# An Academic Laboratory for All-Electric Energy Communities: the Case Study of PVZEN Microgrid

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# An Academic Laboratory for All-Electric Energy Communities: the Case Study of PVZEN Microgrid

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***Abstract*— This paper presents the PhotoVoltaic Zero Energy Network (PVZEN) laboratory, which is an academic energy community built at the Politecnico di Torino campus. The PVZEN laboratory consists in three users, each of them including a photovoltaic generation system, lithium batteries and utilities, capable of exchanging power according to dedicated logics. In particular, this work evaluates the energy flows for a typical sunny day and for one month. In addition, this paper investigates the improvements in terms of self-sufficiency and self-consumption due to the introduction of the energy community with respect to the independent users-configuration.**

***Keywords—energy community; microgrid; prosumers; energy exchange; smart metering; self-sufficiency, self-consumption.***

## I. INTRODUCTION

The European Union (EU) is currently facing the challenges of increasing the efficiency of energy systems and lowering their polluting emissions. In this context, the concept of Energy Community (EC) plays a significant role in the transition to low-carbon energy systems and can help to accelerate the local adoption of renewable energy technologies [1]. An “energy community”, or “microgrid” is an organization or group of people, homes, or businesses banding together to jointly manage and share energy resources and services within a specific geographic area [2]. These communities are built to increase the local consumption of renewable energy. Indeed, energy communities permit to decentralize energy production, i.e., to decrease the energy losses and the energy demand for long-distance transmission, by promoting the creation of local prosumers. In addition, energy can be shared within the community by redistributing the energy surplus through virtual net metering or peer-to-peer energy trading platforms. Finally, the diversification of energy sources and the promotion of local energy production in energy communities enhance their resilience against energy supply disruptions and price fluctuations in the electrical grid.

In the EU countries, the existing energy communities are almost ten thousand, although great disparities occur regarding their organizational structure (cooperatives, associations, partnerships), their size and the installed technologies. In particular, the most diffused renewable generation systems are based on photovoltaic technology, thanks to their low maintenance costs [3]; wind turbines, thanks to their remarkable energy production with low degradation rate [4] although the real energy production is lower than calculated because wind speed measurement requires proper correction methods [5]; biomass and heat pumps.

Almost half of these communities (about 4800) are located in Germany. Actually, in the village of Feldheim (Germany), an energy community based on a local energy system powered by wind turbines, photovoltaic generators, and biogas was created [6]. A Danish Island, Samso, achieved the carbon neutrality, having annual $CO_2$ emissions close to zero, thanks to on-shore and off-shore wind turbines, biomass-fueled district-heating plants, photovoltaic systems and electric vehicles [7]. In Brooklyn (USA, New York), an energy community was set as a part of a peer-to-peer energy trading platform, in which residents generating renewable energy can sell surplus electricity to the neighbors using blockchain technology [8]. The Perth Community in Australia is currently adopting an Energy Resilient City policy based on four strategic directions including solar power generation and energy efficiency initiatives. One of this consists in promoting energy communities to improve the energy resilience of the Perth Community [9]. The Eigg Island (Scotland) operates as an independent, off-grid energy community since its electricity needs are fulfilled by renewables including hydro, solar, and wind power plants [10]. In Italy, Ecoisola is an innovative energy community located on Salina Island that satisfies its demand using a combination of solar and wind power plants, energy storage, and demand response technologies [11]. In the Netherlands, the energy community LochemEnergie fulfils its consumption using local renewable energy projects (mainly, wind and solar installations) [12]. Autonomous province of South Tyrol (Italy) is involved in multiple sustainable energy projects, including local renewable energy production [13]. Finally, after the Fukushima nuclear disaster, the Fukushima Renewable Energy Institute (Japan) is currently exploring renewable energy alternatives focusing on research and development in clean energy technologies like energy communities [14].

This paper presents the PhotoVoltaic Zero Energy Network (PVZEN) laboratory, which is an energy community built in the Politecnico di Torino campus. It includes three users with photovoltaic generation systems, lithium batteries and utilities. The users can share their production according to dedicated logics in order to increase their self-sufficiency and self-consumption. This work presents the energy flows for a typical sunny day in the worst period of the year and the monthly values for January. Moreover, the boost of self-sufficiency and self-consumption due to the energy sharing in the community with respect to the independent users-configuration is quantified and discussed. The paper is organized as follows: section II includes the description of the PVZEN laboratory, while its possible system configurations are described in Section III, and section IV presents the case study under analysis. Section V provides the energy results of the experimental activity, while section VI contains the conclusions.

## II. DESCRIPTION OF PVZEN LABORATORY

In this section, the PVZEN laboratory is described. The laboratory is built in the Politecnico di Torino campus (Turin, Italy). The goal of the project is to create an all-electric energy community that uses PV-storage systems to meet its energy demand and reduce the absorption from the electricity grid [15].

### *A. The generation systems by PV modules*

The PVZEN microgrid includes three users equipped with PV-storage systems (PV systems shown in Fig. 1). High-efficiency mono-crystalline silicon (m-Si) PV modules with rated power of 370 W and efficiency of 21.4% are installed on a building roof in the Politecnico campus to optimize the space exploitation. These specifications are provided by the manufacturer in Standard Test Conditions (STC, with solar irradiance = 1000 W/$m^2$, module temperature = 25 °C, and air mass = 1.5) [16]. In addition, the modules have a Nominal Module Operating Temperature (*NMOT*) of 44°C.

Fig. 1. PV generators in the PVZEN laboratory.

The total nominal power of the generators amounts to 11.1 kW, and it is split between the three users in the following way:

- 4.44 kW for user #1, including 12 modules with orientation of -64° relative to South (-90° is East, 0° is South and 90° is West).
- 2.22 kW for user #2, including 6 modules with orientation of 116°.
- 4.44 kW for user #3, including 6 modules with orientation of -64° and 6 modules with orientation of 116°.

The PV modules have a slope of about 10°.

### *B. The storage systems by lithium batteries*

The most important parameters of batteries are their energy capacity, the State Of Charge (*SOC*), and their limits. The energy capacity is the maximum energy that can be stored in storage units, while the *SOC* at a certain time instant is the energy that is currently stored in the batteries with respect to their nominal capacity. The behaviour of storage systems is affected by several factors that can accelerate their aging, such as not optimal charging patterns, overcharging, undercharging, and abnormal cycling conditions caused by atypical charging temperatures. In order to extend the lifetime of storage systems, two limits are generally set by the manufacturer. The first limit regards the maximum power that can be absorbed and provided by batteries to avoid the flow of too high currents in the units [17]. The second limit prevents the batteries from being completely discharged or charged. Indeed, the energy capacity of batteries is not fully available for the user, and their *SOC* ranges between a minimum value higher than zero ($SOC_{\min}$) and a maximum value lower than 100% ($SOC_{\max}$). The difference ($SOC_{\max}$- $SOC_{\min}$), called the Depth Of Discharge (*DOD*), is the real energy capacity of the batteries that is available for the user [18]. For lithium batteries, typical energy limits fall within the ranges of $SOC_{\min}$ = 5−20% and $SOC_{\max}$ = 85−90% [19].

In the PVZEN laboratory, the storage systems of the three users have the same energy capacity: each user has 4 batteries with an energy capacity per unit ($C_{\mathrm{E,batt}}$) of 2.4 kWh, for a total capacity of 9.6 kWh. Therefore, the total energy capacity of the storage systems in the laboratory is 28.8 kWh. These batteries have a rated voltage of 48 V, a rated current of 50 Ah, a maximum current in charging and discharging phases equal to 100 A for 1 min and a *DOD* of 90%.

### *C. The purely electrical and thermal loads*

In the PVZEN laboratory, electrical loads consist of two components. The first component includes the thermal demand of the buildings, arising from space conditioning, and the second component consists in the consumption due to electrical equipment, such as lighting and appliances. To optimize the utilization of local electrical renewable energy sources, the thermal demand must be converted into an electrical one. The conversion can be achieved by utilizing electric reversible heat pumps, which efficiently convert heating and cooling demands into electrical loads [20]. In the laboratory, the loads might include real contributions (i.e., the electricity consumption of university offices and laboratories) and/or emulated power consumption of real-time simulated buildings, reproduced by resistive banks. Software for building energy simulations, such as EnergyPlus, might be used to assess the thermal demand, given the features of the building envelope, its intended use and location [21].

## III. SYSTEM CONFIGURATIONS OF PVZEN LABORATORY

The PVZEN laboratory [22] was created to study different configurations of energy communities, in which the participants (or users) are connected to each other and/or to the electrical grid. Some of the possible configurations are listed below:

- Configuration A - Autonomous Island. Each user is independent from the others and there are no connections to the external grid. Each user utilises only his own PV-storage system to meet his electrical load.
- Configuration B - Autonomous users with grid connection. Each user is independent from the others but is connected to the external grid. The grid helps to meet loads when PV is not productive and the energy storage is discharged. However, the generic user cannot directly supply the electrical loads of the others.
- Configuration C - Parallel connection to the grid. The three users are in parallel with each other and with the grid, as shown in Fig. 2. In this configuration, the users can exchange energy within the microgrid and with the grid.
- Configuration D - Master/slave with grid connection. One user is connected to the grid and plays the role of “master”. The other users are connected to the master and are called “slaves”. Energy exchange takes place between the users. In case of need, the electrical grid can be used to meet the loads, taking into account the limits of the single connection point. Fig. 3 shows the scheme of this configuration.
- Configuration E - Master/slave without grid connection. One user plays the role of master, and the other users (slaves) are connected to the master. The microgrid is not connected to the electrical grid.

These configurations can be realized thanks to switches and contactors that allow changing the electrical connections, moving from one configuration to another.

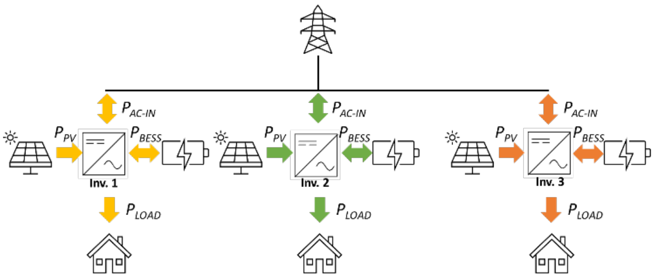

Fig. 2. Scheme of configuration C (Parallel connection to the grid).

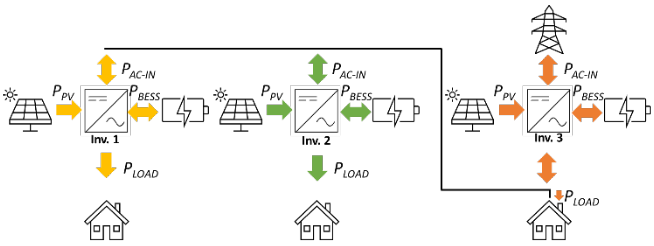

Fig. 3. Scheme of configuration D (Master/slave with grid connection).

## IV. DESCRIPTION OF THE CASE STUDY

### A. *The electrical loads*

The PV generators of the users supply the consumption of different university rooms: the PV system of user #1 feeds the room hosting the main electronic devices of the PVZEN laboratory like the data acquisition system, the internet access points, two desktop computers and one server (almost constant consumption of about 200 W). On the contrary, user #2 fulfils the loads of a calibration laboratory (variable load up to 1500 W including desktop computers, electronic appliances, and the heating demand) and user #3 satisfies the consumption of a server room (constant term equal to about 600 W).

### B. *The energy exchange logic*

This work analyses the energy flows for configuration D of the energy community ("Master/slave with grid connection"). In particular, for each user, the satisfaction of its loads follows a priority list of generation systems in the microgrid (PV-storage system of the user, PV-storage system of other users, and the electrical grid) aiming to maximize the self-sufficiency and the self-consumption. Fig. 4 describes in detail this logic.

## V. EXPERIMENTAL AND SIMULATION RESULTS

This section presents the power profiles for a typical sunny day in January (January 28th); in addition, the most important energy flows and indicators are reported for this sunny day and for the month of January. Fig. 5 shows the PV power profiles ($P_{PV}$) for the three users during sunlight hours: users #1 and #3 have a similar production pattern, exceeding 1500 W in the middle of the day, while user #2 reaches peak values of ≈750 W. Fig. 6 shows the load profiles ($P_{LOAD}$) for the three users, being almost constant throughout the day.

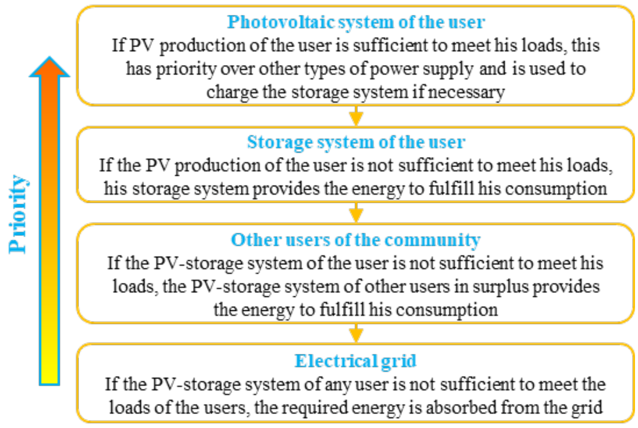

Fig. 4. Priority list for the satisfaction of each user's consumption.

In particular, the loads of users #1 and #2 are equal to ≈200 W and ≈300 W, respectively, while the load of user #3 oscillates around 600 W. Fig. 5 and Fig. 6 show that users #1 and #3 can fulfil their consumption using PV energy during sunlight hours with a significant energy surplus that is not consumed. On the contrary, during sunlight hours, the PV energy surplus for user #2 is almost negligible since his PV production is slightly higher than his load. This occurs because the PV rated power of users #1 and #3 is double that of user #2.

Fig. 7 shows the power exchanges within the Energy Community (EC) and with the external grid ($P_{EXCH}$). In the plot, a positive power ($P_{EXCH} > 0$) indicates a power injection by the user, while a negative power ($P_{EXCH} < 0$) means an absorption. Before PV systems start generating power, all users absorb energy from the external grid as the storage systems are fully discharged (*SOC* = 30%, as shown in Fig. 8). Power absorption from the grid is reduced to zero when PV power equals the power absorbed by the loads. Once each PV system produces more energy than its associated load, the PV surplus is used to charge the user's own storage. Energy exchange between microgrid users takes place in the afternoon. In particular, user #1 supplies energy to users #2 and/or #3. At the same time, user #1 continues to charge his own storage up to 95%, reached at around 15:00. Thanks to the energy shared by user #1, the storage of user #2 does not discharge until 19:30, as shown by its constant *SOC* in Fig. 8.

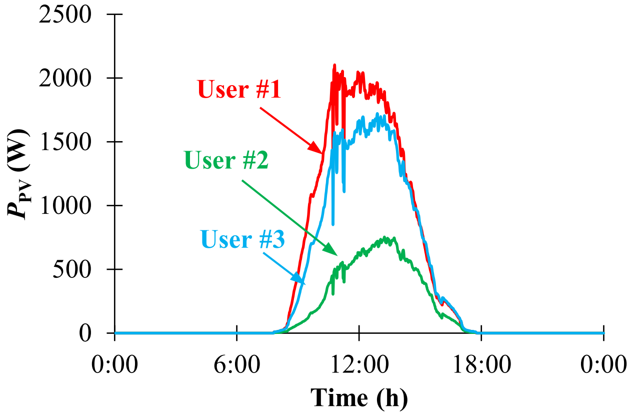

Fig. 5. Photovoltaic power profiles on 2023, January 28th for the three users.

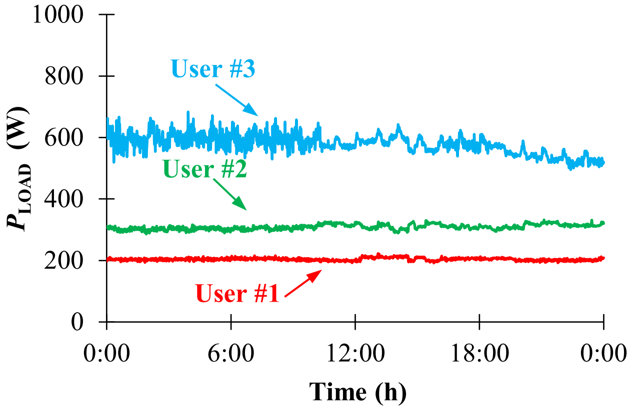

Fig. 6. Load power profiles on 2023, January 28th for the three users.

On the contrary, at around 22:00, the storage system of user #3 is fully discharged ($SOC$ = 30%), and the user absorbs power from the external grid.

Fig. 9 shows the charge/discharge power profiles of the storage systems ($P_{BESS}$) for the three microgrid users. In the plot, a positive power ($P_{BESS} > 0$) indicates that the storage is charging, and a negative power ($P_{BESS} < 0$) means that the storage is discharging. For all three users, the power profiles follow the evolution of the $SOC$s: null power exchanges occur before sunrise, while the surplus PV production in the morning charges the storages (positive power exchanges). In the afternoon, the batteries' charging continues but with lower PV surplus. In the late afternoon, when PV production is not sufficient to meet the loads, negative power exchanges occur (storages are discharging) to avoid electricity absorption from the external grid. Table I shows the daily energy flows of the energy community. The best orientation of PV generators for user #1 results in the highest PV generation ($E_{PV}$ = 10.1 kWh), while the lowest production is for user #2 (with half PV rated power and the worst orientation). According to the results in Table I, user #1 has the highest energy surplus ($E_{PV} >> E_{LOAD}$): in addition, since its injection into the grid is not negligible ($E_{EXCH,INJ}$ = 2.83 kWh), this amount of energy is not exploited in case of independent users. On the contrary, the energy community permits to achieve an optimal exploitation of this surplus energy ($E_{EXCH,INJ} \approx 0$ for the EC).

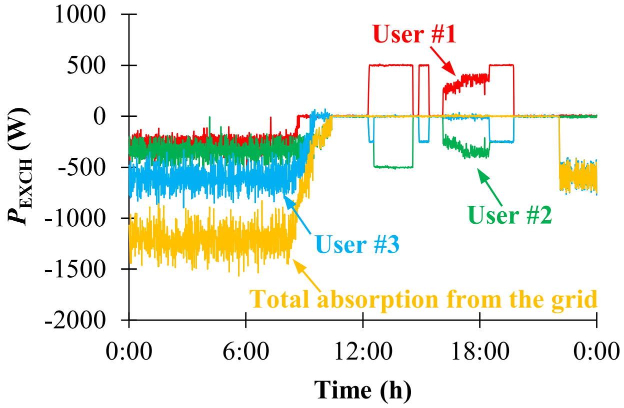

Fig. 7. Exchange power profiles on 2023, January 28th for the three users.

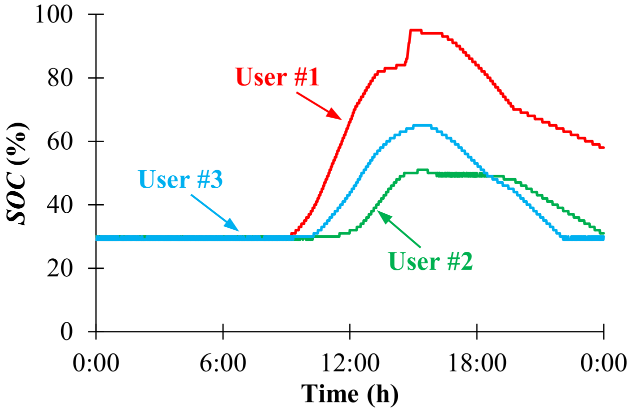

Fig. 8. Evolution of storage *SOC*s on 2023, January 28th for the three users.

In this case, user #1 provides energy to the others in case of deficit. As a consequence, the absorption from the grid of the energy community is lower than the overall absorption of the independent users.

In this day (2023, January 28th) the self-sufficiency is low (≈52% for independent users and ≈60% for the energy community, with an improvement of ≈16%). This is due to the high energy absorption from the grid during the night to guarantee the minimum *SOC* of 30% for the batteries. On the other hand, the self-consumption is high, being ≈71% for independent users and ≈84% for the energy community, with an improvement of ≈18%.

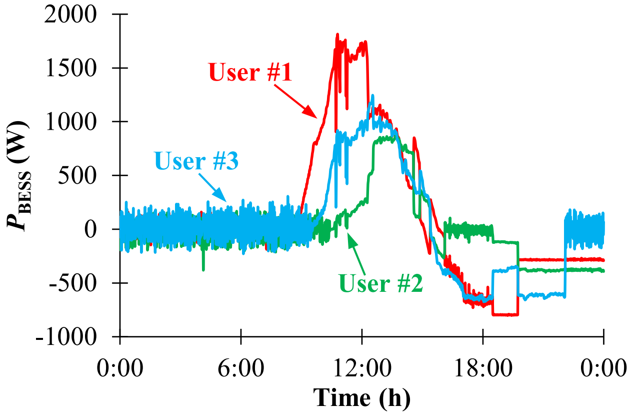

Fig. 9. Storage power profiles on 2023, January 28th for the three users.

TABLE I. DAILY ENERGY FLOWS FOR THE THREE USERS AND THE ENERGY COMMUNITY ON 2023, JANUARY 28TH

| Energy flow | User #1 (kWh) | User #2 (kWh) | User #3 (kWh) | EC (kWh) |
|---|---|---|---|---|
| $E_{PV}$ | 10.1 | 3.37 | 8.37 | 21.8 |
| $E_{LOAD}$ | 4.89 | 7.41 | 13.9 | 26.2 |
| $E_{BESS, DISCH}$ | 3.86 | 2.49 | 3.86 | 10.2 |
| $E_{BESS, CHAR}$ | 6.57 | 2.48 | 4.56 | 13.6 |
| $E_{EXCH, ABS}$ | 2.23 | 5.62 | 6.68 | 12.2 |
| $E_{EXCH, INJ}$ | 2.83 | 0.01 | 0.03 | 0.02 |

Table II. Monthly Energy Flows for the Three Users and the Energy Community on 2023, January

| Energy flows | User #1 (kWh) | User #2 (kWh) | User #3 (kWh) | EC (kWh) |
|---|---|---|---|---|
| $E_{PV}$ | 161 | 58.6 | 139 | 359 |
| $E_{LOAD}$ | 152 | 225 | 435 | 811 |
| $E_{BESS, DISCH}$ | 98.8 | 49.7 | 78.8 | 227 |
| $E_{BESS, CHAR}$ | 107 | 49.6 | 76.6 | 233 |
| $E_{EXCH, ABS}$ | 76.4 | 213 | 337 | 604 |
| $E_{EXCH, INJ}$ | 23.5 | 0.08 | 1.58 | 0.19 |

The sharing of energy within the microgrid improves the self-sufficiency and the self-consumption with respect to the independent users-configuration. This is obtained thanks to a better exploitation of PV energy for user #1, which is not injected into the electricity grid but is used to satisfy the loads of the other users in case of deficit. The same behaviour is observed by analysing the entire month, and Table II reports the monthly energy flows for the three users and the energy community in January. In this case, the self-sufficiency and self-consumption improvements thanks to the creation of the energy community are still significant, although lower than daily improvements on January 28th. Actually, the monthly self-sufficiency and self-consumption in case of independent users are ≈34% and ≈91%, respectively, while they increase to ≈37% and ≈98%, respectively, with the energy community (improvements of ≈7% and ≈8%).

## VI. CONCLUSIONS

The PVZEN laboratory is an academic energy community established within the Politecnico di Torino campus. The laboratory consists of three users, equipped with photovoltaic generation systems (total rated power of 11.1 kW), lithium batteries (total energy capacity of 28.8 kWh), and utilities, capable of exchanging power through dedicated logics. This paper evaluates, for a case study of the laboratory, the energy flows and the improvements in self-sufficiency and self-consumption resulting from the introduction of the energy community, compared to independent users, for a sunny day in January and for the month of January.

The results of the experimental activity show the effectiveness of the energy community configuration in increasing the self-sufficiency and the self-consumption of the system. In particular, the sharing of energy within the microgrid allowed for better exploitation of PV energy, mainly for user #1. Actually, the energy absorption from the grid compared to independent users got significantly reduced. For a typical sunny day in January, the energy community achieved a self-sufficiency and self-consumption of about 60% and 84%, improving of around 16% and 18% the independent users-configuration. The monthly results are consistent with these results, confirming the effectiveness of the energy community.

In future works, emulated buildings will replace the electrical loads of the presented case study (university rooms), enabling the performance analysis of different energy communities. Furthermore, the current energy exchange logic, which aims to maximise self-sufficiency and self-consumption, could be changed to optimise other kinds of indicators, e.g., economic indicators.

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