. In this analysis, the initial value of the correlation coefficient is decreased down to $\rho = 0{,}41$. Fig. 10 shows that halving the correlation factor significantly affects the standard deviation of NPV, while the expected values are left almost unchanged. The interpretation of this phenomenon is simple. When the prices of gas and electricity change with the correlated trajectories, the ratio of their prices are not changed within wide limits, so the customer savings are similar from month to month. When the correlation decreases, the ratio of the price of gas and electricity oscillates more. Therefore, in cases with expensive electricity the savings are getting greater and in cases with expensive gas the savings are getting lower. This increases the deviation of the results, but the average value of the profit does not experience a remarkable change.

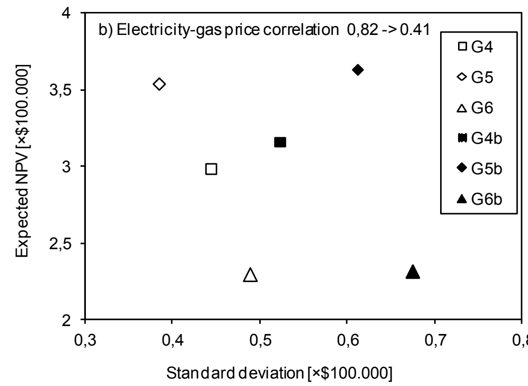

Fig. 10. Case B: Changes in expected value and standard deviation of profit NPV due to decrease in correlation between the prices of natural gas and electricity.

3) Case C: Natural Gas to Electricity Mean Level Ratio

The gas/electricity price ratio is one of the most important factors that dictate the amount of achievable savings for the customer. Case C will test the impact of this variable. The mean level of natural gas price logarithm is therefore changed from initial 1,35 to an arbitrary new value of 1,54. As might be expected, the impact on the achievable savings will be very strong. Because of the expensive gas, distributed generation will be used much rarely, mainly just for the peak shaving. Results in Fig. 11 show that the alternative with C1000 very likely finishes its life time with negative NPV of the profit. The alternatives C600 and C800 keep the profits positive, but the expected values of NPV are more than halved in comparison with the base case. Once again, C800 remains the best investment alternative.

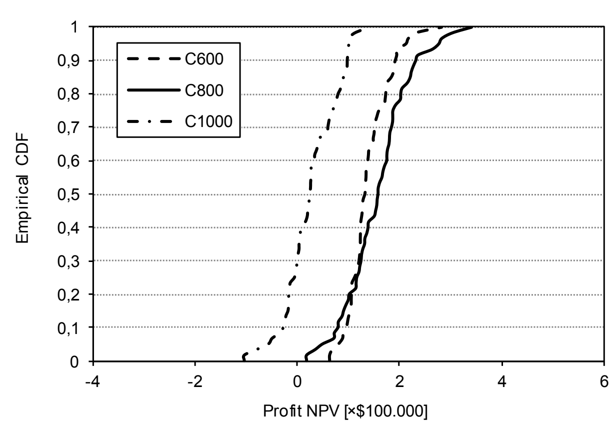

Fig. 11. Case C: Empirical CDFs for considered investment alternatives.

4) Case D: Load deviation

Case D covers the influence of uncertainty in customer load to the amount of savings achievable by DG. The standard deviation of the customer load from the base case is doubled here and the Monte Carlo simulations are performed again for the alternatives G4-G6. Increased deviation of the load logically leads to an increase in the monthly peak demand. Therefore, C1000 comes into play since it has the largest potential for the peak shaving. As per Fig. 12 the overall performance of C1000 almost reaches the results achievable by C800. C600 as the facility with the smallest output power is not significantly affected by the change in the load deviation.

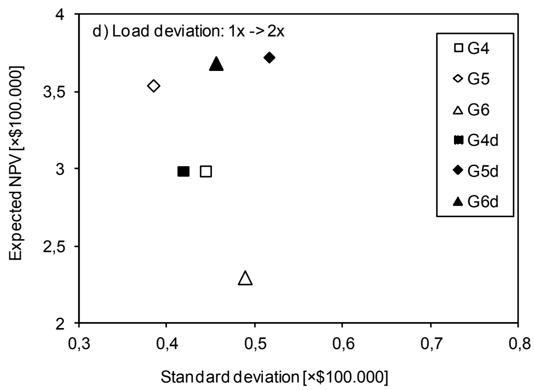

Fig. 12. Case D: Changes in expected value and standard deviation of profit NPV due to increase in deviation of the customer load.

D. Contribution in Reliability Improvement

It is interesting to determine which portion of the total benefits is related to improved reliability. According to principles described in [16], the customer loads are sorted in a priority order, so as in case of the grid outage, the most critical loads are served first by distributed generation. Although the less critical loads are left disconnected, the customer does not incur a significant additional damage. For the customer considered in this paper, microturbine facility C600 with 600kW rated power is sufficient to cover the most critical loads. Therefore, C800 and C1000 with their surplus of output power are not worth much in terms of reliability. Fig. 13 illustrates that the benefits of improved reliability are practically the same for each investment alternative. The expected present value of reliability benefits are about 16,5% of the overall customer benefits. With modifications of input parameters defined in cases A to D, the results obtained for the base case are not significantly changed.

E. Final Decision Based on Power Aspects

Using the results of presented comprehensive analysis, the customer would select the alternative based on C800 microturbine facility. This alternative shows the best results for the wide range of change in crucial input parameters. The risk of loss (i.e. negative profit NPV) is negligible.

The customer primarily benefits on cutting costs for energy supply. The benefits of improved reliability are just 1/6 of the total benefits. It should be noted that the ratio between particular benefits can be significantly changed under different conditions. For example, for the customers connected to unreliable distribution grid, the benefits of improved reliability can be even greater than the benefits of cheaper energy supply.

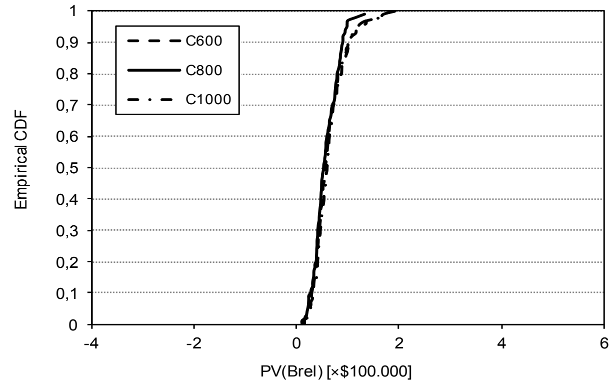

Fig. 13. Base case: Contribution of reliability improvement to the total profit NPV

F. Combined Heat and Power

Microturbine exhaust gases contain a respectable amount of heat energy. Heat to power ratio for microturbine technology is regularly greater than 1,5. By investing in a system of heat exchangers, available heat energy might be used for space heating, water heating, etc. It depends on the nature of the customer how much of the available heat can be effectively utilized.

We tested how much heat energy is available for six investment alternatives (G1–G6), while the microturbines are dispatched according to the proposed ETC algorithm. It is assumed that the customer used their own boiler to produce heat, prior to the investment in distributed generation. Natural gas is bough at the retail prices, as same as for microturbine purposes. The boiler efficiency is set to 80%. We calculated the amount of avoided purchase of natural gas thanks to the use of heat recovered from the microturbines. The heat exchanger investment costs are deducted from the value of benefit in order to compute the net profit of the investment.

Fig. 14 shows that the upgrade in CHP has a huge theoretical maximum potential. If total available heat energy would be utilized, the investment in CHP would be very profitable. On the other hand, it is not easy to achieve a perfect matching between the load profiles of electricity and heat. In a simple case of space heating, the available heat would be used only during the colder months.

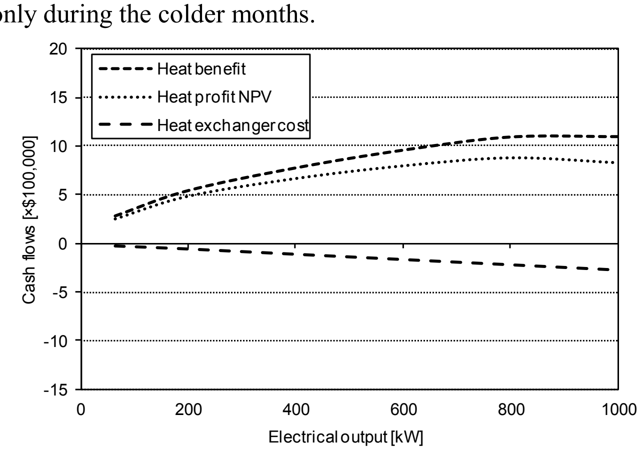

Fig. 14. Cost-effectiveness of investment in microturbine heat exchangers

In order to precisely calculate the benefits of recovered heat, a detailed model of customer heat load profile is necessary. In this paper, we determine just the profitability thresholds expressed as a percentage of the theoretical maximum, where the investment in CHP upgrade is still profitable for the customer. The results are summarized in Table IV.

It should be noted that the investments in CHP can be subsidized under certain circumstances, which would additionally lower the profitability thresholds.

TABLE IV
PROFITABILITY THRESHOLDS FOR INVESTMENT IN CHP UPGRADE

	Unit	C65	C200	C400
CHP investment cost NPV	$\times10^5$\$	0,24	0,55	1,09
Benefit NPV	$\times10^5$\$	2,79	5,44	7,76
Profitability threshold	%	8,5	10,1	14,1

	Unit	C600	C800	C1000
CHP investment cost NPV	$\times10^5$\$	1,64	2,19	2,73
Benefit NPV	$\times10^5$\$	9,61	10,98	11,02
Profitability threshold	%	17,1	19,9	24,8

V. CONCLUSION

In this paper the profitability of investing in customer-driven distributed generation has been considered. The target customers are industrial and commercial users of electricity, which are billed not only for the volumetric consumption but also for the monthly peak demand. Presented methodology is capable of providing the answer whether or not it is profitable to invest in distributed generation, and which is the most appropriate investment option for the customer. The proposed methodology has been comprehensively tested on one integrated illustrative example.

REFERENCES

[1] G. Pepermans, J. Driesen, D. Haeseldonckx, R. Belmans, and W. D'haeseleer, "Distributed generation: definition, benefits and issues", *Energy Policy*, vol. 33, pp. 787-798, 2005.

[2] A. A. Chowdhury, S. K. Agarwal, and D. O. Koval, "Reliability modeling of distributed generation in conventional distribution systems planning and analysis", *IEEE Transactions on Industry Applications*, vol. 39, pp. 1493-1498, 2003.

[3] A. Moreno-Munoz, J. J. G. de-la-Rosa, M. A. Lopez-Rodriguez, J. M. Flores-Arias, F. J. Bellido-Outerino, and M. Ruiz-de-Adana, "Improvement of power quality using distributed generation", *International Journal of Electrical Power Energy Systems*, vol. 32 pp. 1069-1076, 2010.

[4] H. A. Gil and G. Joos, "On the quantification of the network capacity deferral value of distributed generation", *IEEE Transactions on Power Systems,* vol. 21, pp. 1592-1599, 2006.

[5] H. A. Gil and G. Joos, "Models for quantifying the economic benefits of distributed generation", *IEEE Transactions on Power Systems,* vol. 23 pp. 327-335, 2008.

[6] I. -S. Bae, J. O. Kim, J. -C. Kim and C. Singh, "Optimal operating strategy for distributed generation considering hourly reliability worth", *IEEE Transactions on Power Systems,* vol. 19, pp. 287-292, 2004.

[7] A. Barina, L. F. Pozzatti, L. N. Canha, R. Q. Machado, A. R. Abaide, and G. Arend, "Multi-objective analysis of impacts of distributed generation placement on the operational characteristics of networks for distribution system planning", *International Journal of Electrical Power Energy Systems*, vol. 32, pp. 1157-1164, 2010.

[8] M. Zangiabadi, R. Feuillet, H. Lesani, N. Hadj-Said, and J. T. Kvaløy, "Assessing the performance and benefits of customer distributed generation developers under uncertainties", *Energy*, vol. 36, pp. 1703-1712, 2011.

[9] C. Marnay, J. Chard, K. Hamachi, T. Lipman, M. Moezzi, B. Ouaglal, and A.Siddiqui, "Modeling of customer adoption of distributed energy resources", Lawrence Berkeley National Laboratory Report LBNL-49582, Berkeley, CA, USA, 2001.

[10] A. S. Siddiqui, C. Marnay, R. M. Firestone, and N. Zhou, "Distributed generation with heat recovery and storage", Journal of Energy Engineering, vol. 133, pp. 181-210, 2007.

[11] Y. Ruan, Q. Liu, W. Zhou, R. Firestone, W. Gao, and T. Watanabe, "Optimal option of distributed generation technologies for various commercial buildings", Applied Energy, vol. 86, pp. 1641-1653, 2009.

[12] B. Coffey and E. Kutrowski, "Demand charge considerations in the optimization of cogeneration dispatch in a deregulated energy market", International Journal of Energy Research, vol. 30, pp. 535-551, 2006.

[13] A. S. Siddiqui and C. Marnay, "Distributed generation investment by a microgrid under uncertainty", *Energy*, vol. 33, pp. 1729-1737, 2008.

[14] Č. V. Zeljković, N. Lj. Rajaković, and S. J. Zubić, "A method for cost minimization applicable to load centers containing distributed generation", in *Proc. IEEE PowerTech Conf.*, Bucharest Romania, June 28 – July 2, 2009, pp. 1-6.

[15] Č. V. Zeljković, N. Lj. Rajaković, and S. J. Zubić, "An application of cost minimization algorithm to economic justification of installing distributed generation", in *Proc. IFAC CMTEE Conference* Vilamoura, Portugal, March 29-31, 2010, pp. 243-248.

[16] Č. V. Zeljković, N. Lj. Rajaković, and S. J. Zubić, "Customer-perspective approach to reliability evaluation of distributed generation", in *Proc. IEEE PowerTech Conf.*, Trondheim Norway, June 19-23, 2011.

[17] R. A. Brealey and S. C. Myers, *Principles of corporate finance*, 7th ed., Boston: McGraw-Hill, 2003.

[18] S. C. Savvides, "Risk analysis in investment appraisal", Project Appraisal, vol. 9, pp. 3-18, 1994.

[19] Č. Zeljković and N. Rajaković, "Cost-saving potential of customer-driven distributed generation," *Electric Power Systems Research*, vol. 92, pp. 87-95, 2012.

[20] J. Nowicka-Zagrajek and R. Weron, "Modeling electricity loads in California: ARMA models with hyperbolic noise", *Signal Processing*, vol. 82, pp. 1903-1915, 2002.

[21] B. Klöckl, G. Papaefthymiou, Multivariate time series models for studies on stochastic generators in power systems, Electr.Power Syst. Res. 80 (2010) 265-276.

[22] G. H. Kjølle, and A. T. Holen, Reliability and interruption cost prediction using time-dependent failure rates and interruption costs, Qual. Reliab. Eng. Int.14 (1998) 159-165.

[23] R. Billinton W. Li, Reliability Assessment of electric power systems using Monte Carlo methods, New York: Plenum, 1994.

[24] L. Goel, X. Liang, and Y. Ou, Monte Carlo simulation-based customer service reliability assessment, Electr. Power Syst. Res. 49 (1999) 185-194.

[25] R. Billinton, R. N. Allan, Reliability evaluation of power systems, 2nd ed., New York and London: Plenum Press, 1996.

[26] R. E. Brown, Electric power distribution reliability, 2nd ed., Boca Raton: CRC Press, 2008.

[27] H. Y. Yamin, Review on methods of generation scheduling in electric power systems, Electr. Power Syst. Res. 69 (2004) 227-248.

[28] K. H. LaCommare, J. H. Eto, Cost of power interruptions to electricity consumers in the United States (US), *Energy*, vol. 31, pp. 1845-1855, 2006.

[29] K. M. Maribu and S. -E. Fleten, "Combined heat and power in commercial buildings: Investment and risk analysis," *The Energy Journal*, vol. 29, pp. 123-150, 2008.

[30] P. S. Curtiss and J. F. Kreider, "Recent developments in the control of distributed electrical generation systems", *ASME Journal of Solar Energy Engineering*, vol. 125, pp. 352-358, 2003.

[31] R. Firestone, M. Stadler, C. Marnay, "Integrated energy system dispatch optimization", *in Proc. 4th Annual IEEE Conference on Industrial Informatics*, Singapore, August 16-18, 2006, pp. 357-362.