Off-grid photovoltaics. Estimation of required battery capacity.

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Summary: the work estimates the required capacity of a battery storage for electricity for an individual consumer, assuming that they have photovoltaics only for their own needs. Energy consumption for lighting, multimedia, washing, vacuuming, microwave, refrigerator, hot water and heating was taken into account.

Tags: photovoltaics, off-grid storage, self-sufficient building, energy self-sufficiency, critique of the idea.

1. Introduction.

The required photovoltaic and inverter power and battery storage capacity will be determined in three consecutive cases:
- RTV + household appliance demand,
- RTV + household appliance demand + hot water,
- RTV + household appliance demand + hot water + heating.

The correlation between generation and demand will be examined and its impact on the required storage capacity will be determined.

The feasibility of the above-mentioned projects has been assessed.

2. Literature.

Literature that undertakes scientific criticism of renewable energy sources is practically non-existent. The author recommends his own publication [1] *Hydrogen. Critique of the idea of application* (only in Polish) where he deals with considerations on a macro scale.

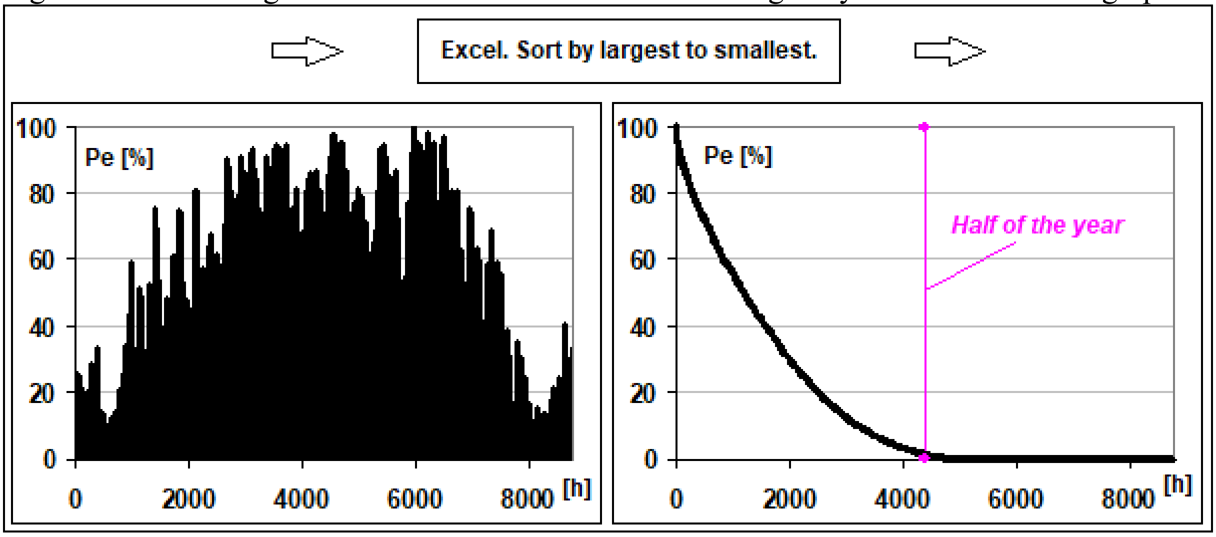
3. Materials and methods of research.

Assumptions.

Generation.
To assess photovoltaic generation, hourly PSE data for 2023 were used. (PSE - Polish network operator). The above data was simply rescaled (reduced) as needed.
The data for the entire country is somehow averaged. In the case of balcony photovoltaics, the situation may be different, e.g. the balcony will only face one way, so its performance will be worse.

Fig. 1 presents photovoltaic generation in Poland for 2023 chronologically and on an ordered graph. To correctly assess the possibilities of photovoltaics, the data should be sorted, for example, from the largest to the smallest. Using chronological graphs can lead to erroneous conclusions: data for 8760 h in a small-sized figure merge and we lose the "special phenomenon" of night. Assessments of photovoltaic possibilities made on chronological graphs on too small a scale, or on monthly bar graphs, give false, overly optimistic results. The true picture of photovoltaic possibilities is shown in Fig. 1 on the right: for half the year it is night, and from the remaining part we have to deduct imperfections resulting from the movement of our day star in the sky and atmospheric disturbances.

Fig. 1. Photovoltaic generation in Poland for 2023 chronologically and on an ordered graph.

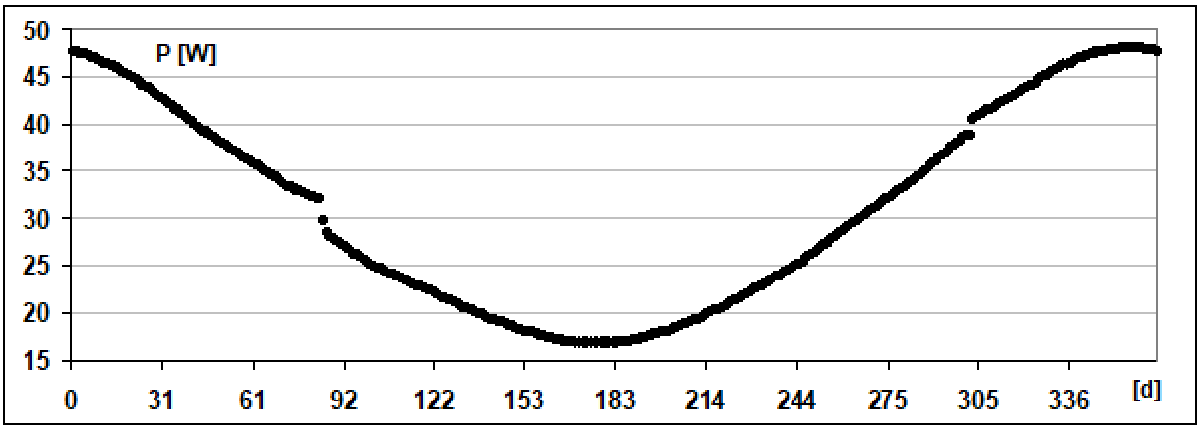


Notes: PSE hourly data.

Demand.
The author did not have a detailed load distribution and created it based on partial measurements and knowledge of the habits of the household members. According to the author, this did not affect the quality of the study, because the energy storage processes here are long-term and minor shifts on an hourly scale do not matter. Certainly, care was taken to distinguish which loads work during the day and which after sunset.

Lighting.
Thanks to the use of LED bulbs, the demand for electrical power for lighting is not large, but it is there and should be taken into account. The smallest demand is of course in the summer. Among other things, the author uses 2 chandeliers with 5 bulbs each and does not save excessively. We are talking about a 3-person family and an apartment with three rooms, a kitchen, a bathroom and a separate toilet. The assumed graph of the demand for power for lighting is presented in Figure 2. The subject figure clearly shows the change time effect on the consumption of electrical energy for lighting. The calculations were made for each hour, while the average daily data is presented.

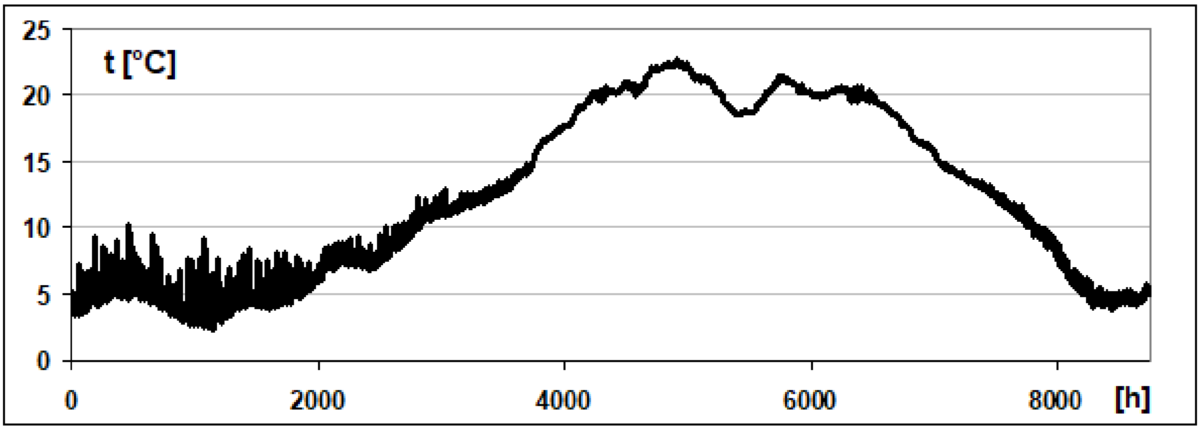
Fig. 2. Demand for power for lighting.



Notes: average daily data.

Temperature of drinking water in the municipal water supply network.
Figure 3 shows the annual temperature profile of water supplied from the municipal water supply network. It is extremely important for our study.

Fig. 3. Annual course of water temperature coming from the municipal water supply network



Notes: based on hourly data, for 2023.

It was assumed that washing would only take place at a temperature of 40 °C. However, with the range of cold water temperatures as in Fig. 3, one wash in summer would require, for example, 0.450 kWh, and in winter 0.764 kWh.

It was assumed that the average consumption of hot water for washing would be 137 l/d. To heat this amount of water from 3 °C to 52 °C, 7.8 kWh of energy is needed, while to heat it from 22 °C to 52 °C, 4.8 kWh of energy is needed.

In the discussed graph, during the winter period, temperature jumps can be observed upwards by several °C. They probably occur when there is a small water intake and cold water is slightly heated by the mere fact of being in the technological channel in the basement of the building, e.g. near the central heating pipes.

The author found it most difficult to consider the issue of hot water. The author did not consider it appropriate to implement heating using a flow-water heater. Such devices require 15-22 kW of power. A boiler with a 1.5 kW electric heater was used. Moreover, in an attempt to positively approach the concept of using photovoltaics, an algorithm was used in which hot water is always heated from 11 a.m. in winter and 10 a.m. in summer until the required water supply is fully heated. (From eleven to full). The proposed concept has its advantages and disadvantages: the thermal insulation of the tanks is not ideal, so rooms with such tanks are always slightly overheated. In the summer, it would require the use of air conditioning, which wasted part of our efforts.

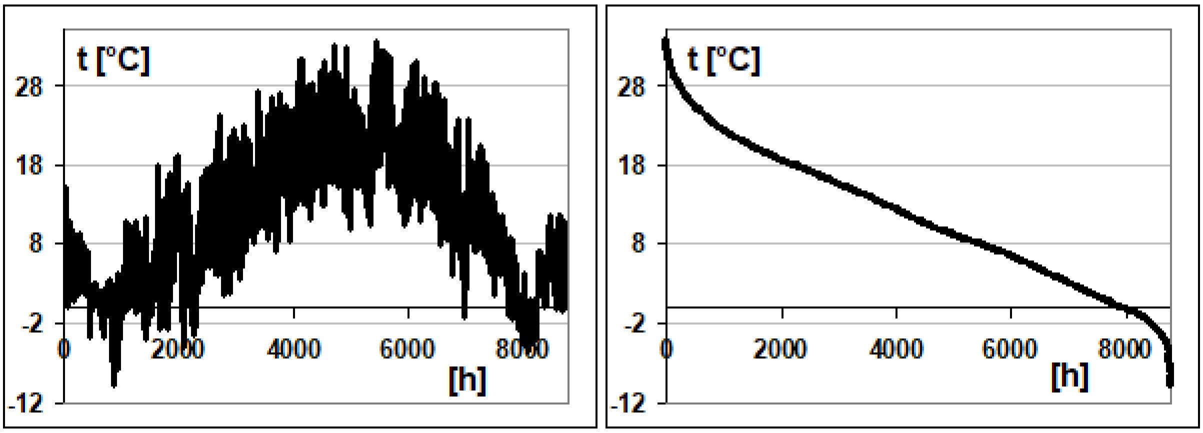
The use of air conditioning is not considered in this study. It was taken into account, however, that the refrigerator should use more energy in the summer.

Electricity consumption for cooking (except for the microwave) is not included. The author uses gas in the kitchen. Please take the author's word for it that in winter, when it is colder in the room and the water temperature is lower, boiling water for tea will also require more energy.

Outside temperature and heat demand.

The assumed outside temperature curve is shown in Fig. 4.

Fig. 4. Assumed outside temperature curve, on a chronological and ordered graph.



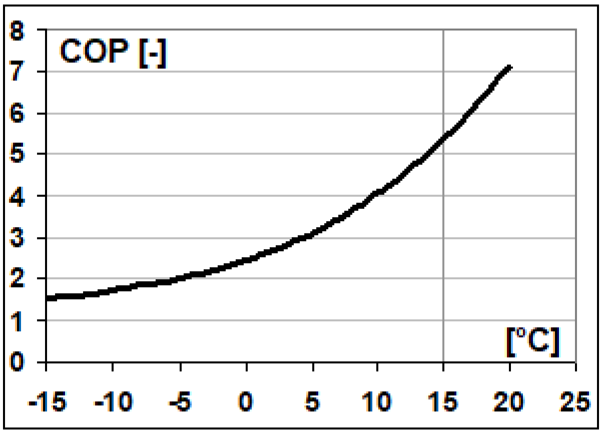
Notes: on hourly data, for the year 2023.

The assumed heat pump efficiency curve is shown in Fig. 5.

Explanations of why we need more energy for heating in winter are unnecessary.

To sum up the assumptions made: all energy consumers (except the refrigerator) create greater demand in winter. Even if not directly (such as lighting), then indirectly – in winter we spend more time in front of the computer, in summer we spend more time, for example, on physical activity.

Fig. 5. Assumed heat pump efficiency curve (COP).



Important details of the computational algorithm.
The following simulation algorithm described below was adopted.
For each of the 8760 h/a:

$$\text{surplus} = \text{generation} - \text{demand}$$

If the surplus is positive, then after a given calculation stepp

$$\text{stock}_{n+1} = \text{stock}_n + \eta_{ES} * \text{surplus}$$

If the surplus is negative, then after a given calculation step

$$\text{stock}_{n+1} = \text{stock}_n + \text{surplus}/\ \eta_{SE},$$

where

η_{ES} - efficiency of energy conversion from electrical to storage form,

η_{SE} - efficiency of energy conversion from storage to electrical form.

Here, $\eta_{ES} = \eta_{SE} =$ **0.96** is assumed

This means that 96% of the surplus will be in the warehouse, and 4% of the losses are attributed to the charging process and half of the storage process. In the case of energy consumption, in order to obtain proper coverage of the demand, more energy must be taken from the warehouse to cover the losses of the discharge process, hence we divide by 0.96. (For more accurate calculations, storage losses should be calculated separately.)

The algorithm provided is universal, the reader can assume for example an electrolyzer efficiency of 65% for the storage charging process and a gas-steam power plant efficiency of 60% burning hydrogen for the storage discharging process. He can also repeat the reasoning for a different configuration of the battery-inverter-PV system.

The research was conducted in such a way that the initial stock must equal the final stock. An academic assumption was made about the admissibility of discharging the warehouse to zero. (In practice, such a method of management would be unacceptable).

The correlation coefficients was determined using the Excel algorithm.

4. Results and discussion.

4.1.1. Demand for consumer RTV and household appliances, calculation results for average annual demand.

In the case of an individual recipient, a load that is constant throughout the year does not exist. Here, an academic case is considered in order to demonstrate the impact of photovoltaic generation variability on the required capacity of the energy storage. However, on a national scale, where due to the non-simultaneity of individual loads, the demand is averaged, the study carried out makes the most sense.

Please note figures 6and 7 below.

Fig.6. Required energy storage reserve to achieve full energy self-sufficiency assuming constant demand.

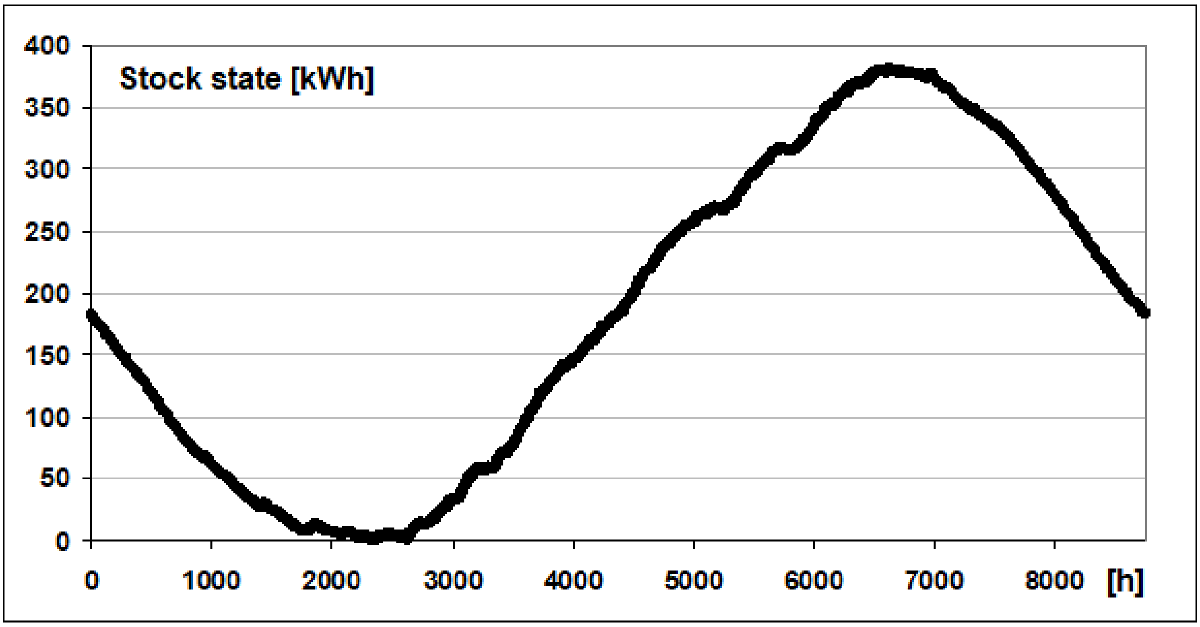
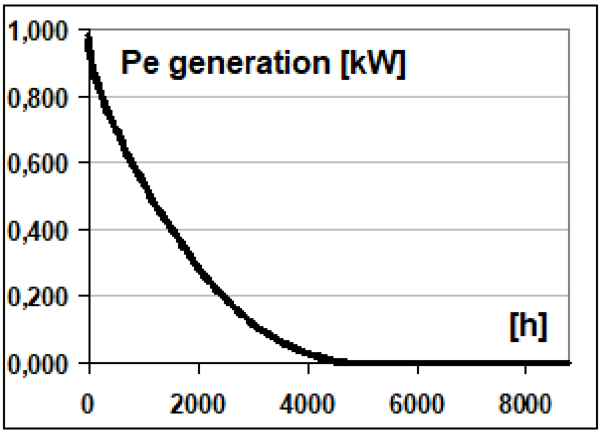
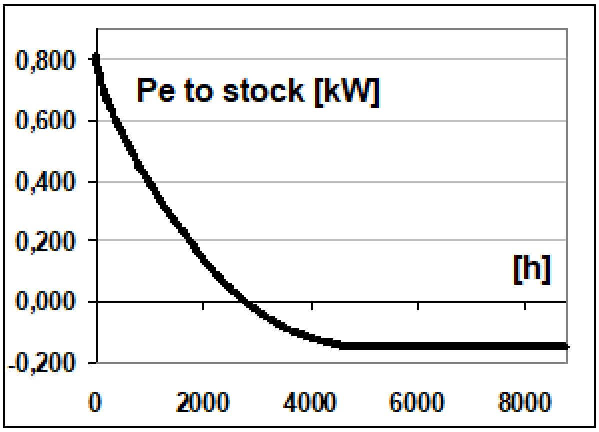


Fig. 7. Left: annual, ordered graph of PV generation at average demand, as for RTV+ household appliance
Fig. 7. Right: annual, ordered graph of power "to storage".





Notes: Negative power = from storage power = consumption.

Let the reader compare for himself the average demand power of 0.152 kW with the installed source power of 0.981 kW.

The remaining data are presented in Table 1. The multiples of installed power were calculated in relation to the average demand.

Table.1. Characteristic values for the task of energy self-sufficiency achieved using photovoltaics and battery storage, with average demand, such as RTV and household appliances.

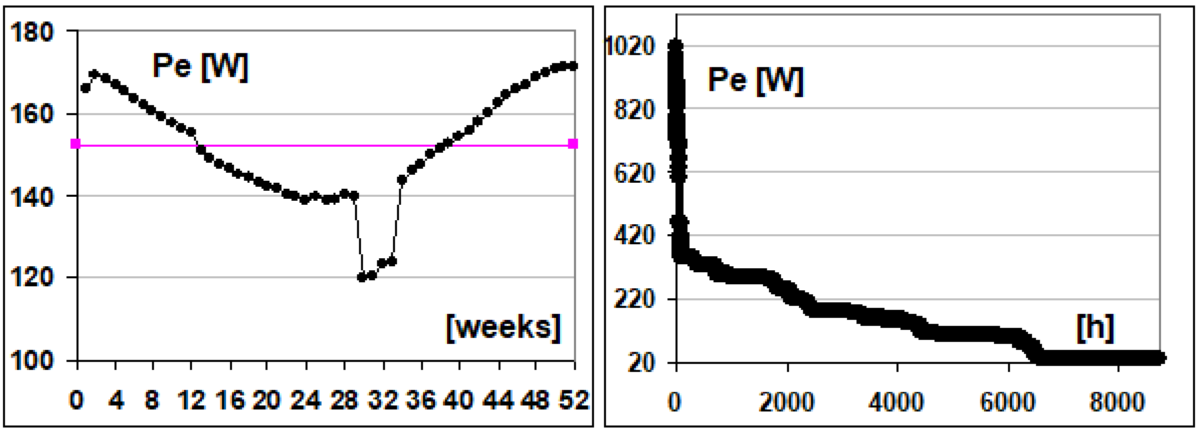
	Max kW	Min kW	Average kW	Annually kWh
Generation PV	0,981	0,000	0,160	1399
Consumption			0,152	1331
To stock	0,829	0,000		868
From stock	0,152	0,000		800
Direct consumption				531
Stock state	Max kWh	Min kWh	Max h av.cons.	Min h av.cons.
	382	0	2 512	0
Stock state	Initial value kWh		Final value kWh	
	182		182	
Source power multiple			6,46	
Charging installation power multiple			5,46	
Discharge instalation power multiple			1,00	

Noteworthy are the required storage capacity of 2512 h and the need to install power installations with a capacity of 646+546=1192% in relation to the average demand.

4.1.2. Demand for RTV + household appliance, calculation results based on hourly data.

A load chart made on hourly data would be illegible due to the small print scale, therefore Figure 8 below shows average weekly loads. On the other hand, an ordered annual chart is presented on hourly data.

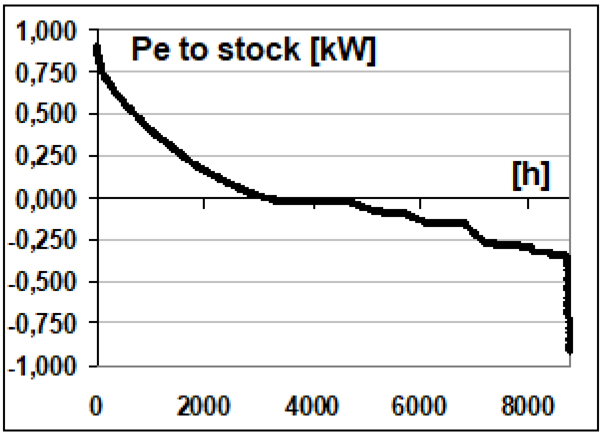
Fig.8. On the left: average weekly loads for RTV + household appliance consumption.
Fig.8. On the right: annual, ordered load graph based on hourly data.



The following are worth noting: summer vacation break, and short-term loads significantly above average. The latter occur when we wash, clean and cook at the same time. This reminds us of the need to significantly oversize home installations. Our average consumption is much lower, but we do not want, for example, simultaneous switching on of the washing machine and microwave to end in a blackout!

So, if our connection to the national grid has so far had a capacity of 5 kW, then if we are serious about energy self-sufficiency, the capacity of the installation drawing from the storage (inverter) must also be 5 kW. (Despite the average demand of 0.152 kW). The proportion of 5000/152=33 undoubtedly means oversizing the installation, but it results from the nature of things and in the first case we are reconciled with it. In the case of multiplying installations, the error of oversizing the property repeats itself.

Fig. 9. Annual, ordered graph of the capacity "for storage" with the demand for RTV + AGD, on hourly data.



The ordered graph of power "in and out" of the storage shown in Fig. 9 was drawn up on hourly data. However, it is noted that a user who had, for example, a 1 kW PV panel and a 1 kW inverter would not actually be able to achieve the task of energy self-sufficiency without the help of an external network, after all, their momentary demand may reach 5 kW.

It is natural that failures occur. Therefore, despite energy self-sufficiency achieved with PV panels and batteries, the user would have to maintain a reserve connection with the same power as before, or have a spare generator.

The remaining results are presented in Table 2.

Table 2. Characteristic values for the task of energy self-sufficiency achieved using photovoltaics and battery storage with RTV + household appliance demand on hourly data.

	Max kW	Min kW	Average kW	Annually kWh
Generation PV	0,985	0,000	0,160	1404
Consumption	1,012	0,028	0,152	1331
To stock	0,910	0,000		930
From stock	0,917	0,000		857
Direct consumption				474
Stock state	Max kWh	Min kWh	Max h av.cons.	Min h av.cons.
	432	0	2 846	0
Stock state	Initial value kWh		Final value kWh	
	203		203	
Source power multiple			6,48	
Charging installation power multiple			5,99	
Discharge instalation power multiple			6,04	

Ultimately, for an average demand of 0.152 kW, a user dreaming of energy self-sufficiency would maintain a 5 kW backup connection, a 5 kW inverter, a 1 kW source and a 432 kWh battery storage. Four installations would be needed to complete one task. A 900 W balcony PV set and an 800 W inverter without external grid support would not even power a washing machine, despite the parameters theoretically correctly corresponding to the average demand.

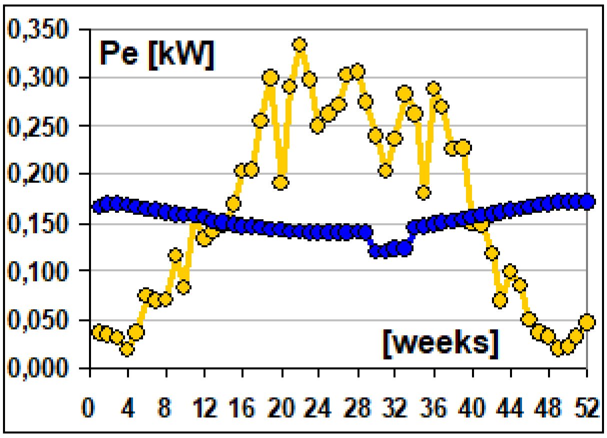
To generalize our considerations, we can say that the use of photovoltaics, some type of storage loading device and storage unloading device (because they do not have to be the same devices) would require 648+599+604=1851% of the installation power for a demand of 100%.

This does not seem to be a prudent way of managing assets.

It is recalled that in this chapter we are considering a system with the demand of "only RTV+ household appliance ". All calculated correlation coefficients between PV generation and demand are negative and reached the values:
- 0.032 for hourly data,
- 0.420 for average daily data,
- 0.849 for weekly averages.

It is recommended to pay attention to Fig. 10, in yellow color generation, in blue demand.

Fig.10. PV generation and demand for RTV+ household appliance.



Notes: Based on weekly averaged data.

4.2.1. Demand for RTV and household appliances + hot water, calculation results for average annual demand.

Table 3. Characteristic values for the task of energy self-sufficiency realized with photovoltaics and battery storage with average demand, such as RTV and household appliances + hot water.

	Max kW	Min kW	Average kW	Annually kWh
Generation PV	3,056	0,000	0,497	4357
Consumption			0,473	4145
To stock	2,583	0,000		2703
From stock	0,473	0,000		2491
Direct consumption				1655
Stock state	Max kWh	Min kWh	Max h av.cons.	Min
	1189	0	2 512	0
Stock state	Initial value kWh		Final value kWh	
	567		567	

The calculation results are presented in Table 3. To cover the average demand of RTV and household appliances + hot water, this family would need a 3 kW photovoltaic system, a 2.6 kW storage charging system, and a storage with capacity 1189 kWh.

4.2.2. Demand for RTV and household appliances + hot water, calculation results based on hourly data.

Table 4. Characteristic values for the task of energy self-sufficiency achieved using photovoltaics and battery storage for RTV and household appliances + hot water demand

based on hourly data.

	Max kW	Min kW	Average kW	Annually kWh
Generation PV	3,019	0,000	0,491	4304
Consumption	2,485	0,028	0,473	4145
To stock	2,734	0,000		2020
From stock	2,312	0,000		1862
Direct consumption				2284
Stock state	Max kWh	Min kWh	Max h av.cons.	Min
	1404	0	2 966	0
Stock state	Initial value kWh		Final value kWh	
	721		721	
Source power multiple			6,38	
Charging installation power multiple			5,78	
Discharge instalation power multiple			4,88	

After taking into account the variability of demand, the required storage capacity increases from 1189 kWh to 1404 kWh, i.e. a storage with a capacity of 2966 h would be needed, counting in relation to the average demand of 0.473 kW.

It is recalled that in this chapter we are considering a system with the demand of "RTV and AGD + hot water". The correlation coefficient between PV generation and demand reached the following values:
+ 0.538 for hourly data,
- 0.645 for average daily data,
- 0.741 for weekly averages.

It is recalled that the author proposed charging the hot water tank only during hours of potentially high availability of photovoltaics. However, in the case of long-term storage, the negative coefficients given above are decisive.

4.3.1. Demand for RTV and household appliances + hot water + heating, calculation results for average annual demand.

The results are presented in Table 5.

Table 5. Characteristic values for the task of energy self-sufficiency realized with the help of photovoltaics and battery storage with average demand, such as RTV and household appliances + hot water + heating.

	Max kW	Min kW	Average kW	Annually kWh
Generation PV	7,402	0,000	1,205	10553
Consumption			1,146	10040
To stock	6,255	0,000		6545
From stock	1,146	0,000		6032
Direct consumption				4007
Stock state	Max	Min	Max	Min

	kWh	kWh	h av.cons.	
	2879	0	2 512	0
Stock state	Initial value kWh		Final value kWh	
	1373		1373	

4.3.2. Demand for RTV and AGD + hot water + heating, calculation results based on hourly data.

The results are presented in Table 6.

Table 6. Characteristic values for the task of energy self-sufficiency implemented using photovoltaics and battery storage for demand for RTV and household appliances + hot water + heating based on hourly data.

	Max kW	Min kW	Average kW	Annually kWh
Generation PV	7,431	0,000	1,209	10595
Consumption	5,407	0,028	1,146	10040
To stock	6,788	0,000		7087
From stock	4,924	0,000		6531
Direct consumption				3508
Stock state	Max kWh	Min kWh	Max h av.cons.	Min
	5661	0	4 939	0
Stock state	Initial value kWh		Final value kWh	
	3227		3227	
Source power multiple			6,48	
Charging installation power multiple			5,92	
Discharge instalation power multiple			4,30	

The high initial value of the storage reserve is worth noting, amounting to 3227 kWh, i.e. 0.57 of the entire storage capacity. During the start-up period of the installation, such a storage capacity would have to be obtained in some way.

The demand for thermal power in the tested system was Qt=16399 kWh/a
The demand for electrical power for heat production was Qe=5894 kWh/a.
The courses of Qt and Pe on hourly data, on the chronological and ordered graphs are presented in Fig. 11.

Fig.11. Heat demand and electrical power for the heat pump in chronological and ordered graphs.

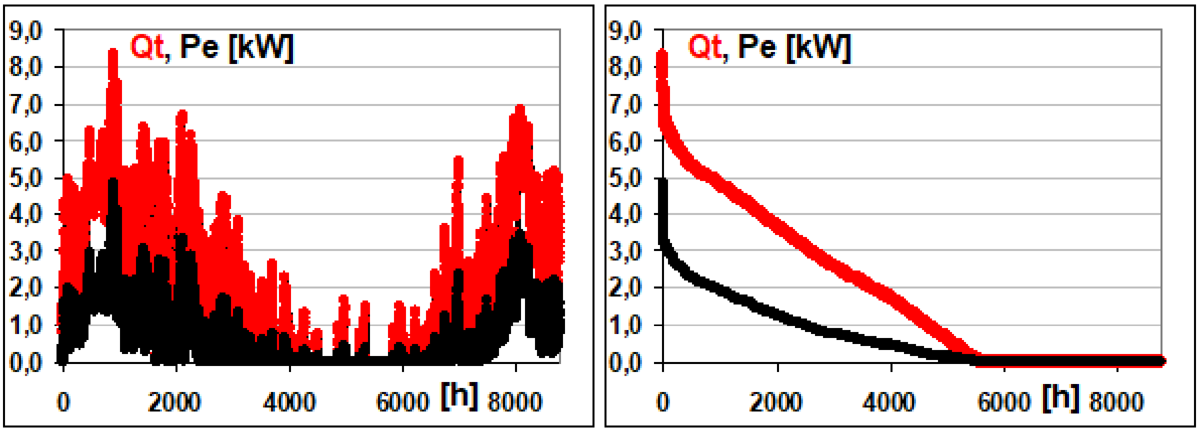


Fig.12. On the left, annual, ordered graph of PV generation for RTV and household appliances + hot water + heating load. On the right, graph of power "to storage".

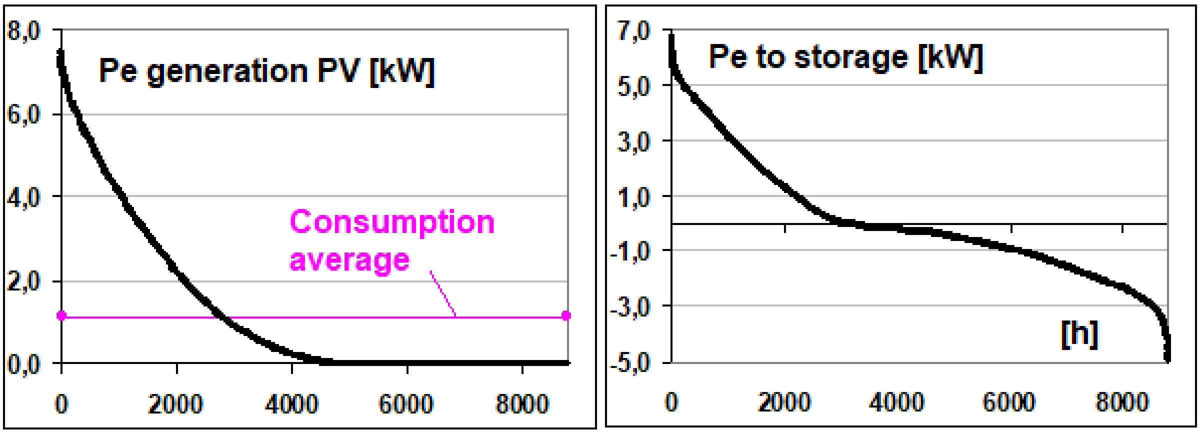
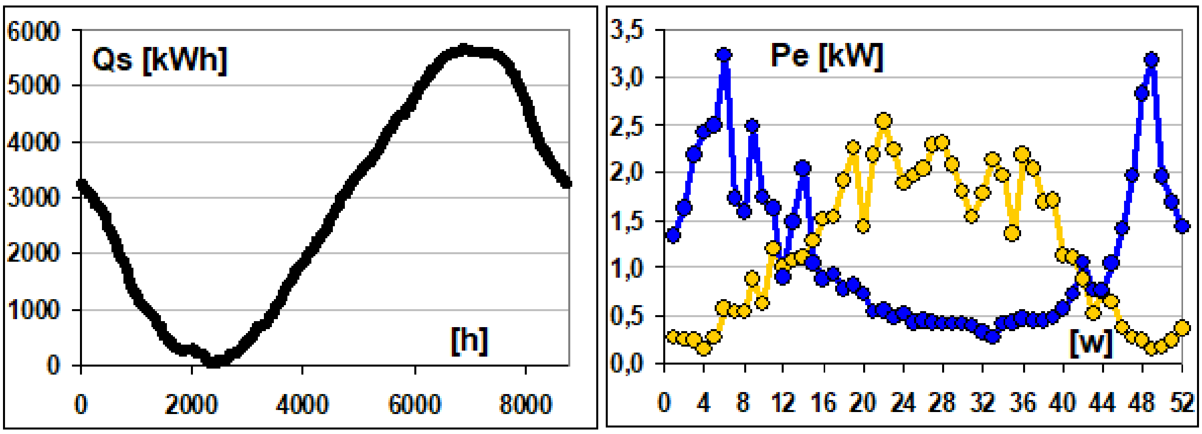


Fig.13. On the left, the course of the storage reserve necessary to cover the load of RTV and household appliances + hot water + heating using photovoltaics.
On the right, the chronological courses of demand (blue) and generation (yellow) averaged over weeks.



It is recalled that in this chapter we are considering a system with the demand of RTV and household appliances + hot water + heating. The correlation coefficient between PV generation and demand reached the following values:

+ 0.033 for hourly data,
- 0.672 for average daily data,
- 0.785 for weekly averages.

So: achieving full energy self-sufficiency using photovoltaics and battery storage for the demand for RTV and household appliances + hot water + heating for one 3-person family would require a battery with a capacity of 5661 kWh, or in other words 4939 h for an average demand of 1.146 kW. Or in other words, it would require a battery with a capacity of over half a year, which is much more than the 3-4 hour capacities currently offered on the market.

5. Conclusions.

Photovoltaic generation is highly variable due to the Earth's rotation around its own axis and its deviation from the axis of orbital rotation. For these reasons alone, balancing supply and demand requires the use of a storage with a capacity of approximately 2500 h of average demand. After taking into account that energy demand is also variable and negatively correlated with generation, the required storage capacities increase:
- from 2512 h to 2846 h, for RTV and household appliances demand,
- from 2512 h to 2966 h, after taking into account hot water heated by storage tanks,
- from 2512 h to 4939 h, after taking into account energy for heating.

The battery needed to achieve energy self-sufficiency for one family would have to have a capacity of 5661 kWh. The capacity of one battery for a Tesla S60 car is 58.5 kWh. Therefore, 97 Tesla batteries would be needed for one family. Apart from the costs, there is no room for such energy storage in our blocks of flats.

We notice that the energy needed for heating alone Qt=16399 kWh/a is equivalent to 3.1 tons of coal 25 MJ/kg for a boiler with a poor efficiency of 0.75. The energy demand for the heat pump is about 3x smaller (we notice this progress), so we would have to keep not three tons, but the equivalent of one ton of coal in reserve. We used to store such amounts of coal in our basements. However, a set of almost 100 Tesla batteries for one apartment would require more space, especially since in addition to the batteries, the required equipment would be necessary.

Looking at both technical possibilities and prices, the intention to achieve energy self-sufficiency using photovoltaics and battery storage is unrealistic. The author does not believe that a reasonable solution to the problem in question will be found thanks to scientific progress. Regardless of the technology used, an electricity storage with a capacity of half a year will always have to be of a sufficiently large size and will therefore always be more expensive. Difficulties resulting from the nature of things cannot be solved by scientific and technical progress: high multiples of device power in relation to demand. This will always be followed by unnecessarily high costs of assets needed to achieve energy self-sufficiency. This is not how an economy is organized, in which we care about the best possible degree of use of assets and capital. In the case of excess production capacity above demand, arrangement bankruptcy is usually declared, and the Administrator begins the process of healing the company by selling off unnecessary assets. In the case of renewable energy sources, oversizing installed capacity, i.e. "planned mismanagement", is the goal.

The photovoltaic balance (relative to demand) is negative for half a year.

Usually, renewable energy lobbyists, after drawing attention to the above, respond almost automatically that "yes, but fortunately in the winter half of the year we have wind generation". Yes, that is true. But there was a demand for self-sufficiency by ordering PV panels to be hung on every house, and this is what this study was about. Using wind farms located by the sea is no longer a task to be carried out independently, it requires the operation of the entire energy installation system with appropriate security. So why was an order issued that is unrealistic? EU citizens were treated like capital donors? They will pay twice, for the first time for the purchase of PV installations that are oversized and unable to perform the task entrusted to them, and they will pay again for their system security.

Incidentally, the mutual complementation of wind turbines and photovoltaics, although it reduces the demand for storage capacity from about half a year to 15-30 days, also does not allow for hope for the success of RES. In our latitude, the key to the RES + storage concept is surviving for about 3-5 weeks without wind and sun in the winter and this is the required capacity of electricity storage.

Currently, in Poland, the capacity of all storage facilities is 6.47 GWh.

For a typical winter demand of 22 GW, this is enough capacity for 18 minutes of work - this is very far from the required capacity of 15 days, and even further from the capacity of half a year.

Is oversizing the power of the panels beyond average needs a way to mitigate the described defect? The installation was supposed to operate independently, without the need to exchange energy with an external grid, so either we admit that this grid is needed, or we admit that our oversized photovoltaics would have to be unnecessarily switched off. And exporting energy to the external grid ultimately means repeating the same problems on a macro scale.

A bricklayer builds houses, a tailor sews clothes...

In Poland, we have an excellent nursery rhyme in which the author (Julian Tuwim) praises the benefits of the division of labor. Why do RES lobbyists deny the basic achievements of humanity and everyone should ensure their own energy production and storage?
Such behavior only fuels consumerism and as such does not serve "saving the climate" at all.

The assumption was to empty the warehouse to zero, because that is the only way to make comparable calculations. In reality, the warehouse stock must be larger, because we are not able to predict whether, for example, "February 20 at 8:00 PM will be the last time the highest consumption will occur, and then it will only get better." On a national scale, a government that allowed energy, food, etc. stores to be depleted to zero would be lynched.

Fig. 14. Example of the process of preparing winter warehouse stocks.

The squirrel, contrary to popular belief, does not have sclerosis and does not forget where to store nuts. The squirrel prepares appropriately large supplies because it does not know whether the winter will be severe or mild. Therefore, the author's findings should be treated as minimal, in reality the storage capacity would have to be larger.

Finally, we ask the question whether such a mathematical apparatus was necessary to determine what we could have determined with a simple logical path? After all, each of us should know from life experience that there is night for half the year and therefore the amount of supplies for winter must be sufficiently large…

Ended 19.11.2024