ISSN 1330-3651 (Print), ISSN 1848-6339 (Online)
https://doi.org/10.17559/TV-20171203150754
Original scientific paper

Simplified Model for Optimal Sizing of the Off-Grid PV System Regarding Value of Loss of Load Probability

Danijel TOPIĆ, Goran KNEŽEVIĆ, Daniel KOSIĆ, Jurica PERKO

Abstract: In this paper, a simplified model for optimal sizing of the off-grid PV system regarding value of loss of load probability is described. The model gives optimal size of system in terms of required number of PV modules, peak power, number of batteries and cost of system regarding the defined value of loss of load probability, load curve and period for which optimal size will be determined. The model is applied for determination of optimal size of the off-grid PV system for the city of Osijek. Based on measured load curve, optimal size of the system is determined for values of loss of load probability from 0.00 to 0.10 in steps of 0.01, and additionally for 0.15.

Keywords: loss of load probability; model; off-grid; optimal; PV system; sizing

1 INTRODUCTION

Because of the limited reserves of fossil and nuclear fuels and their negative impact on environment, usage of renewable energy sources for electricity production is increasing every year. According to [1] total renewable power capacity (excluding large hydro power plants) in 2015 was 785 GW and at the end of 2016 was 921 GW. Total installed capacity of photovoltaic (PV) systems is also increasing every year the same as PV cells global production. At the end of 2016 total installed capacity of PV systems was 303 GW (at the end of 2015 it was 228 GW) (Ren21, n.d.). According to [2] production data for global PV cell production in 2015 varied between 56 GW and 61 GW for 2016 and estimates for 2016 are in the 65 to 75 GW range. These data are mainly related to grid-connected PV systems, because total installed capacity of off-grid PV systems is very difficult to track. However, that does not mean that off-grid PV systems are not important for reduction of fossil fuels consumption.

Off-grid PV systems (and other renewable off-grid systems as well) can be very helpful for reduction of fossil fuels and CO_2 emissions, for power supply of rural areas where there is no electrical grid, for power supply of cottages etc. For such purposes, it is important to find optimal system depending on consumers' needs. Rossi, Toppano and Brunelli in [3] presented real time optimization of battery banks in hybrid residential electrical systems with the aim of maximizing lifetime of the battery banks and to reduce energy bills by managing variability of PV production in price-varying scenarios. Bhandari et al., in [4] presented a review of trends of optimization techniques of hybrid renewable energy power systems. Furthermore, in [5] authors presented a case study for PV micro-grid for rural electrification in India, while Hassan et al., in [6] presented usage of the off-grid PV systems as a solution for the ambient pollution avoidance in rural areas of Iraq. Abdulateef, in [7] presented a simulation model of off-grid PV system which is designed for system sizing in case of maximum solar radiation. Merei et al. in [8] introduced optimization model of the off-grid hybrid power system for supply of telecommunication base station where they investigated combination of three different battery technologies. Huneke et al., in [9] used linear programming for optimization of hybrid off-grid energy systems. There are many other researches related to optimization and sizing of PV systems such as [10-15] and [16]. In this paper, simplified model for optimal sizing of the off-grid PV system regarding value of loss of load probability (*LOLP*) is presented. This model enables to find optimal size of the off-grid PV system according to desired value of the *LOLP*. The advantage of this model in comparison with the previously described papers is that it enables to find optimal off-grid PV system size for desirable period of year.

This paper consists of 4 chapters. First chapter presents introduction. In the second chapter, description of the simplified model is shown. In the third chapter the results and discussion description of the off-grid PV system, case scenario description and results of the case study are presented. The fourth chapter presents conclusions of the paper.

2 DESCRIPTION OF THE SIMPLIFIED MODEL

This model can be used for finding optimal size of the off-grid PV system in a way to determine optimal number of PV modules, number of batteries and peak power for defined load profile curve in respect to minimum cost of the system and defined value of *LOLP*. Another advantage of this model is it that can determine optimal size of the system regarding different periods. E.g. it can determine optimal system for usage period of one year, season, month, week or any other period. In Fig. 1 block diagram of simplified model for optimal sizing of the off-grid PV system in respect to value of *LOLP* is shown.

According to the block diagram presented in Fig. 1, mathematical description of the model is presented as follows. For each hour t, electricity production of PV modules is calculated according (1):

$$P_{\mathrm{PV}i,t} = G_t \cdot A \cdot i \cdot \eta_r \tag{1}$$

Where: G_t - average insolation in hour t for the given module angle, A - surface size of the observed module, i - number of modules, η_r - rated efficiency of the observed PV module.

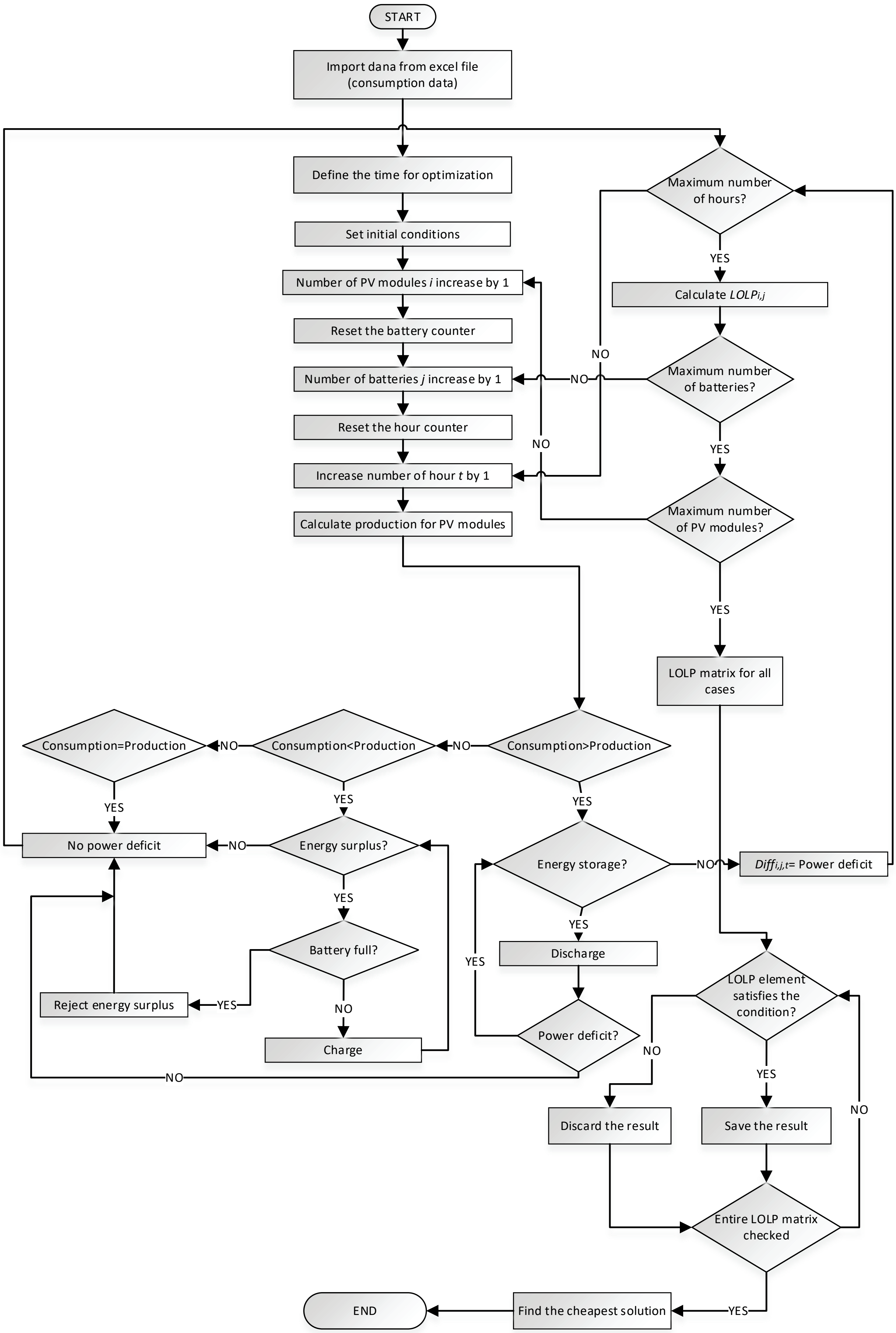

Figure 1 Block diagram of simplified model

Observe that value of the average output power of PV modules in particular hour t equals the electricity production in the same hour t.

Maximum and minimum capacity of batteries is defined as (2) and (3):

$$C_{BMAX\,j} = C_{BMAX} \cdot j \tag{2}$$

$$C_{BMIN\,j} = C_{BMAX} \cdot j \cdot \delta \tag{3}$$

Where: C_{BMAX} - average insolation in hour t for the given module angle, δ - coefficient setting the minimum remaining battery capacity, j - number of batteries.

Difference between output power of the PV modules and load in hour t is calculated using (4):

$$D_{i,t} = Load_t - P_{PV\,i,t} \tag{4}$$

Then, for a given combination of number of the PV modules i and number of batteries j, in each hour t variable $Z_{i,j,t}$ is calculated according (5):

$$Z_{i,j,t} = C_{BAT\,j,t-1} - D_{i,t} \tag{5}$$

Where: $C_{BAT\,j,t-1}$ - battery capacity for a number of batteries j at the end of previous hour, for the first hour $C_{BAT\,j,t-1}$ equals $C_{START\,j}$, i.e. level of battery capacity at the begging of the observed period.

Then three logical tests are examined:

a) if $Z_{i,j,t} < C_{BMIN\,j}$

$$C_{BAT\,j,t} = C_{BMIN\,j} \tag{6}$$

$$Diff_{i,j,t} = D_{i,t} - (C_{BAT\,j,t-1} - C_{BMIN\,j}) \tag{7}$$

Where: $C_{BAT\,j,t}$ - battery capacity for a number of batteries j at the end of hour t, $Diff_{i,j,t}$ - power deficit in hour t, for a given combination of a number of PV modules i and number of batteries j.

b) if $Z_{i,j,t} \geq C_{BMIN\,j}$ and $Z_{i,j,t} \leq C_{BMAX\,j}$

$$C_{BAT\,j,t} = Z_{i,j,t} \tag{8}$$

c) if $Z_{i,j,t} \geq C_{BMAX\,j}$

$$C_{BAT\,j,t} = C_{BMAX\,j} \tag{9}$$

At the end of observed period, loss of load probability $LOLP_{i,j}$ is calculated for a given combination of the number of PV modules i and number of batteries j as the following (10):

$$LOLP_{i,j} = \frac{\sum_{t=1}^{n} Diff_{i,j,t}}{\sum_{t=1}^{n} Load_t} \tag{10}$$

In a double *for loop* for the given range of i and j, is calculated for each pair of i and j for the observed period n using expression (10) and taking into account expressions (1)-(9). The obtained matrix of $LOLP_{i,j}$ related to tested i and j is searched for values that are smaller than requested $LOLP_{SET}$.

If $LOLP_{i,j} < LOLP_{SET}$ the price of the associated system is calculated as:

$$COST_{i,j} = i \cdot P_R \cdot PV_{COST} + j \cdot C_R \cdot BAT_{COST} \tag{11}$$

Where: P_R - rated power of the PV module (W), C_R - rated capacity of the battery (Wh), PV_{COST} - capital cost of PV system per W (includes installation and the cost of the inverter), BAT_{COST} - capital cost of battery per Wh (includes installation and the cost of the charging regulator).

Minimal $COST_{i,j}$ reveals the cheapest system consisting of a number of PV modules i and number of batteries j which satisfied requested value of $LOLP$.

3 RESULTS AND DISCUSSION

3.1 Description of the Off-Grid PV System

In this section off-grid PV system is described. Off-grid PV system consists of: PV modules, batteries, inverter/charge controller and loads. In Fig. 2 simplified scheme of the system is shown.

In this off-grid PV system mono crystalline PV modules with the following characteristics are assumed: peak power 250 W and efficiency 15.3 %. Deep cycle batteries with the following characteristics are assumed: voltage 12 V, capacity 160 Ah and charging depth 20%.

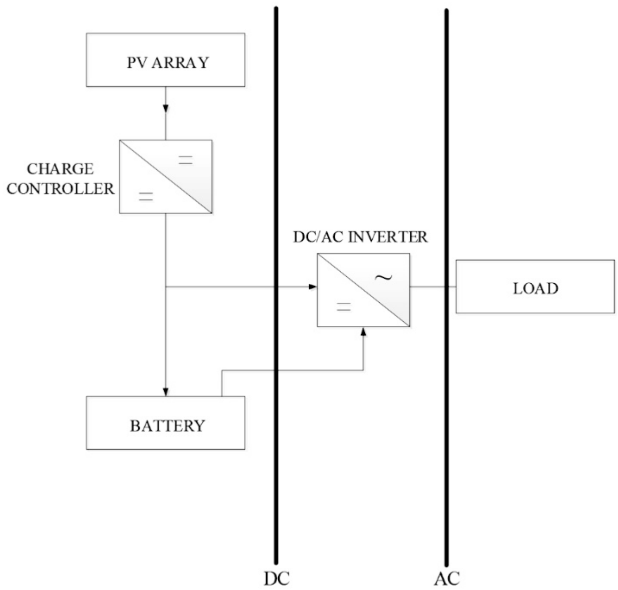

Figure 2 Scheme of the off-grid PV system

In Tab. 1 specific costs for different components of off-grid PV system are shown. Costs are calculated based on realistic price for different PV system components available in [17]. Data from table 1 will be used in model for finding optimal size of the off-grid PV system. PV_{COST} includes cost of the all system components except batteries and it is expressed in EUR per peak kW of system. BAT_{COST}

represents cost of the batteries and it is expressed in EUR/kWh.

Table 1 Costs of PV system elements

	EUR/kW
PV modules	773.33
Mounting elements	33.33
Cables	4.67
Charge controller/inverter	233.33
PV_{COST}	**1044.67**
	EUR/kWh
Batteries	146.67
BAT_{COST}	**146.67**

3.2 Case scenario description

The model described in chapter 2 is used to find optimal size of the off-grid system for a house in Osijek, Croatia. Data for solar irradiation are taken for the city of Osijek according to PV GIS ("PV GIS", n.d.). Mean hourly data of solar radiation for one year are used. Characteristics of the components in the system are assumed as it is described in chapter 3.1.

In Fig. 3, weekly load diagram is shown. Weekly load diagram is measured for 7 days and based on this measurement yearly load diagram will be generated. To get yearly load diagram, for each week weekly diagram from Fig. 3 is assumed. Maximum load power is 2286.5 W and the minimum load is 14.8 W.

In this case scenario, model is used to find optimal size of the system for power supply for period from 1st June to 31st August. Different values of *LOLP* in this case scenarios are assumed. Optimal size of the off-grid system for the following values of *LOLP* is determined: 0.00, 0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, 0.08, 0.09, 0.10, and 0.15, respectively.

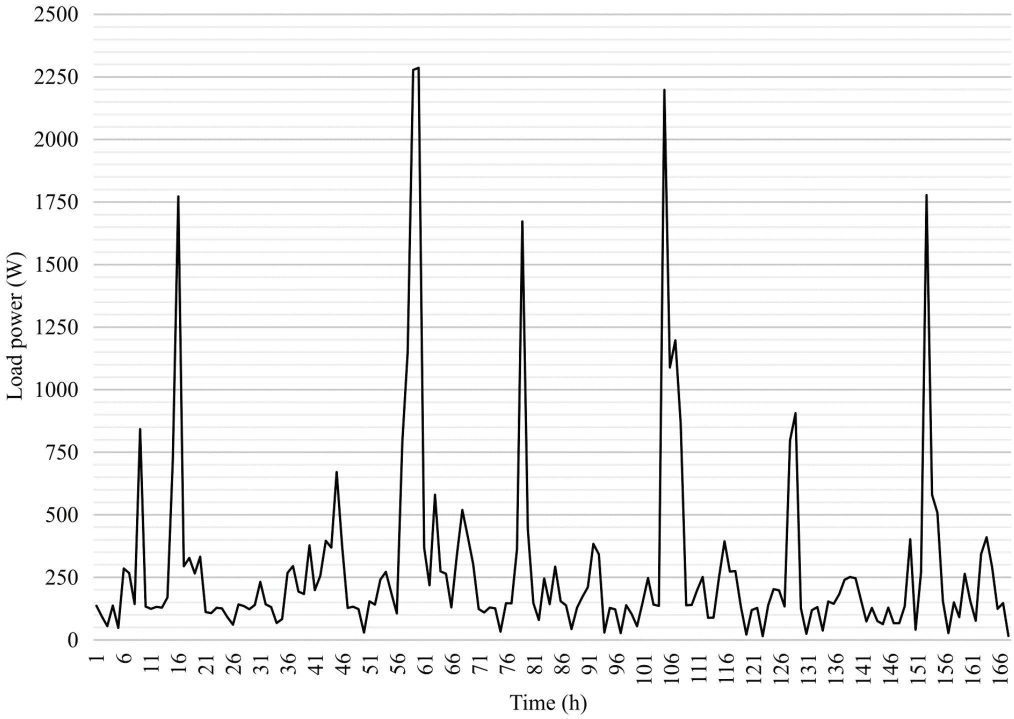

Figure 3 Weekly load diagram

3.3 Results of Case Study

In Tab. 2 results for different values of *LOLP* are presented. Results are presented with optimal size of the off-grid PV system which includes number of PV modules, number of batteries, peak power of the system and cost of the off-grid system for different values of *LOLP* and for the period from 1st June to 31st August. Optimal size of the off-grid PV system for value of *LOLP* 0.00, 0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, 0.08, 0.09, 0.10, and 0.15, respectively is presented.

In Fig. 4, savings in investment cost in respect to different values of *LOLP* are shown. As can be seen in Fig. 4, a considerable part of the investment cost (34% in respect to scenario when *LOLP* equals 0) can be saved if investor is willing to accept *LOLP* value of 0.03. Further increase in *LOLP* value does not have justification in substantial investment cost reduction.

Table 2 Costs of PV system elements

LOLP	Number of PV modules	Power of the system (kW)	Number of batteries	Cost (EUR)
0.00	6	1.5	12	4946.28
0.01	7	1.75	10	4644.24
0.02	7	1.75	7	3799.42
0.03	6	1.5	6	3256.64
0.04	9	2.25	3	3195.33
0.05	8	2	3	2934.16
0.06	6	1.5	4	2693.43
0.07	7	1.75	3	2672.99
0.08	8	2	2	2652.55
0.09	6	1.5	3	2411.82
0.10	7	1.75	2	2391.38
0.15	6	1.5	2	2130.22

Due to the excessive number of data and the clarity in the result presentation, in Figs. 5-7 results are presented only for period of one week from 1st July to 7th July. In Fig. 4 load power, PV generation and battery capacity for the period from 1st July to 7th July for value of *LOLP* = 0 are shown. As it can be seen, the battery capacity does not reach the minimum value of 20% of total capacity which implies that there is no shortage in powering the load. This is the most expensive system consisting of 6 PV modules and 12 batteries.

In Fig. 6 load power, PV generation and battery capacity for period from 1st July to 7th July for value of *LOLP* = 0.1. As it can be seen, the battery capacity reaches minimum value of 20% of total capacity in hours 61, 62 representing 11 h and 12 h of 3rd July, in hour 79 representing 7 h of 4th July and in hour 129 representing 9 h of 6th July. In Fig. 7 load power, PV generation and battery capacity are shown for period from 1st July to 7th July for value of *LOLP* = 0.15. In this case, the additional period of shortage in powering the load can be seen in respect to the case of *LOLP* = 0.1.

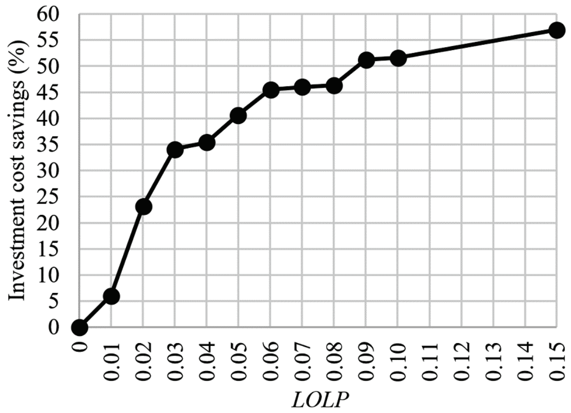

Figure 4 Savings in investment cost in respect to different values of *LOLP*

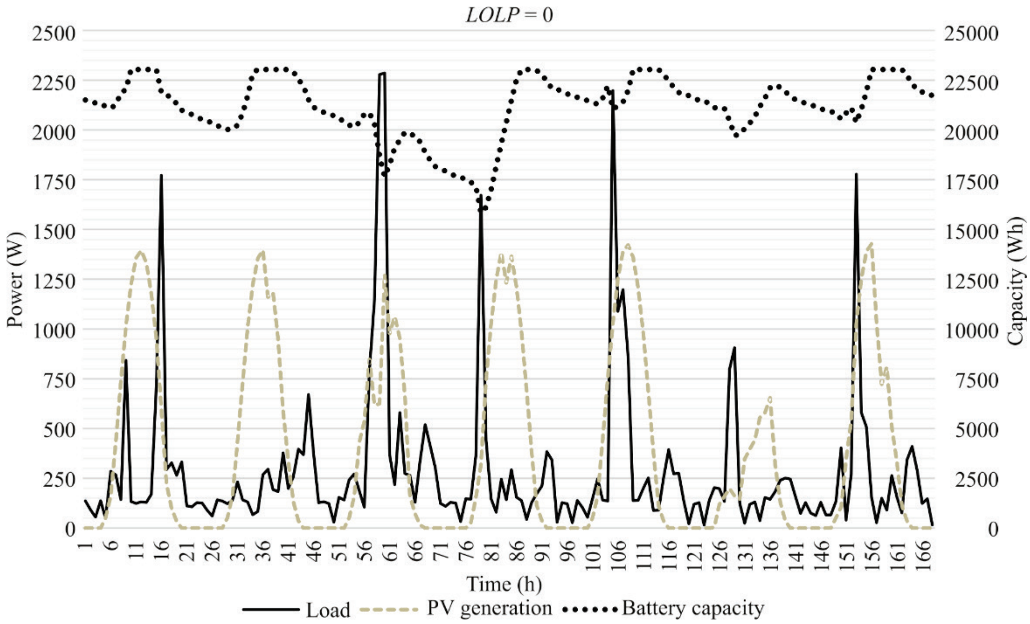

Figure 5 Load power, PV generation and battery capacity for period 1.7 to 7.7 for value of *LOLP* = 0

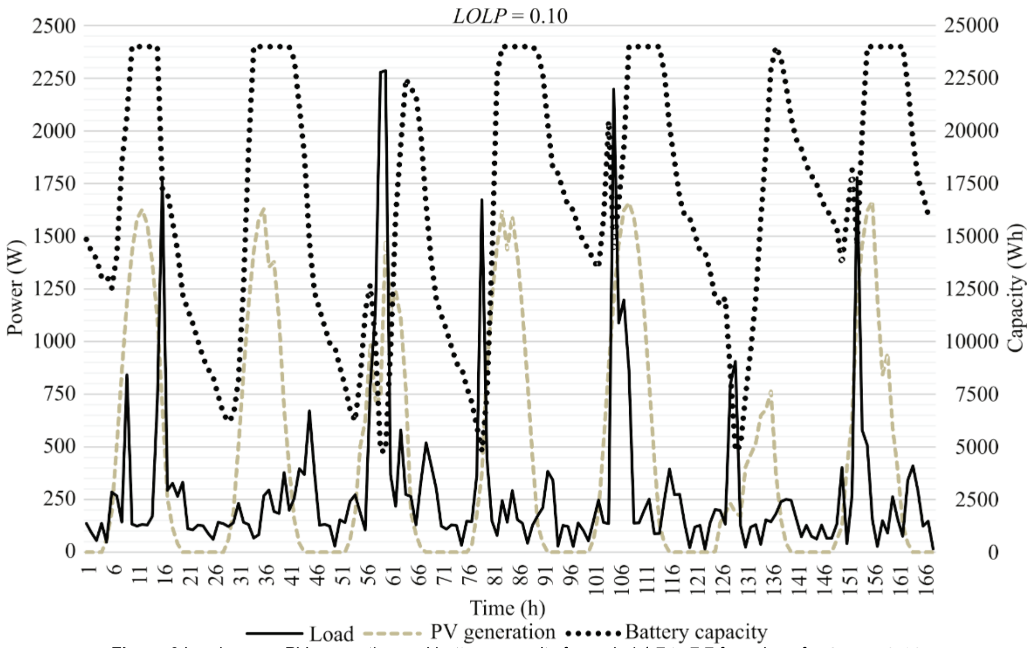

Figure 6 Load power, PV generation and battery capacity for period 1.7 to 7.7 for value of *LOLP* = 0.10

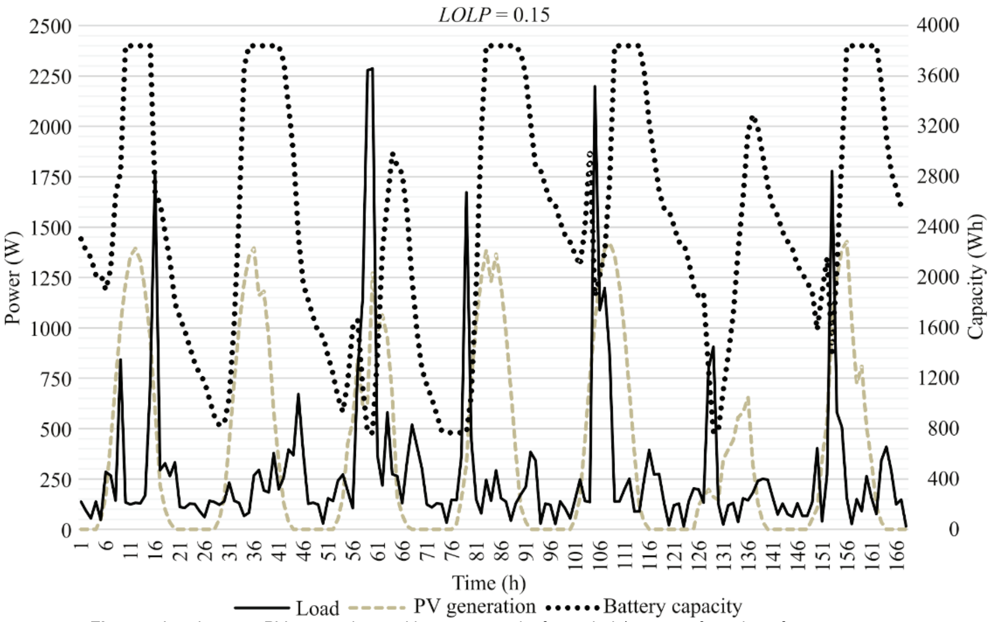

Figure 7 Load power, PV generation and battery capacity for period 1.7 to 7.7 for value of *LOLP* = 0.15

4 CONCLUSION

Simplified model for optimal sizing of the off-grid PV system in respect to value of loss of load probability is described. The model is applied to find optimal size of the off-grid PV system for the city of Osijek. Optimal size of the off-grid PV system which includes the number of PV modules, number of batteries, peak power of the system and cost of the off-grid system in respect to values of *LOLP* and for the period from 1st June to 31st August is determined. Optimal size of the off-grid PV system for values of LOLP 0.00, 0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, 0.08, 0.09, 0.10, and 0.15, respectively is determined. Savings in investment cost in respect to different values of *LOLP* are shown. A considerable part of the investment cost (34% in respect to scenario when *LOLP* equals 0) can be saved if investor is willing to accept *LOLP* value of 0.03. Further increase in *LOLP* value does not have justification in substantial investment cost reduction.

Acknowledgements

This research is part of the project "Optimization of off-grid photovoltaic systems regarding the value of expected energy not served" financed by FERIT and RuRES, HUHR/1601/3.1.1/0033 project financed in frame of Interreg V-A Hungary-Croatia Co-operation Programme 2014-2020.

5 REFERENCES

[1] Ren21. (2017). *Renewables 2016 - Global Status report*. Retrieved from http://www.ren21.net/wp-content/uploads/2016/06/GSR_2016_Full_Report.pdf

[2] Commission, W. E., Report, P. V. S., & Technologies, F. E. (2016). *PV Status Report 2016 PV Status Report 2016*. https://doi.org/10.2790/682995

[3] Rossi, M., Toppano, A., & Brunelli, D. (2014). Real-time Optimization of the Battery Banks Lifetime in Hybrid Residential Electrical Systems. *Proceedings of the Conference on Design, Automation & Test in Europe*, 139:1--139:6. https://doi.org/10.7873/DATE2014.152

[4] Bhandari, B., Lee, K-T., Cho, Y-M., & Ahn, S-H. (2015). Optimization of Hybrid Renewable Energy Power system: A review. *International Journal of Precision Enginnering and Manufacturing-green Technology, 2*(1), 99-112. https://doi.org/10.1007/s40684-015-0013-z

[5] Loka, P., Moola, S., Reddy, S., Skumanich, A., Fulton, S., Siah, S. C., & Mints, P. (2013). A case study for micro-grid PV: Rural electrification in India. *Conference Record of the IEEE Photovoltaic Specialists Conference*, *95032*(1), 3379-3382. https://doi.org/10.1109/PVSC.2013.6745174

[6] Hassan, Q., Jaszczur, M., Mohamed, M., Styszko, K., Szramowiat, K., & Gołaś, J. (2016). Off-grid photovoltaic systems as a solution for the ambient pollution avoidance and Iraq's rural areas electrification. *1st International Conference on the Sustainable Energy and Environment Development (SEED 2016)*, Volume 10, 1-5. https://doi.org/10.1051/e3sconf/20161000093

[7] Abdulateef, J. (2014). Simulation of solar off- grid photovoltaic system for residential unit. *International Journal of Sustainable and Green Energy*, *4*(3), 29-33. https://doi.org/10.11648/j.ijrse.s.2015040301.15

[8] Merei, G., Magnor, D., Leuthold, M., & Sauer, D. U. (2014). Optimization of an Off-grid Hybrid Power Supply System Based on Battery Aging Models. *IEEE 36th International Telecommunications Energy Conference (INTELEC)*, 1-6. https://doi.org/10.1109/INTLEC.2014.6972127

[9] Huneke, F., Henkel, J., Benavides González, J. A., & Erdmann, G. (2012). Optimisation of hybrid off-grid energy systems by linear programming. *Energy, Sustainability and Society, 2*(7). https://doi.org/10.1186/2192-0567-2-7

[10] Topić, D., Knežević, G., & Fekete, K. (2017). The mathematical model for finding an optimal PV system configuration for the given installation area providing a maximal lifetime profit. *Solar Energy*, *144*, 750-757. https://doi.org/10.1016/j.solener.2017.02.011

[11] Šljivac, D., Nakomčić-Smaragdakis, B., Vukobratović, M., Topić, D., & Čepić, Z. (2014). Cost-benefit comparison of on-grid photovoltaic systems in pannonian parts of croatia and serbia. *Tehnicki Vjesnik*, *21*(5), 1149-1157.

[12] Khandelwal, A. (2017). Design and Assessment of Solar Photovoltaic System For a Village of Rajasthan. *International Research Journal of Engineering and Technology (IRJET), 4*(11), 155-162.

[13] Mbodji, N., Arisily, T. A. A., & Hajji, A. (2016). Optimal Design of an Off-Grid Hybrid Solar Photovoltaic-Diesel System in Community Electrification of a Fishing Village in

Morocco. *4th International Renewable and Sustainable Energy Conference*, At Marrakech, Morocco, 946-955. https://doi.org/10.1109/IRSEC.2016.7983984

[14] Mandelli, S., Brivio, C., Colombo, E., & Merlo, M. (2016). Effect of load profile uncertainty on the optimum sizingof off-grid PV systems for rural electrification. *Sustainable Energy Technologies and Assessments*, *18*, 34-47. https://doi.org/10.1016/j.seta.2016.09.010

[15] Klaić, Z., Fekete, K., & Šljivac, D. (2015). Demand side management in the distribution system with photovoltaic generation. *Tehnicki Vjesnik-Technical Gazette*, *22*(4), 989-995. https://doi.org/10.17559/TV-20141205092803

[16] Veldhuis, A. J., & Reinders, A. H. M. E. (2015). Reviewing the potential and cost-effectiveness of off-grid PV systems in Indonesia on a provincial level. *Renewable and Sustainable Energy Reviews*, *52*, 757-769. https://doi.org/10.1016/j.rser.2015.07.126

[17] Solar Shop. (2017). Retrieved from http://www.solarno.hr

Contact information:

Danijel TOPIĆ, PhD, Assistant Professor
(Corresponding author)
Josip Juraj Strossmayer University of Osijek
Faculty of Electrical Engineering, Computer Science and Information Technology Osijek
Kneza Trpimira 2b, 31000 Osijek, Croatia
danijel.topic@ferit.hr

Goran KNEŽEVIĆ, PhD, Assistant Professor
Josip Juraj Strossmayer University of Osijek
Faculty of Electrical Engineering, Computer Science and Information Technology Osijek
Kneza Trpimira 2b, 31000 Osijek, Croatia
goran.knezevic@ferit.hr

Jurica PERKO, M.Sc.
Regional Energy Agency North
Miroslava Krleze 81, 48000 Koprivnica, Croatia
jurica.perko@rea-sjever.hr

Daniel KOSIĆ, M.Sc.
Ciratec
Steenakkerstraat 30, 3590 Diepenbeek, Belgium
d.kosic@ciratec.be