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Technology Optimisation of Hybrid PV Systems for Covering Energy Needs of Emergency Shelters for Ukrainian War Refugees

Milan Belik[1, 2*], *Olena* Rubanenko[3,4,5]

[1] Faculty of electrical engineering University of West Bohemia, 301 00 Pilsen, Czech Republic
[2] Česká fotovoltaická asociace, z. s. , 301 00 Pilsen, Czech Republic
[3] RICE, Faculty of Electrical Engineering University of West Bohemia, 301 00 Pilsen, Czech Republic
[4] Department of power plants and system, Vinnytsia National Technical University, Vinnytsia, 21009, Ukraine
[5] Department of Wind Power, Institute of Renewable Energy of the National Academy of Sciences of Ukraine, Kyiv, 02094, Ukraine

Abstract. Hybrid photovoltaic systems have become a common solution for decreasing energy consumption for specific objects and customers at present time. The efficiency of the entire system depends strongly also on the technology of the used battery inverter. In general, DC-coupled inverters are recognized to be more energy efficient. Surprisingly, in some specific cases, AC-coupled systems can offer better results. Ukraine escalates the problem with internal migration, that can be solved just through constructing new communities of emergency shelters. Integrating these units into Ukrainian overloaded and damaged distribution grids must be projected very precisely to limit not just power consumption but also power injection. Particular savings can be reached with the proper application of AC or DC-coupled systems. This article describes that phenomenon presented on specific real cases defined through own consumption profile, battery storage system management, climate conditions, and PV system design. The presented results show that the proper choice of battery inverter technology can save interesting amount of energy produced from the installed PV system. The AC coupled system can offer not just higher flexibility and modularity, but also higher energy efficiency of the hybrid system, lower grid feed-in.

1 Introduction

Modern photovoltaic systems are often designed as hybrid to increase energy efficiency [1]. The PV inverter is somehow connected to the battery storage, but does not communicate with the rest of the system.

* Corresponding author: olenarubanenko@ukr.ne

The classic solution using AC coupling offers considerable variability in layout and choice of components, but in principle means higher losses due to multiple DC-AC and AC-DC conversion. In the case of common current inverters (e.g. Fronius SymoHybrid), this efficiency is around 97% when used as a photovoltaic inverter and 96% as a battery inverter.

In contrast, DC coupling (hybrid inverter) offers higher overall efficiency, but is considerably limited in terms of layout, since the inverter with the battery is one compact unit. The layout of the building, the load-bearing capacity of the floors, fire and safety regulations may in specific cases exclude this theoretically better solution. However, it is a little-known fact that DC coupling systems, although they have a higher conversion efficiency, can result in lower or worse time utilization of solar energy [2-4].

The ongoing Russian aggression in Ukraine has caused and is still causing a massive migration of the Ukrainian population from the most affected areas to safer, more western parts of the country. This brings with it large and long-term overcrowding problems that can only be solved by rapidly building communities or neighborhoods made up of simple, cheap, but energy-efficient buildings.

Within the framework of several projects we dealt with, it was verified that these buildings can have relatively low energy requirements, offer a sufficient standard of living, but cannot be completely energy self-sufficient even as a community unit [5, 6].

Connecting such communities, consisting of hundreds or thousands of objects, to the overloaded Ukrainian distribution networks, which were already in an unsatisfactory state before the war and are currently being destroyed by targeted missile attacks, requires a perfect balancing of consumption and production at the community level. The right choice of battery storage connection technology can have a significant impact.

Simulations have shown that a suitable combination of AC coupling and DC coupling systems in one community can mean energy savings in the order of units of percent and even make the resulting consumption diagram more efficient. The following text will clarify the different behavior of both variants of the hybrid system under relevant conditions [7-9].

Emergency shelters proposed for the war refugees can be partially supplied from various types of RES to decrease the dependence and influence on the supply network. This aspect is crucial above all in the war conditions when the distribution and transsmition grids suffer with frequent attacks leading to the decrease of its capacity and usability. Beside of that, the conditions of Ukrainian supply grids were challenging already before the war, because almost all equipment has become obsolete and almost at the end of its service life. From these reasons, newly connected shelters (better said shelter quarters or communities) should limit their influence on supply network [10].

2 Hybrid PV System In The Application Of Emergency Housing For War Refugees

Both systems offer a slightly different approach to the use of photovoltaic energy and a different strategy for its accumulation. This is related to different losses and their different time course. Although batteries of the LiFePo or LiNiMnCo type are most often used in hybrid PV systems today, gel lead batteries (Moll 3-OPzV) were chosen for the purposes of the application of cheap emergency housing for war refugees. Another important feature of lead-acid batteries for this application is less sensitivity to extreme temperatures (in this case, especially low) [11-13]. Fig. 1 shows the discharge characteristics of the used battery and its cycle life.

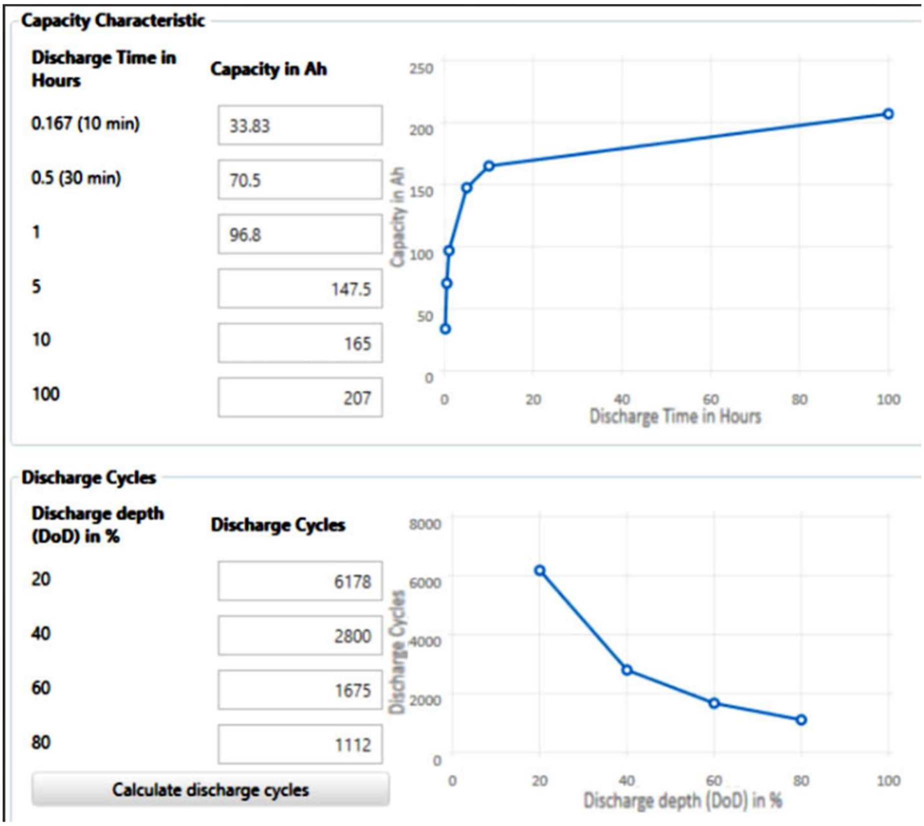

Fig. 1. Discharging characterisitc of MOL 3-OPzV (PV*SOL Premium 2023)

In order to exclude the deviation caused by the different characteristics of the technologies of different manufacturers, in both cases (AC and DC coupling) Fronius SymoHybrid inverters were used [14], which actually offers all these possibilities. Fig. 2 shows the characteristics of the sample inverter.

The selected inverter can be used as a purely PV inverter connected to an existing battery system with its own battery management using AC coupling, further as a purely battery inverter (BMS) connected to an existing PV system and, of course, as a separate hybrid inverter combining photovoltaic and battery inverters in one unit. Fig. 3 presents the general model of such device.

Control of standard inverter means changing the width of the pulse in reference to the amount of time that the power is on. It must be compared to the amount of time that the power is off. This control mechanism refers to the fact that the size of the pulse can be easily adjusted to control the power we want to supply to the device. This model is used either for PV inverter or for battery inverter.

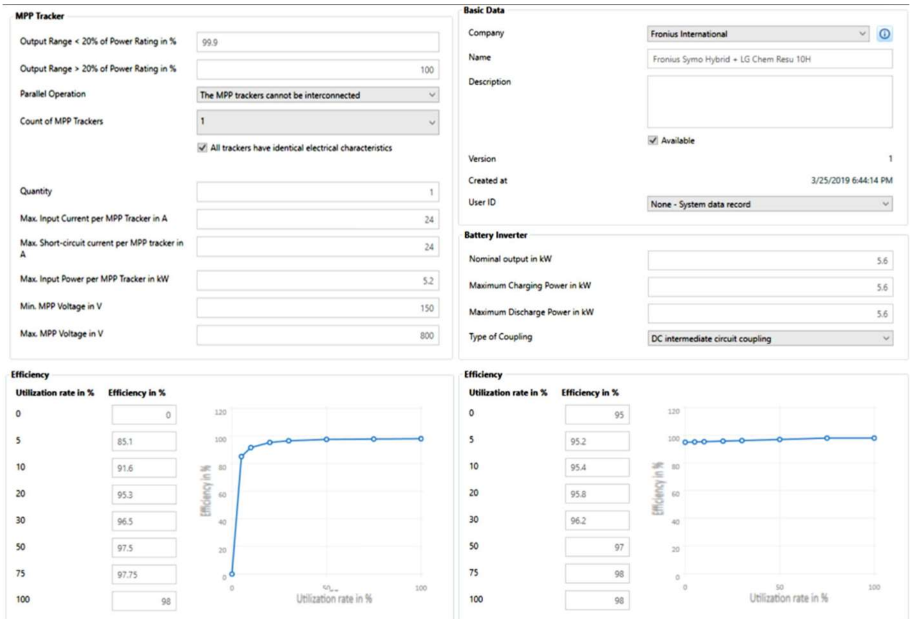

Fig. 2. Characteristics of inverter Fronius SymoHybrid (PV*SOL Premium 2023)

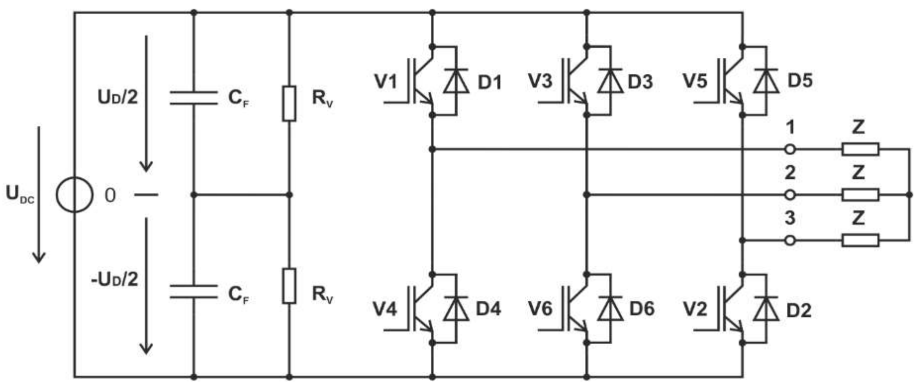

Fig. 3. Topology of 3 phase inverter

The basic equation for setting the duty cycle, which is the ratio of the pulse width to the period of the PWM signal, is 1.

$$Duty\ Cycle = ((Pulse\ Width)/Period)\cdot 100\% \qquad (1)$$

Peak-to-peak output voltage for necessary first output RC filter can be expressed as the function of PWM frequency and RC time constant 2.

$$V_{ripple} = \frac{e^{\frac{-d}{f_{PWM}RC}} \cdot \left(e^{\frac{1}{f_{PWM}RC}} - e^{\frac{d}{f_{PWM}RC}}\right) \cdot \left(1 - e^{\frac{d}{f_{PWM}RC}}\right)}{1 - e^{\frac{1}{f_{PWM}RC}}} \cdot V_{+} \qquad (2)$$

where d means the duty cycle (0..1). The ripple has largest value for d = 0.5, and fPWM represents the PWM frequency.
PWM frequency is limited by cut-of frequency. It can be calculated from 3 for Sallen-Key filter.

$$f_c = \frac{1}{2\pi\sqrt{R1\ R2\ C1\ C2}} \tag{3}$$

Fig. 4 demonstrates the real shape of the sinusoid (1 phase) for basic and advanced model of the inverter.

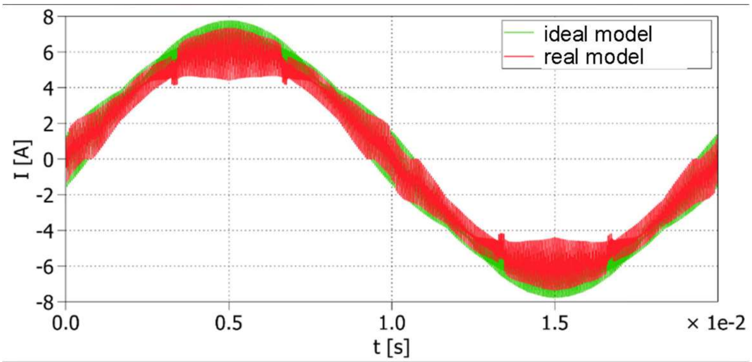

Fig. 4. Inverter current (1 phase) – simulation of the model inverter

Fig. 5 summarizes main parameters of the sample inverter that is used for simulation of AC and DC coupled PV inverter powering 1 single refugee shelter with battery storage system connected to supply grid.

Fig. 6 represents typical topology of DC coupled system using internal DC circuit. Modern pure hybrid inverters are coupled according to this scheme. This solution offers in general the best efficiency.

Fig. 7 demonstrates the difference to the second topology of DC coupled systems. This system couples battery inverter in one string of the PV generator. This system couples battery inverter in one string of the PV generator. This is rather unusual solution but has several advantages such as flexible topology of the PV array and MMP trackers of the inverter.

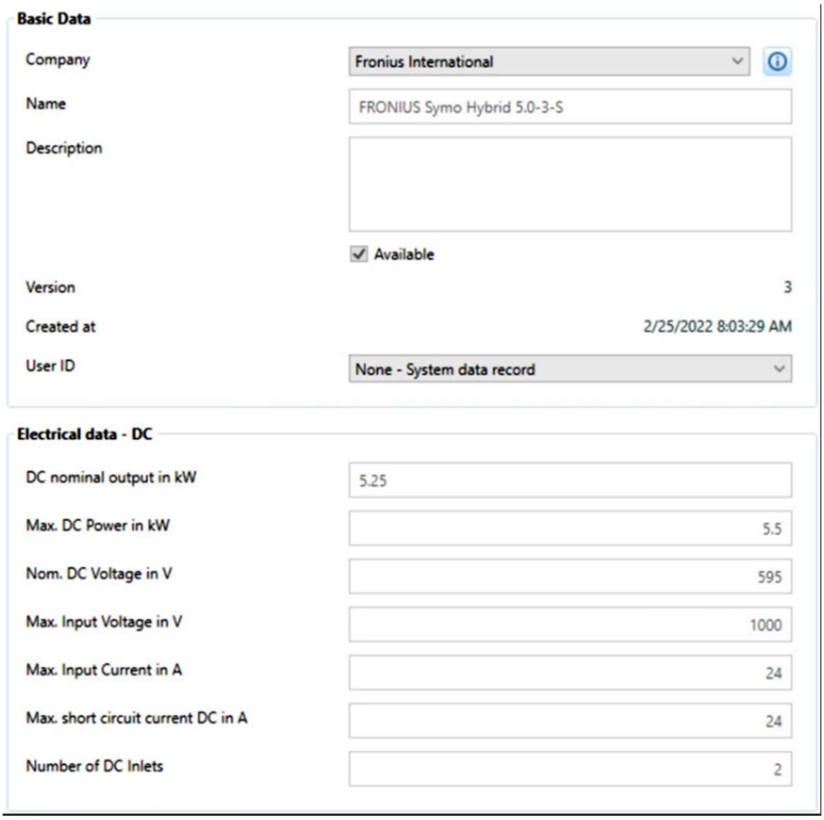

Fig. 5. Parameters of inverter Fronius SymoHybrid (PV*SOL Premium 2023)

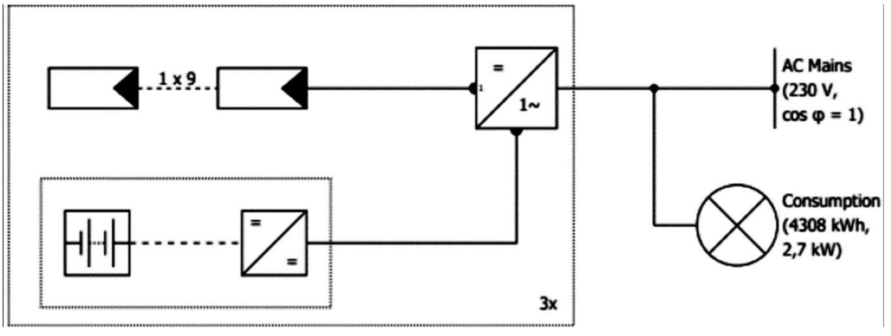

Fig. 6. DC coupled system - internal circuit (PV*SOL Premium 2023)

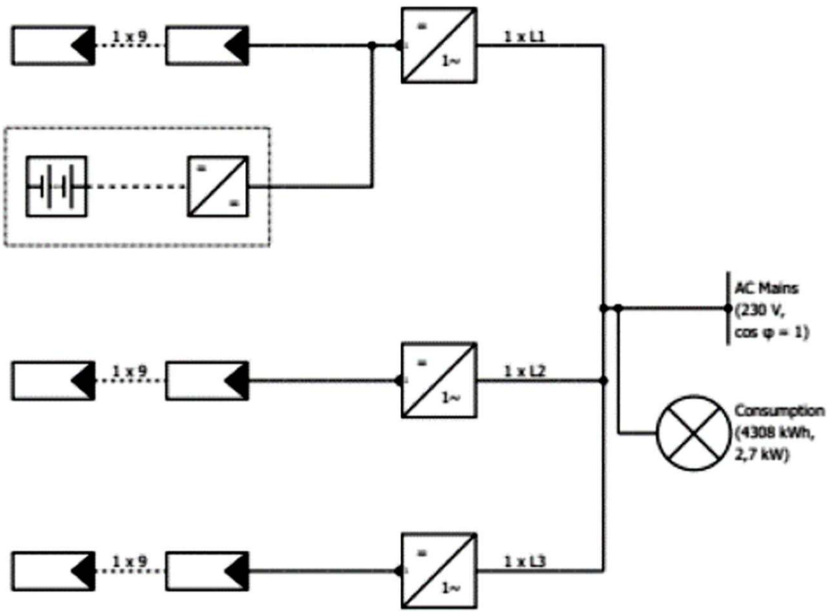

Fig. 7. DC coupled system - generator circuit (PV*SOL Premium 2023)

The last possible connection of the inverter is presented in Fig. 8. It is the most simple AC coupled system. This variant should theoretically have the worst efficiency, but its main advantage is very flexible combination between various components and real topology.

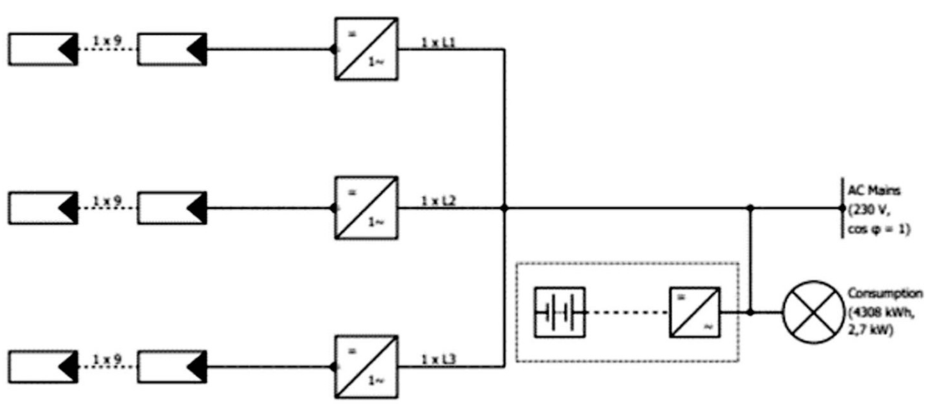

Fig. 8. AC coupled system (PV*SOL Premium 2023)

Optimization of the energy consumption in the sample shelter is presented in Fig. 9. This chart is based on optimizations of the load chart, high RES integration, low energy standard

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of the building, costs and connection to the grid with minimal influence on power quality. Deeper analyses of the load chart optimization is not the topic of this paper.

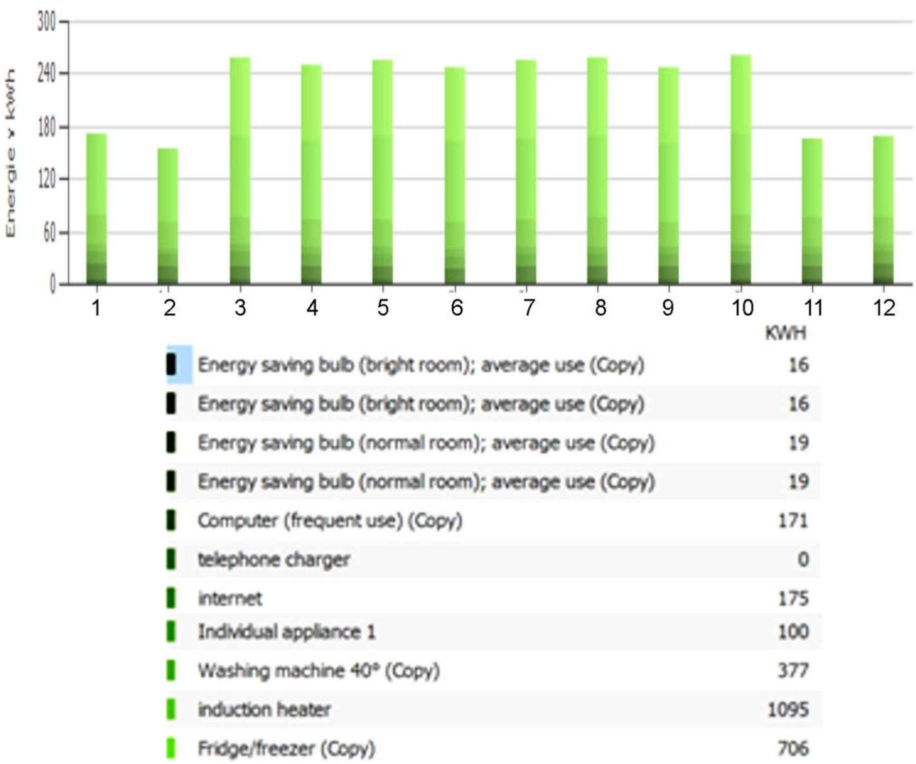


Fig. 9. Load chart of the sample shelter

3 AC coupled vs DC coupled PV system for model shelter of war refugees

Simulations performed for a model object simulating emergency housing for war refugees located in the Vinnytsia region demonstrated different energy gains and behavior of the two systems. This result cannot be generalized and only applies to the respective consumption diagram, battery system, PV system and climatic conditions. Fig. 9 shows the difference in consumption from the supply network for both cases.

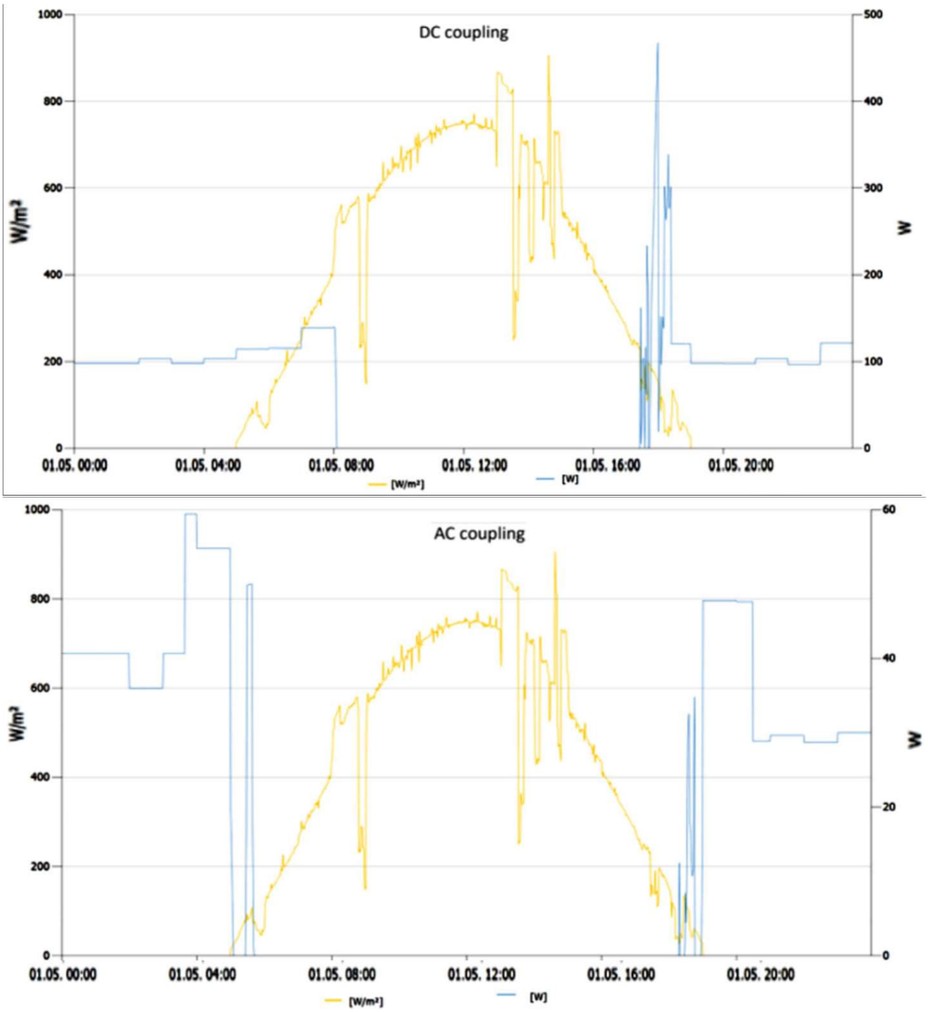


Fig. 10. Energy from grid simulations - DC coupling / AC coupling (PV*SOL Premium 2023)

What is interesting is not only the different course, but also the time shift of the withdrawals. Fig. 11 represents the difference in SOC of the batteries for the same situation and Fig. 12 losses during the charging and discharging phase. Again, not only the course of the individual quantities but also the beginning and end of the time intervals of the respective phases of the cycle are essential, as evident on the charts.

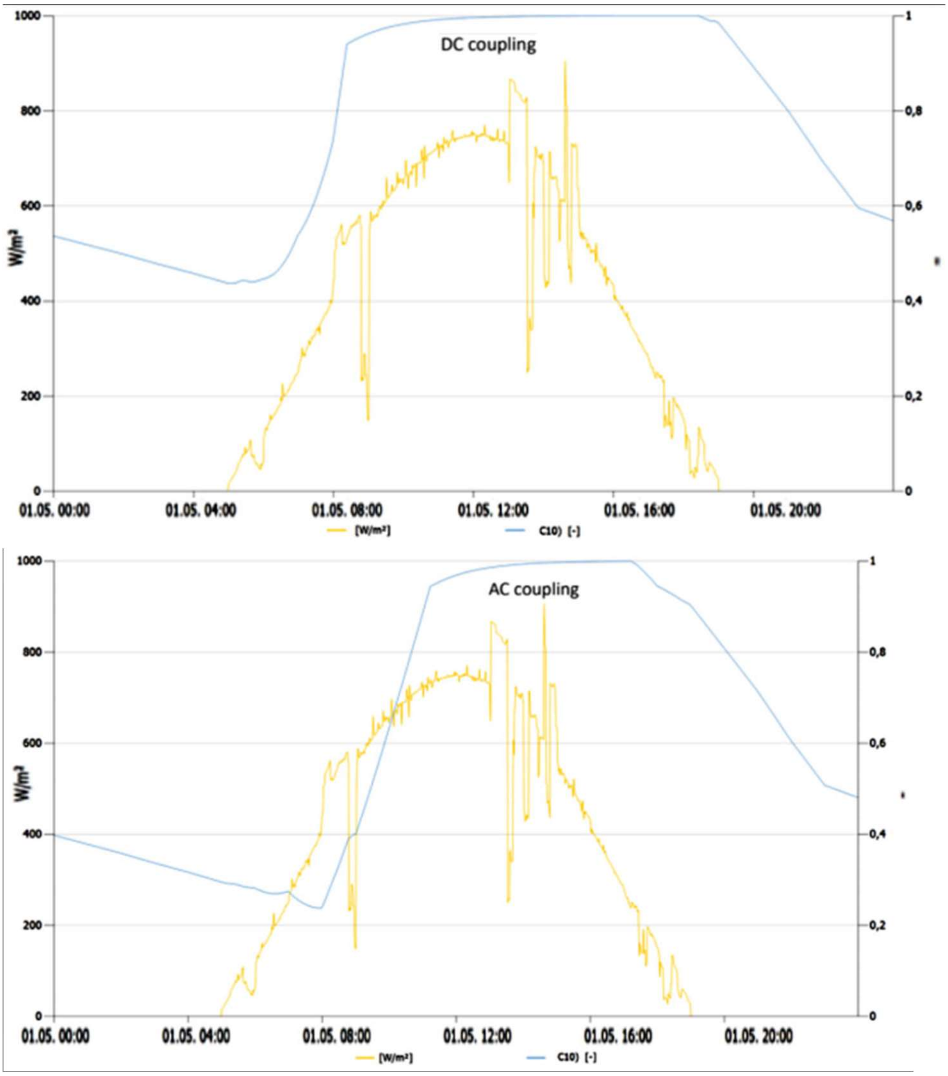


Fig. 11. Charge/discharge of battery - DC coupling / AC coupling (PV*SOL Premium 2023)

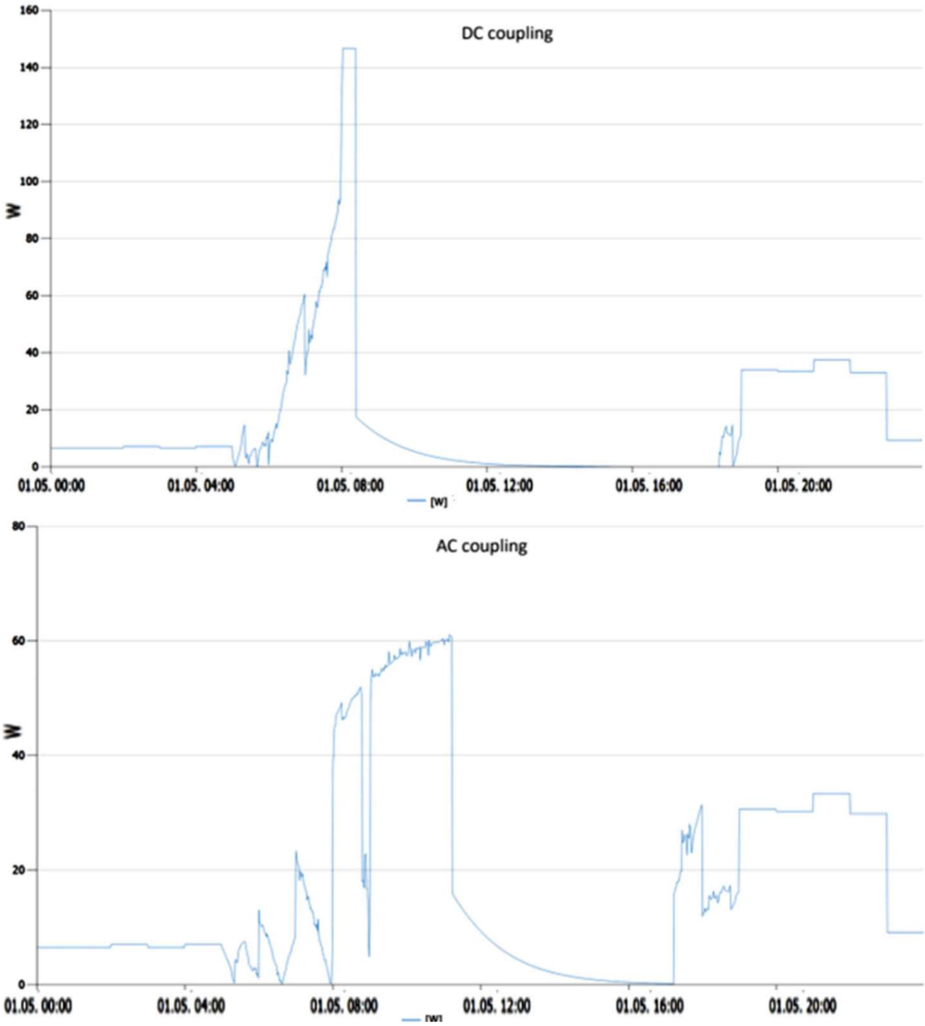
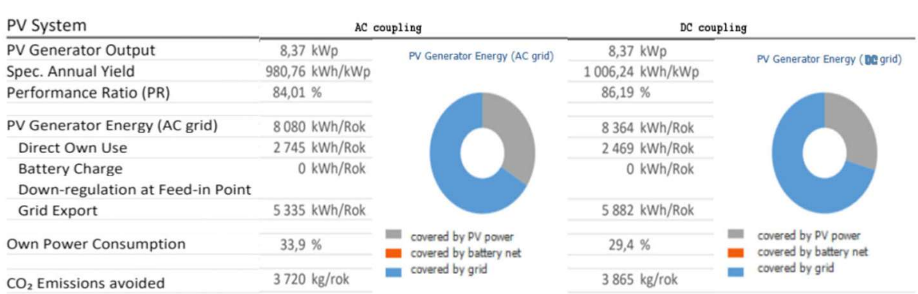


Fig. 12. Charging / discharging losses - DC coupling / AC coupling (PV*SOL Premium 2023)

Fig. 13 presents a comparison of the energy yield from the AC coupling system and the DC coupling system. It is obvious that the DC variant offers a seemingly greater energy yield, but less resulting battery usage and therefore greater flows into the network.



PV System	AC coupling	DC coupling
PV Generator Output	8,37 kWp	8,37 kWp
Spec. Annual Yield	980,76 kWh/kWp	1 006,24 kWh/kWp
Performance Ratio (PR)	84,01 %	86,19 %
PV Generator Energy (AC grid)	8 080 kWh/Rok	8 364 kWh/Rok
Direct Own Use	2 745 kWh/Rok	2 469 kWh/Rok
Battery Charge	0 kWh/Rok	0 kWh/Rok
Down-regulation at Feed-in Point		
Grid Export	5 335 kWh/Rok	5 882 kWh/Rok
Own Power Consumption	33,9 %	29,4 %
CO_2 Emissions avoided	3 720 kg/rok	3 865 kg/rok

Fig. 13. Comparison between AC and DC coupled systems (PV*SOL Premium 2023)

It is clear from the results that the AC coupling system with an apparently lower conversion efficiency, but in this case offers a better overall energy use. If we compare these technologies applied in the conditions of emergency shelters, we see several significant differences that are usually not expected:

- DC coupling
  - lower battery drain
  - later battery discharge phase
  - earlier battery charge phase
  - longer full battery charge state
- AC coupling
  - deeper battery discharge
  - faster battery charge
  - shorter full battery charge state

4 Conclusions And Results

The presented study proved that in some specific cases, with regard to a better time course of consumption or energy supply to the network, it may be more advantageous to use the connection of the battery system using AC coupling, although this method is theoretically characterized by lower efficiency due to a greater number of DC/AC and AC/ DC.

This proved to be practical in applying more units within planned communities for Ukrainian war refugees. Respectively, we do not expect just one stand-alone object (refugees shelter) but large block of these structures called shelter city. In large amount of the shelters with various coupling strategy, significant energy savings can be found.

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