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Reliability And Costs Of Conventional Electric Power Supply Versus Self Sufficient Supply

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Abstract

The electrical power system is changing rapidly from a topology of smaller number of larger power supply units towards a larger number of more distributed smaller units. The objective is to discuss the realistic costs of specific household being self-sufficient in terms of electric energy supply and to discuss reliability issues. The mathematical model of the method includes four modules, which interact with each other. The models of specific households include several locations and consecutive years which were evaluated for each. The results from the year 2015-2018 are presented for a selected location. The results show a function of yearly solar power plant production and a function of the battery state of charge using intervals every half an hour. The optimization of costs of self-sufficient household with solar power plant and battery is presented and the minimal costs are evaluated in each year. The reliability of self-sufficient household may be smaller if not connected to the power system.

Keywords: self-sufficient, power, supply, battery, solar

1. Introduction

The electrical power system is changing rapidly from a topology of smaller number of larger power supply units towards a larger number of more distributed smaller units. We had concentrated electric energy generation years or decades ago, which means a small number of large power plants: nuclear, thermal and hydropower. Nowadays, we have more and more dispersed electric energy generation sources including wind and solar power sources and a smaller number of larger power units.

Electric energy supply at home is an issue, which now offers more solutions than years ago. Some households are transferring to their own electric power supply in addition or instead of getting the electric power supply from the power system.

The term self-sufficient is introduced with installed solar power for households. We define a self-sufficient power supply, but the technical meaning of definition is in paradox. Namely, pure definition of self-sufficient means, that household does not rely on anything else, and household is fully self-sufficient. On the other hand, a partial self-sufficient power supply is a possible interpretation. So, sometimes the household is self-sufficient, sometimes it relies on a power supply from the power system (e.g. during the night, if it has only solar power). If household does not have some storage, the consumption in the night period cannot be covered by solar power plants obviously. So, the term partial self-sufficient power supply would be more appropriate.

Self-sufficient factor (SSF) can be defined, which is a ratio between energy consumed from the own production (E_{own}) versus energy consumed from own production increased for energy obtained from power system (E_{EPS}).

$$SSF = \frac{E_{own}}{E_{own} + E_{EPS}} \tag{1}$$

Self-sufficient factor can be related also to the reliability of self-sufficient power system. We can require total self-sufficiency with $SSF = 1$ and investigate the related costs of electric power supply.

The objective is to discuss the realistic costs of the specific household being self-sufficient in terms of electric energy supply and to discuss reliability issues. The household power supply is assumed from solar power plant with certain nominal power (which is related to area of solar power) and with electric battery of certain capacity. The nominal power of solar power plant and the capacity of the battery can be optimized. Optimization is based on minimal costs of electric energy assuming the yearly household consumption as a realistic time function and a requirement that no power supply from the power system is expected. This means a fully self-sufficient household. The costs can be evaluated and compared to a case of conventional power supply with larger power plants.

2. Methods

A household is specified at a specific location with specific orientation of roof capable of mounting the solar power plant with specified parameters on the roof. Weather data for solar power density as time dependent function on this specific location is needed as the input. In addition, place for the electric battery is reserved in a house. The battery provides electric power to the household, when not enough power comes from the solar power plant on the roof.

The mathematical model of the method includes four modules, which interact with each other (Čepin, 2023).

- Evaluation of realistic time dependent function of electric energy production from solar power plant depends on the weather parameters and size of solar power plant (either nominal power, or its surface can be the main parameter, because they are linearly connected anyway).

$$E_p = \sum_{i=1}^{ii} G_i \cdot A_{SPP} \cdot \eta \cdot t = \sum_{i=1}^{ii} E_{p\_i} \tag{2}$$

  - E_p – electric energy produced in solar power plant (kWh)
  - E_{p_i} – electric energy produced in solar power plant in time step i (kWh)
  - G_i - density of solar radiation at time step i (W/m^2)
  - t – time interval between consecutive time step readings of density of solar radiation (h)
  - ii – number of time steps
  - A_{SPP} – surface of solar power plant (m^2)
  - η – efficiency of solar power plant
- Assessment of realistic time dependent function of household electric energy consumption bases on all household consumers and their use. Figure 1 shows selected examples of consumption in three selected days.

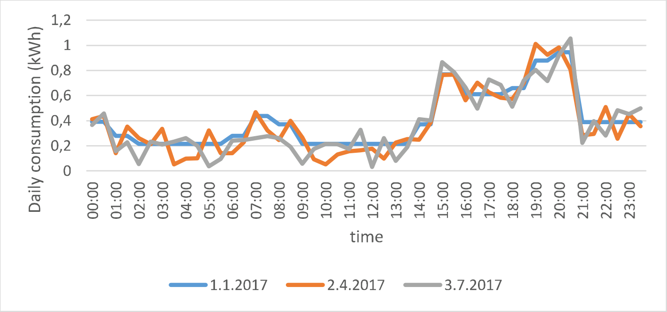

Fig. 1. Consumption in three selected days.

- Evaluation of realistic time dependent function of electric battery state of charge depends on difference between solar power plant production and household consumption. The evaluation adopts the efficiency of charging and efficiency of discharging the battery.

$$E_{bSOC_{i+1}} \begin{cases} = E_{bSOC_i} + E_{to\_i} \cdot \eta_{ci}\left(E_{bSOC_i}\right) & if\ E_{p_i} \geq E_{c_i};\ E_{to\_i} = E_{p\_i} - E_{c\_i} \\ = E_{bSOC_i} - \dfrac{E_{from_i}}{\eta_{di}\left(E_{bSOC_i}\right)} & if\ E_{p_i} < E_{c_i};\ E_{from\_i} = E_{c\_i} - E_{p\_i} \end{cases} \tag{3}$$

  - E_{bSOC_i} – state of charge of battery in the time interval related to time point i (kWh),

- ΔE_{bSOC_i} - change of state of charge of battery in the time interval related to time point i (kWh),
- E_{from_i} - electric energy supplied to the system from the battery in the time point i (kWh),
- E_{to_i} - electric energy supplied to the battery from the system in the time point i (kWh),
- $\eta_{di}(E_{bSOCi})$ - efficiency of battery discharge as a function of battery state of charge,
- $\eta_{ci}(E_{bSOCi})$ - efficiency of battery charge as a function of battery state of charge,
- E_{p_i} – electric energy produced in solar power plant in time step i (kWh),
- E_{c_i} – electric energy consumed in time step i (kWh).

The battery state of charge can range from the totally empty to fully charged battery. The fully charged battery has nominal battery capacity. No decrease of battery capacity with the time is assumed.

$$0 \leq E_{bsoc_i} \leq E_{b\_cap} \tag{4}$$

E_{b_cap} – nominal battery capacity (kWh)

A simple change of algorithm is possible to adopt a scheme for extension of the lifetime of the battery, which is realised if the battery is not fully emptied.

$$0{,}2 \cdot E_{b\_cap} \leq E_{bsoc_i} \leq E_{b\_cap} \tag{5}$$

Both charging and discharging are limited with upper limit of allowed current in the system.

$$E_{to\_i} \cdot \eta_{ci}\left(E_{bsoc_i}\right) = U \cdot I_c \cdot t \leq U \cdot I_{max} \cdot t \tag{6}$$

$$\frac{E_{from_i}}{\eta_{di}\left(E_{bsoc_i}\right)} = U \cdot I_d \cdot t \leq U \cdot I_{max} \cdot t \tag{7}$$

- U - battery voltage (V)
- I_c - battery charging current (A)
- I_d - battery discharging current (A)
- t - time interval between consecutive time steps (h) – normally smaller than one hour
- I_{max} - upper limit of allowed current in the system (A)

- Optimization of costs of electric energy production from the solar power plant and from batteries is performed in a way that the solar power plant varies in size and battery varies in capacity in a way that all the year under consideration the household consumption is covered either by the solar power plant or by battery.

$$C = C_{SPP}(A_{SPP}) + C_B(E_{bat\_cap}) \rightarrow minimum \tag{8}$$

- C – costs (EUR),
- C_{SPP} – all costs of solar power plant (EUR),
- A_{SPP} – area of solar power plant (m^2),
- C_B – all costs of battery (EUR),
- E_{bat_cap} - battery capacity (Ah or kWh).

The resolution of the solar power system is 10 m^2. This means that the smallest difference between two sizes of solar power plants is such. The resolution of the battery capacity is 1 kWh. This means that the smallest difference between two sizes of battery capacity is such.

3. Analysis and results

The models include several locations and consecutive years that were evaluated for each. Results from the year 2015 to the year 2018 are presented here for the location Bezigrad. The pairs of figures (Figure 2 and Figure 3 for the year 2015, Figure 4 and Figure 5 for the year 2016, Figure 6 and Figure 7 for the year 2017 and Figure 8 and Figure 9 for the year 2018) show the yearly solar power plant generation and the battery state of charge. The time intervals last 30 minutes, because this is the time resolution of weather data. However, it is possible to change this time intervals to different values according to the needs of the power system or if the weather data time resolution changes. The figures show results for a case with a small solar power plant and large battery in a non-optimal arrangement. It is assumed that the battery can be fully discharged if needed. A comparison of years shows the effect of variability of weather in different years.

At the end of winter, the battery is nearly empty. Most of the year, not counting winter months, the battery is nearly full. The start of evaluation is not January first but rather April first in order that the evaluation is a more realistic one. Namely, the realistic year cannot start in January first with the full battery, because in December with less sunny hours we cannot realistically expect that the battery can be completely full at the beginning of January.

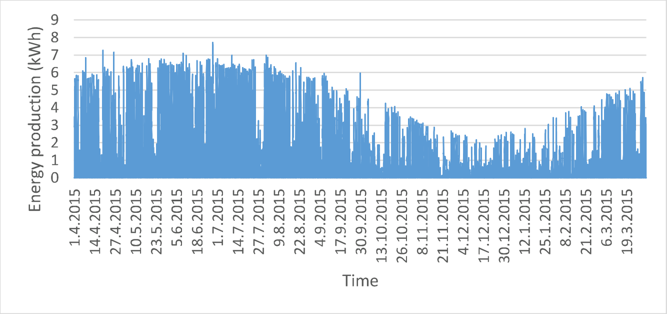

Fig. 2. Solar power plant energy production in the year 2015.

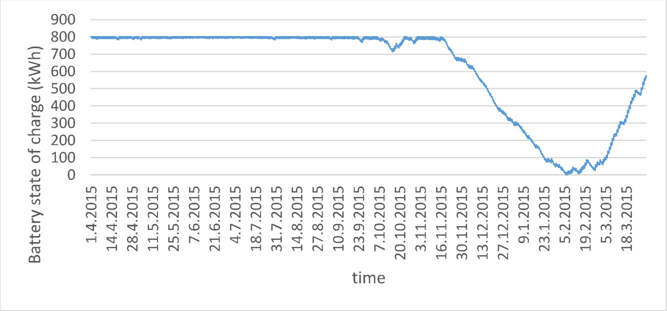

Fig. 3. Battery state of charge in the year 2015 (solar power 70 m^2, battery 800 kWh).

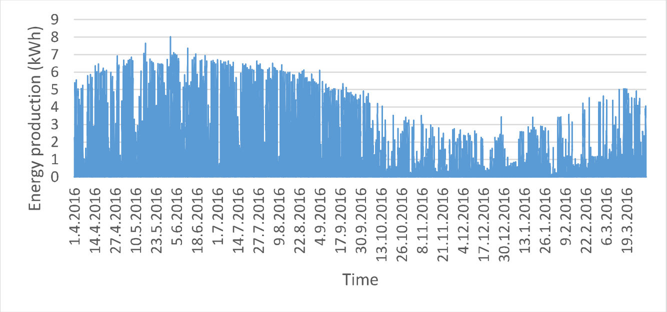

Fig. 4. Solar power plant energy production in the year 2016.

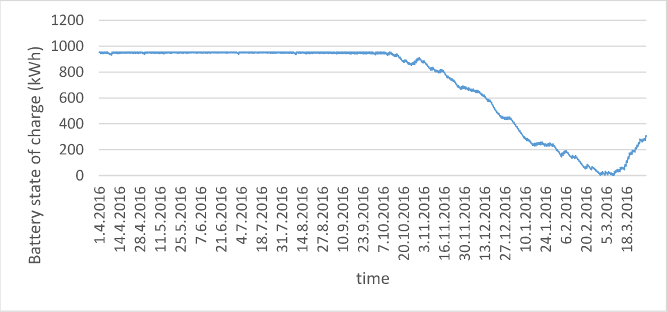

Fig. 5. Battery state of charge in the year 2016 (solar power 70 m2, battery 954 kWh).

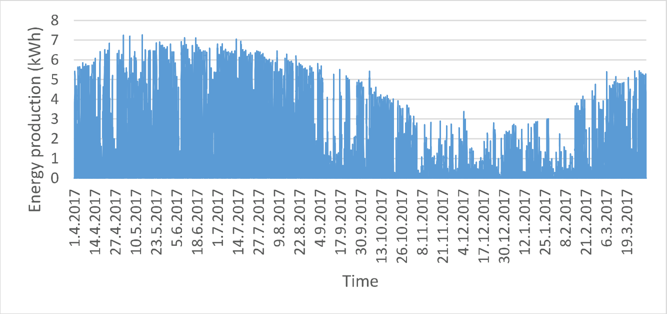

Fig. 6. Solar power plant energy production in the year 2017.

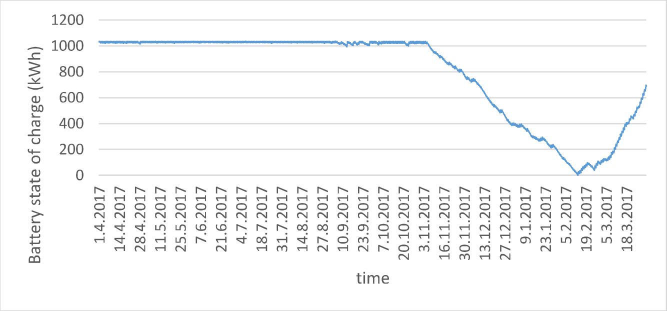

Fig. 7. Battery state of charge in the year 2017 (solar power 70 m2, battery 1034 kWh).

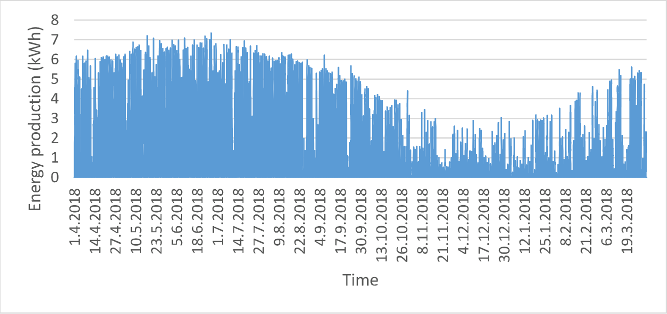

Fig. 8. Solar power plant energy production in the year 2018.

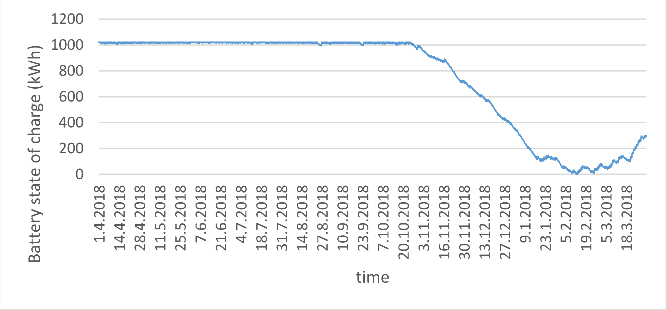

Fig. 9. Battery state of charge in the year 2018 (solar power 70 m^2, battery 1023 kWh).

Figure 10 shows the results for a case with an optimal size of solar power plant and battery for the year 2015. The size of solar power is 150 m^2. The capacity of battery is 116 kWh. It is assumed that the battery is not discharged below 20% of its capacity to extend its lifetime. The larger solar power plant and smaller battery are evaluated compared to cases shown on previous figures.

Figure 11 shows the results for a case with an optimal size of solar power plant and battery for the year 2016. Figure 12 shows the same for the year 2017. Figure 13 shows the same for the year 2018.

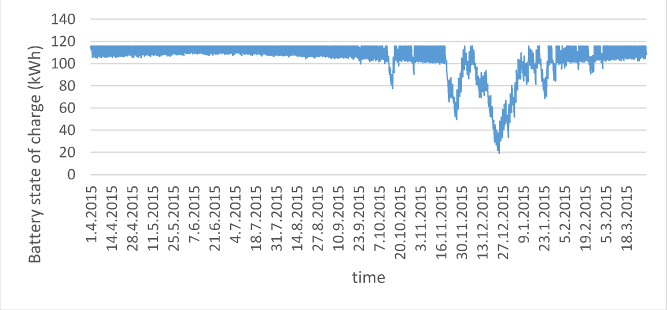

Fig. 10. Battery state of charge in the year 2015 (solar power 150 m^2, battery 116 kWh).

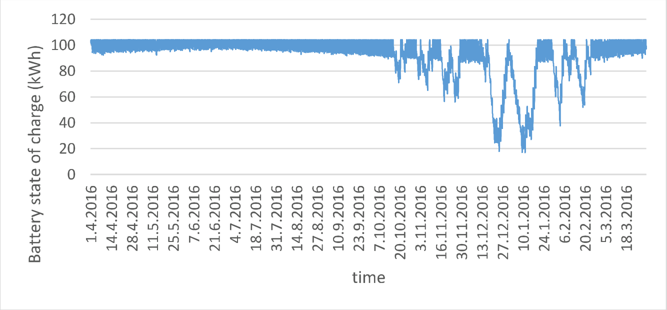

Fig. 11. Battery state of charge in the year 2016 (solar power 150 m^2, battery 104 kWh).

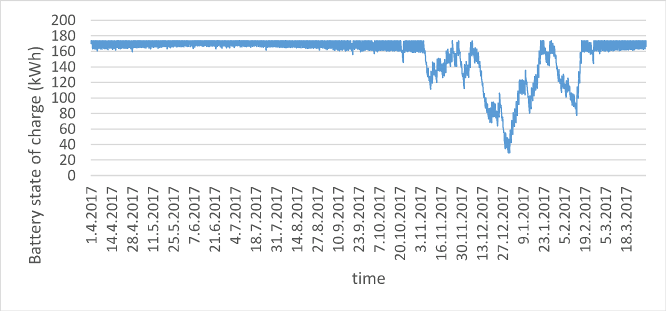

Fig. 12. Battery state of charge in the year 2017 (solar power 150 m^2, battery 173 kWh).

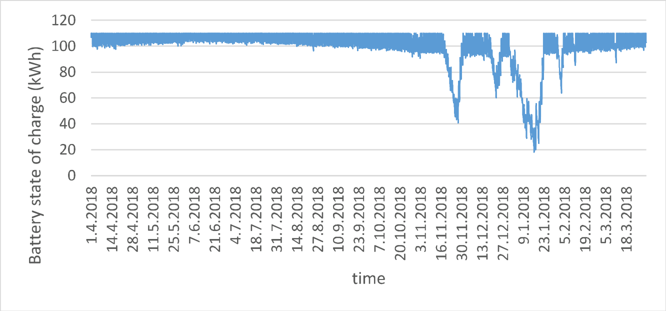

Fig. 13. Battery state of charge in the year 2018 (solar power 150 m^2, battery 110 kWh).

Figure 14 shows the results of total self-sufficient household cost optimization. The costs of self-sufficient power system with the solar power plant and battery, which can be totally discharged, for a household is in the order of 50 000 EUR. The high costs are in larger part the consequence of solar power plant costs and in smaller part the consequence of battery costs. It is assumed that the battery lifetime is as large as solar power plant lifetime, which is an optimistic assumption.

If the algorithm is modified and evaluation is repeated with the condition that battery can never be less empty than 20% of its capacity in order not to decrease its lifetime, the size of the battery needs to increase, and consequently the costs increase in the order of some percents. Costs are relatively larger for combinations of larger battery and smaller solar power, and they are relatively smaller for combinations of smaller battery and larger solar power.

The results related to costs of self-sufficient households are less favorable as it is communicated in public.

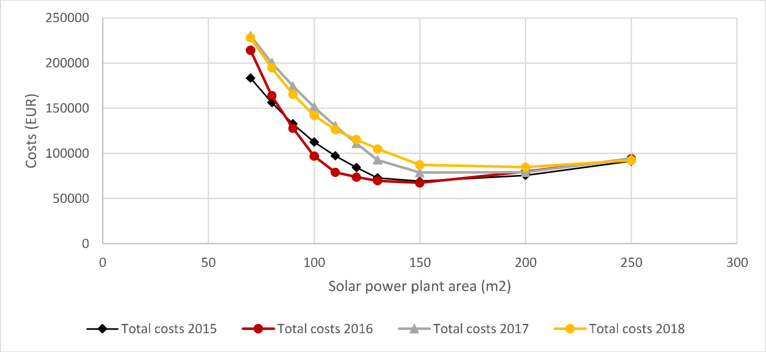

Fig. 14. Household self-sufficient electric power system costs optimization.

4. Conclusions

The costs of reliable self-sufficient household with the solar power plant as the primary source of electric energy and reserve power supply with the battery are optimized. The method is defined and the procedure for optimization is developed. The models are identified and the data for their realistic evaluation is collected. The areas with more sunny hours in a year are identified with smaller costs for the self-sufficient power supply system.

The main issue for the future work is a comparison of reliability and safety of self-sufficient household and a household with power supply from the power system. The issue is not simple, and a large uncertainty is expected. Namely, the new concepts are not related with enough data. For example, the fire hazard of household solar power plants is a relatively new issue, and it is difficult to compare it to a classical household fire hazard. The fire hazard of domestic household battery is another difficult issue. Reliability of self-sufficient household is expected to be smaller than reliability of household connected to the power system. The proof for such a statement can be observed through a larger reliability of more cross-connected systems, which is more the case for transmission system than for distribution system. If a self-sufficient household is not connected to the power system, may face a longer time to restore in the case of specific failure. Those times to restore the power system, which is a mature system and subjected to maintenance by a dedicated organization, are relatively short. They may be longer in the case of failures of self-sufficient household. All those speculations are difficult to prove before enough data is collected.

But the orders of magnitude and the general facts are known. E.g. the most important node in the power system from the point of view of large reliability is a switchyard of a nuclear power plant (Čepin, 2011). Several power lines are connected there and even a gas power plant in an island mode or operation can be connected, if needed, so the reliability of power supply there is very high. Reliability of power supply in this switchyard is for an order of magnitude higher than reliability of transmission power system (Čepin, 2020).

Reliability of the transmission power system, which has a topology of a network with many cross-connections, which means that each point is supplied from several power lines. Reliability of the transmission power system is for an order of magnitude larger than the reliability of the distribution system (Report on Quality of Electric Power Supply in the year 2021).

Reliability of the distribution system, which leads to specific end users, is in many points radial, which means that many specific end users have only one connection to the power supply.

Reliability of specific end user of the power system, which is connected to the power system falls into the reliability category of reliability of distribution system. The distribution system operator assures reliability of the distribution power system and acts immediately and quickly if problems in the power supply appear.

If the end user or household is not connected to the power system and depends only on the self-sufficient power supply will be on its own in the case of failure. The reaction time may be longer and the restore time after elimination of the failure may be longer. The reliability of household connected to the distribution power system may be significantly larger than the reliability of household not connected to the distribution power system.

Therefore, even if the households are going to be self-sufficient, their connection to power system just in case (for better reliability) may represent a significant feature to their larger power supply reliability. This needs to be regulated in the way that the mutual benefits of both parties will be considered. Such regulation is one of the important issues for the future power systems.

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