

# Battery storage technology optimisation for Ukrainian War Refugees Emergency Shelters

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**Abstract.** The paper deals with optimisation of energy storage systems technology for emergency shelters (tiny houses) for Ukrainian War refugees. Huge number of Ukrainian citizens lost their houses or had to leave their homes. These refugees increase population in the rest of Ukraine what escalates problems with accommodation and integration into native communities. Emergency living in communal properties has unpleasant influence on the communities and is acceptable just for limited period. It becomes important to build new quarters or urban areas using cheap but energy efficient technologies. This research is based on real shelter project realised between Ukrainian non-government organisation Synergy and German development agency weChange.

Main task of this paper is optimisation of energy strategy in community consisting of hundreds or thousands units and called shelter city. Solution of one single tiny house with implemented RES is task deeply evaluated in several projects, but we must take into account cooperation of large amount of units to limit total influence on Ukrainian distribution and transmission networks. Ukrainian infrastructure was already in unpleasant state before war and new connections of these consumers would dramatically overload existing infrastructure. This task is yet more complicated in nowadays war conditions, where crucial parts of the networks are being repeatedly damaged. From this point of view, it is essential to design the shelter community like consumer or prosumer with perfectly balanced load and production chart.

The shelters should be built in passive standard to achieve minimal acquisition and operational costs. Also very efficient but cheap energy storage system must be integrated on the level of particular shelter or entire shelter city. Influence of various battery technologies using different coupling schemes is being discussed. AC coupling, DC coupling with intermediate circuit or PV generator circuit are tuned for specific load charts to optimise the influence on distribution network.

**Key words.** battery storage system, AC coupling, DC coupling, shelter city, influence on grid.

## 1. Introduction and motivation

The Russian invasion to Ukraine escalated long lasting problems within all areas of Ukrainian industry, economy, environmental protection, power engineering, green energy and sustainable low-carbon development. The

energy networks and generation units in Ukraine were obsolete and almost beyond their life period already before the war. Russian military actions further damaged more than 35% of Ukrainian energy infrastructure and this process still did not stop. At the end of summer 2022, 785 settlements (about 615 thousand consumers) did not have electricity supply and more than 235 000 citizens cannot use gas at all [1, 2].

During the pre-war period, Ukraine started to increase the usage of renewable energy source and to develop decentralized power engineering. Photovoltaic, hydro, wind and biomass units experienced rapid evolution similar to solar boom in Czech Republic during 2008-2010. At the end of summer 2022, more than 30% of installed PV plants and 90% of wind units were damaged. During the autumn 2022, continuing Russian attacks completely destabilised all energy networks, so that energy supply in all country become intermittent and unpredictable. It has become standard that customers received electricity just for 2 hours between 4 or 6 hours without energy supply [2, 3].



Fig. 1. Example of damaged power engineering infrastructure during the Ukrainian war.

Beside that, the war launched huge fluctuation and migration of citizens. Extensive Russian attacks to large territories in eastern and central Ukraine caused massive evacuation into less endangered regions in the west. Westerly situated cities has become overcrowded, what aside many social problems, evoked large problems with

accommodation of these escapers. Usage of existing capacities in municipality properties is just temporary solution. It is evident that new communities need to be built in surroundings of current cities or in new suitable locations. Connection of these users to present public networks is challenging task, because these networks or particular connection points are at limits of their capacity. New consumers must be almost self-sufficient without any significant disturbance or influence on the grid (consumers but also prosumers) [3, 4].

Our project focuses on balancing these energy needs and energy flows between particular shelter or shelter city and the public network. In fact, there are 3 parts of the complex solution to be optimised:

- energy consumption (load chart),
- energy production (RES – namely photovoltaic),
- accumulation (namely battery storage systems).

Just adequate composition of all these 3 elements can give resilient, efficient, economic and favourable solution [3, 5, 6].

This paper evaluates various technologies of batteries and inverter coupling schemes for this application. Due to grid limitations, this task is very specific and standard solutions fail in some particular parameters. In general, we are speaking about almost island operation (off-grid) of the shelter or shelter community with very limited sources. This issue can be illustrated on battery selection. Modern lithium based batteries are very pleasant from electrical parameters (SOC, DOD, charging strategy, etc.) but are very sensitive for their environment (location, operating temperature, etc.), so surprisingly conventional Pb batteries appear for our application more favourable. Similarly, the solution of inverter coupling strategy is very tricky as deeply described in following text [7-10].

## 2. AC and DC coupling of battery system for single shelter application

In newly built photovoltaic applications, the DC coupling became generally very popular. Many hybrid inverters (also offering true island mode) are on the market. Main benefits of this topology are limitations of total losses in DC/AC chain and probably more compact equipment. Photovoltaic and battery inverter are usually manufactured in one compact unit (sometimes together with battery). There is just one DC/DC conversion and one DC/AC. On the other side, AC coupling offers more variations in displacement of particular components, but means probably higher energy losses because of 3 particular conversions (DC/AC + AC/DC + DC/AC) in the entire chain: PV generator – battery – consumption [9, 11, 12].

But these premises can be very misleading in some specific applications – like the shelter for war refugees cooperating with unstable and unpredictable grid in war conditions. This application has very specific energy needs, economical background and reasonable technical solutions. Unique type of the load chart and very specific connection conditions can make AC coupling more preferential. Economic or displacement reasons are

important, but surprisingly also lower energy losses can be reached in our application. Particular solutions are discussed and all details explained in following chapters. Fig. 2 shows sample simulation of symmetric 3 phase DC coupled system with intermediate circuit (standard hybrid inverter) while Fig. 3 demonstrates asymmetric 3 phase system with DC coupled battery to 1 string of the generator circuit [12-14].

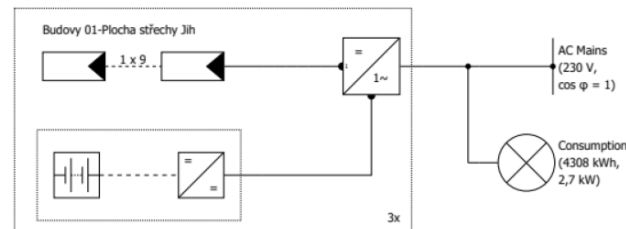


Fig. 2. Topology of shelter power supply with DC coupled battery system (intermediate circuit).

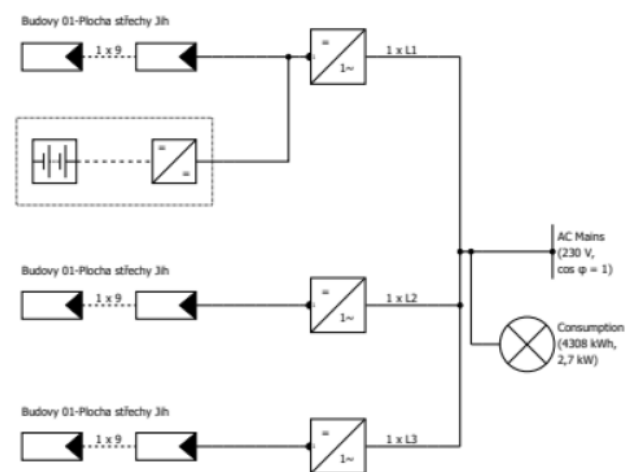


Fig. 3. Topology of shelter power supply with DC coupled battery system (generator circuit)

Fig. 4 illustrates shelter with symmetric 3 phase AC coupled battery system. Symmetry in this case allows in result the best usage of solar energy with load chart of the shelter.

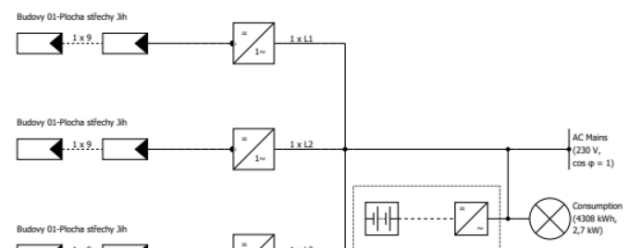


Fig. 4. Topology of shelter power supply with AC coupled battery system.

All simulations are performed in PV\*SOL Premium 2023 and partially verified in PVSyst 7.3. The geographical location of model shelter and shelter city is close to Vinnytsia city near Rovets lake (49°07'33.2"N 28°19'17.4"E). All calculations are based on Meteonorm weather database for that location. Perez-Ineichen clear sky model (1) is used for basic computations of global horizontal irradiance, direct normal irradiance including diffuse component of the irradiation [15].

$$E_d = DHI \times \left[ (1 - F_1) \left( \frac{1 + \cos(\theta_T)}{2} \right) + F_1 \left( \frac{a}{b} \right) + F_2 \sin(\theta_T) \right] \quad (1)$$

where  $F_1$  and  $F_2$  are complex empirically fitted functions that describe circumsolar and horizon brightness and DHI is diffuse horizontal irradiance.

Calculations of irradiance on inclined plane are based on the Hay-Davies equation (2) using isotropic and circumsolar components [16].

$$E_d = DHI \times \left[ A_i R_b + (1 - A_i) \frac{1 + \cos(\theta_T)}{2} \right] \quad (2)$$

where DHI is the diffuse horizontal irradiance,  $R_b$  is coefficient depending on the angle of incidence,  $Z$  is the solar zenith, and  $O_T$  is the tilt angle of the array.

Power losses resulting from drop-in-voltage on the bypass diodes are estimated equal to 0,5 %. Power losses resulting from mismatching and reduced yield of panels are estimated to be 2,0 %. Total ground reflections (albedo) is expected 31,4 % for winter season while 19,5 % for the rest of year and are calculated from weighted particular components respecting the topology and climate of the location (3).

$$r_{tot} = 0,42 r_g + 0,24 r_i + 0,18 r_w + 0,09 r_o + 0,07 r_r \quad (3)$$

where  $r_g$  means reflection of grass areas,  $r_b$  reflection of bushy areas,  $r_w$  close water surfaces,  $r_o$  reflection on near objects and  $r_r$  reflection from communications [21].

Losses due to annual soiling are expected to be 2 % constantly. Time step of all simulations is 1 min.

### 3. Single shelter with intermediate circuit DC coupled battery storage system

This solution is based on standard symmetric hybrid inverter Fronius Symo Hybrid 4 kW and 7 kWh lithium-ion battery LG Chem RESU7H. Fig. 5 demonstrates comparison of energy production in installed PV system, energy consumption in shelter, energy supply from grid and energy injection into the grid. This solution offers the best conversion efficiency, but requires symmetrical control on all phases [13, 14, 19].

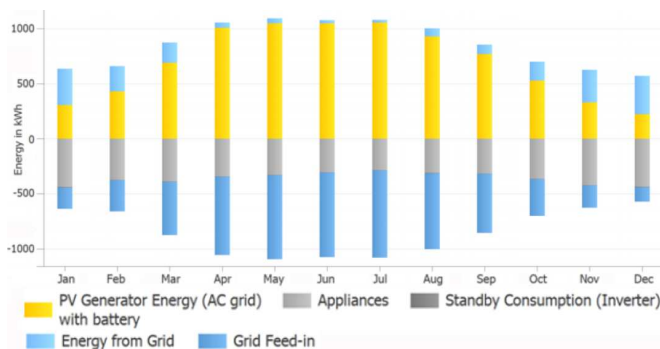


Fig. 5. Shelter energy production and consumption (DC coupling, intermediate circuit).

Fig. 6 shows generated photovoltaic energy compared to shelter consumption, SOC of the battery, energy supplied from grid and energy injected to the grid during sample spring day (1.5.).

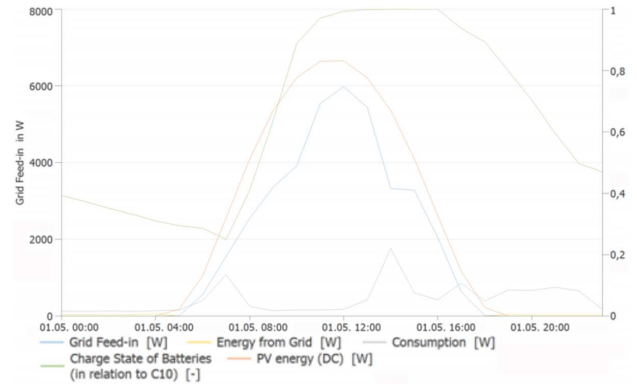


Fig. 6. Shelter energy balance (DC coupling, intermediate circuit).

### 4. Shelter with generator circuit DC coupled battery storage system

This solution is based on asymmetric configuration of 3 separate inverters Fronius Primo 4 kW and 7 kWh lithium-ion battery LG Chem RESU7H connected to PV string with Fronius Symo 4 kW like battery inverter. This solution offers good conversion efficiency, but surprisingly does not guarantee good energy usage in the sum of all three phases. Fig. 7 demonstrates comparison of energy production in installed PV system, energy consumption in shelter, energy supply from grid and energy injection into the grid [17, 18, 20, 22].

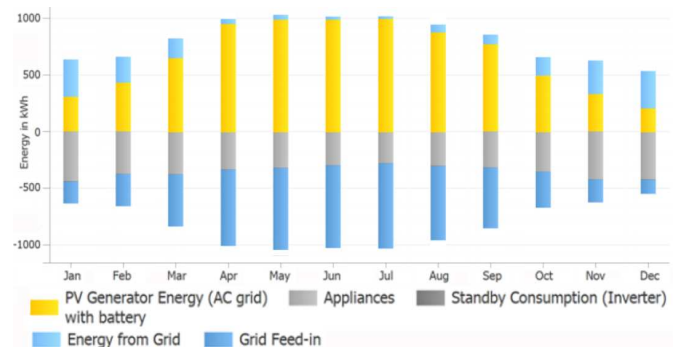


Fig. 7. Shelter energy production and consumption (DC coupling, generator circuit).

The annual results are in distribution similar to previous case, but absolute values significantly differ. The original configuration with intermediate circuit offers annual production 8364 kWh, while this example with generator circuit expects annual production just 7947 kWh. The main difference is usage of just 1 phase for charging the batteries. Although the capacities are identical, the usage of particular phases is different and also the charging strategy differs. The differences are more evident on Fig. 8. It shows the same situation like Fig. 6 (generated photovoltaic energy compared to shelter consumption, SOC of the battery, energy supplied from grid and energy injected to the grid) during the sample spring day (1.5.). The different behaviour between both DC coupled

systems is evident on Fig. 6 and Fig. 8 in the second part of the day. Very vivid is also the peak value in both cases. Higher absolute values in first configuration correspond with more efficient usage of all 3 phases for charging.

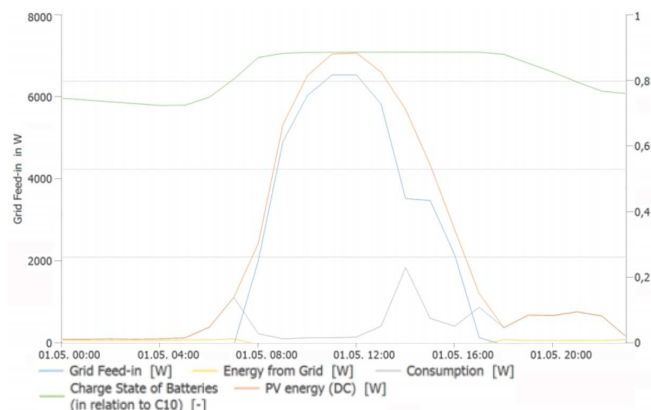


Fig. 8. Shelter energy balance (DC coupling, generator circuit).

### 5. Shelter with AC coupled battery storage system

This solution is again based on asymmetric configuration of 3 separate inverters Fronius Primo 4 kW and 7 kWh lithium-ion battery LG Chem RESU7H connected to AC grid with Fronius Symo 4 kW like battery inverter. This solution offers the worst conversion efficiency, but surprisingly gives the best energy usage 48497 kWh in the sum of all three phases. Fig. 9 demonstrates comparison of energy production in installed PV system, energy consumption in shelter, energy supply from grid and energy injection into the grid.

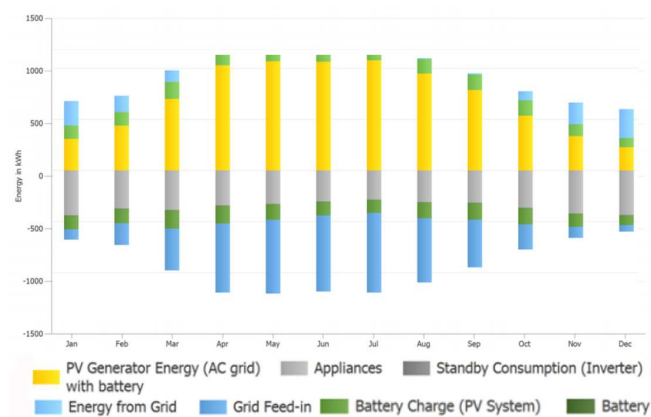


Fig. 9. Shelter energy production and consumption (AC coupling).

Fig. 10 shows generated photovoltaic energy compared to shelter consumption, SOC of the battery, energy supplied from grid and energy injected to the grid during sample spring day (1.5.). The best behaviour of this AC coupled system compared to both DC coupled systems can be traced on Fig. 6, Fig. 8 and Fig. 10. Very different behaviour of all 3 variants during the day (mainly in the second half) and different peak values are evident. These differences depend mainly on particular load in all phases (including battery charging in the configuration with DC generator circuit) and inverter control strategies.

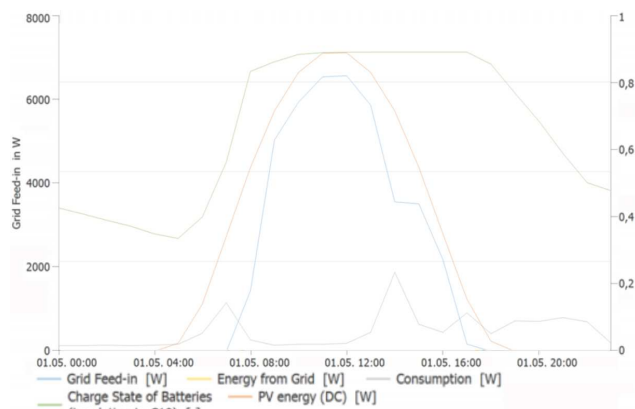


Fig. 10. Shelter energy balance (AC coupling).

Surprisingly system with the worst conversion chain gives with specific load chart of the shelter the best energy usage and battery charging efficiency.

On the other side, the longest battery lifetime in the variant of generator circuit can be expected. The simulation proved that SOC in this configuration is more flat than in other cases. The Fig. 8 shows daily variations between 0,88 and 0,76 while AC coupling variant uses the battery between 0,92 and 0,36 and the intermediate circuit even between 1,00 and 0,29. Similar difference can be found in entire season. This significantly affects the battery lifetime and can be expected, that the batteries can be used approximately twice longer with the generator circuit variant.

In case of Pb batteries are the differences in all variants a bit lower, because the charging strategies does not allow so deep discharging like in simulations discussed above. SOC in the generator circuit configuration for the same sample day (1.5.) will vary between 0,89 and 0,74 what just indicates a bit higher self-discharge loses. But the battery usage in other cases will be different. AC coupling variant will use the battery between 0,94 and 0,51 and similarly the intermediate circuit variant between 0,98 and 0,54. The limited capacities for deep discharge play the main role. The lifecycle of Pb batteries for all configurations will be more close – for 54 % better in the intermediate circuit variant. Although the Pb technology basically offer worse parameters, we must take into account also purchasing costs and, above all, more simple technology. For example, qualified service of Li-ion battery packs can be in nowadays Ukrainian condition tricky task. Also it is necessary to calculate different behaviour of both batteries in high and low temperatures during summer and winter.

But it is important to highlight, that we do not optimise the battery lifecycle, but the influence on the Ukrainian distribution network in the war conditions. From this point of view, the best energy usage provides in most of the period the AC coupling variant. The energy consumption from grid in AC coupling variant is for 46,4 % lower and power injection even for 51,8 % lower than in the DC generator configuration.

## 6. Shelter city consisting of large number of shelters

As it was mentioned at the beginning, our main goal is not to optimise operation of one particular shelter but of large community consisting of large number of tiny houses. This problem is much more complex, because we can combine several different configuration of shelters. Fig. 6, Fig. 8 and 10 show variations in behaviour of all solutions during one sample day. It is evident that parallel operation of large number of these units can overload the distribution network in some parts of day. This influence on network was calculated using DNCalc software. Fig. 11 presents the basic scheme of community of 200 shelters using photovoltaic plants connected to U11 connection point in grid with existing consumption in point U13 and supplied via transformer T4 from 110 kV grid.

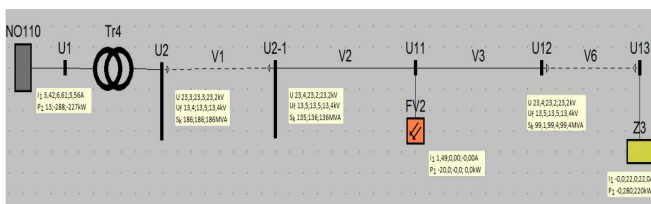


Fig. 11. Grid connection of a shelter city.

The simulations showed that the influence of this shelter city exceeded the limits 2 % voltage increase for the 110 kV grid. The violation was detected during 197 cases throughout the year. Most problems (72 %) occurred between 1.4. and 30.9. The strongest disturbance (6,12 %) was detected 27.6. at 14:37 o'clock.

Results of the simulations led to distributed structure of the shelter city. All 3 variants of battery coupling described above were used and the mix was optimised. As evident from Fig. 6, Fig. 8 and 10, each variant proposes different schedule of injected energy. Standard Newton method (4) was used to optimise the composition of the mix in the shelter city.

$$f(x) \approx m(x) = m_k(x) = f(x^k) + (x - x^k)^T \nabla f(x^k) + \frac{1}{2} (x - x^k)^T \nabla^2 f(x^k) (x - x^k) \quad (4)$$

where  $x^k$  is k-th iteration and  $x$  is particular position.

For the situation of 200 tiny houses in predefined location near Vinnytsia with the very same load chart of consumption and equipped with same PV generator, the optimal composition consisted of 124 units with AC coupling, 18 units with intermediate circuit and 58 units with DC generator coupling. Repeated simulations of the influence showed significant decrease of the overvoltage violations. In this case, only 12 violations were detected and the highest disturbance was 3,71 %. Although these results does not meet the typical standards of power quality, can be accepted in the war conditions in the Ukrainian network.

This solution could be further optimised with modification of the consumption or production load chart of particular

shelters. But this means very complicated management of the shelter city, many variants of shelters and other complex aspects eliminating mass manufacturing and simple servis of the units. Instead of that, another simplification was retested. Because the 18 units using the intermediate circuit have quite similar effect like the AC coupled units, they were replaced with the units using the AC coupling. This decreases the complexity of the entire system just into 2 unit types differing in coupling topology. The final influence is a bit worse than in ideal case, but still acceptable (16 disturbances with worst voltage increase 3,86 %).

## 7. Conclusions

Model situation for shelter city near Vinnytsia was elaborated. 3 particular variants of shelter power supply were simulated with focus of minimal influence on supply network – DC coupling with intermediate circuit, DC coupling with generator circuit and AC coupling. The shelter structure, consumption load chart and PV generator keep the same for all variants. Surprisingly, the lowest influence in consumer and prosumer mode offers the theoretically less efficient variant using AC coupling. Economical and practical reasons further specified the solution for usage of conventional Pb batteries.

The shelter city of 200 tiny houses of these 3 types was hereafter simulated. Uniform structure using just the best solution for single standing shelter caused 197 annual cases exceeding the voltage increase 2 % for the 110 kV networks.

Following optimisation arising from structuralised shelter city consisting of all 3 shelter types decreased the negative influence to just 12 violations, but for price of utilisation of 3 different shelter units. Next simplification of this solution to just 2 most common types a bit increased the disturbances (16 cases), but simplified the structure of the final shelter city.

It would be theoretically possible to yet decrease the influence with optimisation of consumption and generation load chart for each particular shelter, but this will unreasonably increase the variability of the shelter city what will strongly complicate the project, installation, operation and service of the units. It will also disable fast and cheap manufacturing of shelters. Instead of that, usage of the very same shelter units (design, equipment, consumption load chart, PV generator, etc.) differing just in 2 versions of the coupling topology (AC coupling or DC generator coupling) significantly decreases the complexity and purchasing cost with minimal downgrade of optimal solution.

It is expected that one model shelter according to this project will be built in proposed location near Vinnytsia and will serve as function sample to initiate crowd funding action to raise sufficient funds to build the whole shelter city what should contribute to improve the humanitarian situation in that region and probably later also in other parts of Ukraine.

## Acknowledgement

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