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Urban Energy System: A Comprehensive Analysis of BIPV-EV coupling

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ABSTRACT

Facade photovoltaic (FaPV) can significantly enhance the capabilities of building-integrated photovoltaic (BIPV) systems as prosumers, while also mitigating the additional electricity demands of electric vehicles (EVs). This study presents a comprehensive analytical framework for optimizing the operation of BIPV-EV systems and evaluating their environmental and economic benefits with a case study in Xiong'an New Area. The Economy-Energy-Environment(3E) parameters are measured for multiple scenarios, and sensitivity analyses are applied to validate the impacts of the changes in electricity prices and BIPV costs on the BIPV-EV system. The simulation results demonstrate that BIPV-EV systems effectively reduce carbon emissions and electricity costs. The installation of FaPV can increase power generation by 67.60% compared to the BIPV system using RPV stand-alone. Regarding urban decarbonization, the adoption of BIPV system can lead to a reduction in CO_2 emissions by 41.91% and 34.99%. In each scenario, the lowest levelized cost of energy (LCOE) scenarios in the short-term and long-term are RPV+FaPV (SE)-EV and RPV+FaPV (SW)-EV, where BIPV generates 48.10% and 31.90% of the total electricity generation, respectively. In terms of EV power consumption, The BIPV-EV system can decrease the grid sell ratio by 15.38% compared to the single BIPV scenario. This framework analyzes the potential of integrated systems with EVs under various BIPV scenarios. In cities with nascent BIPV and EV markets, the framework can be used as a strategic tool for urban planners to plan BIPV-EV systems that improve sustainability and energy efficiency.

Keywords: rooftop photovoltaic, facade photovoltaic, building-integrated photovoltaic, electric vehicle, BIPV-EV system, Xiong’an New Area

NONMENCLATURE

Abbreviations	
PV	Photovoltaic
RPV	Rooftop photovoltaic
FaPV	Facade photovoltaic
BIPV	Building-integrated photovoltaic
EV	Electric vehicle
XANA	Xiong'an New Area
LCOE	Levelized cost of energy
3E	Economy-Energy-Environment
V2G	Vehicle to grid
O&M	Operations and maintenance
FIT	Feed-in tariff
Symbols	
$BIPV_G$	Electricity generated by BIPV
$Grid_P$	Electricity purchase from the grid
$Gird_S$	Electricity sell back from the grid
CE_{system}	Carbon emission by whole system
Ef_g	Carbon emission factor of the grid
EI_{system}	Power transmission capacity of the grid
CE_{FV}	Carbon emission by fuel vehicles
P	Total electricity generation
CEI_{system}	System carbon emission intensity
BRA_i	Building rooftop area of land type *i*
CA_i	Construction land area of land type *i*
BD_i	Building density of land type *i*
TBRA	Total building rooftop area of land type *i*

1. INTRODUCTION

In the current context of rising urban carbon emissions and land scarcity [1], distributed BIPV systems, as PV systems installed on unused surfaces of buildings, can effectively utilize urban space. While roofs usually take on other functions of the building, the remaining exploitable area of the rooftop is limited. Whereas, with the development of FaPV technology,

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the utilization of unused areas of buildings can be greatly improved, increasing the BIPV potential [2].

Many researches have been conducted to optimize energy systems by integrating 3E parameters in the analysis of urban energy systems. With the growing trend of electric vehicles increasing the demand for urban power systems, multi-scenario analysis has found that BIPV-EV systems can effectively address this issue. However, in BIPV system research, existing literature rarely considers FaPV and lacks quantitative analysis of the impact of FaPV on BIPV systems.

In order to solve the above problems, this paper develops a model for evaluating the BIPV-EV system with economic and environmental parameters, and analyses the potential of each installation surface in BIPV to optimize the urban BIPV-EV system. The main contributions of this paper are as follows:

(1) To comprehensively analyze the impacts of BIPV aspects on the BIPV-EV system, the economic-energy-environmental analysis framework is utilized to expand the techno-economic study of BIPV.

(2) From the energy hybrid system, four indicators are provided for multi-scenario analysis to optimize the environmental potential as well as the economics of the system.

(3) Sensitivity analysis is used to explore the impact factors of BIPV-EV systems.

2. METHOD AND DATA

2.1 Assessment framework

In this study, an integrated assessment framework was constructed to analyze the 3E potential of multi-scenario BIPV-EV systems (Fig. 1).

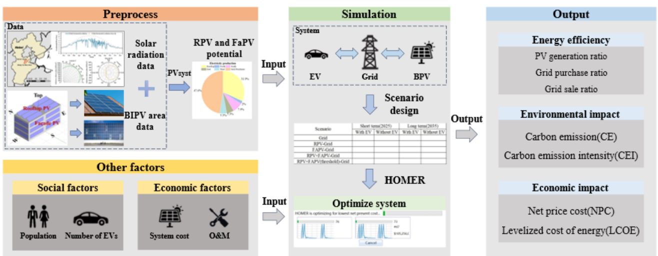

Fig. 1 Assessment framework of this study

In the preprocess stage, the PVsyst model is used to analyze the local solar resource. In order to evaluate the BIPV-EV system in further detail, the maximum BIPV potential of the local building complex and the BIPV potential at best economic efficiency need to be analyzed. Finally, the HOMER model was used to simulate the BIPV-EV system and investigate its 3E potential.

2.2 Scenario design

In terms of scenario design, the system was evaluated in detail to better understand the impact of RPV and FaPV on the BIPV-EV system. Considering the type of PV in the building, the grid load, the grid power supply, and the V2G system, the BIPV-EV scenario is designed (Table 1). Especially considering that FaPV can have an impact on the economics of the overall system due to the complexity of the construction location and high costs. Therefore, thresholds are used in the analysis of new construction scenarios to screen out FaPV with high potential.

Table 1. Scenario design scheme and definition

Scenario	Definition
EV	Connecting EVs directly to the grid is the simplest V2G system
Only BIPV	The BIPV system only supplies residential and industrial electricity
RPV-EV	The potential of urban RPV when combining EVs with PV systems
FaPV-EV	The potential of urban FaPV when combining EVs with PV systems
RPV+FaPV-EV	The potential of urban RPV and FaPV when combining EVs with PV system

2.3 3E parameter impact evaluation of BIPV-EV system

2.3.1 Energy impacts

The impact of the BIPV-EV system on the security and stability of urban power supply was evaluated by using three indicators: BIPV generate ratio, Grid purchase ratio, and Grid sale ratio, the formulas are as follows:

$$BIPV_G\ ratio = \frac{BIPV_G}{BIPV_G + Grid_P} \times 100\% \tag{1}$$

$$Grid_P\ ratio = \frac{Grid_P}{BIPV_G + Grid_P} \times 100\% \tag{2}$$

$$Grid_S\ ratio = \frac{Grid_S}{Total\ consumption} \times 100\% \tag{3}$$

where $BIPV_G$ is the electricity generated by BIPV, $Grid_P$ is the externally purchased electricity of the grid, $Grid_S$ is the electricity sold by the grid.

2.3.2 Environmental impacts

To accurately measure the degree of carbon emission reduction, this study uses detailed carbon emission and carbon emissions intensity as key evaluation indicators. This is done by calculating the total amount of fuel consumption and carbon emissions from the grid supply for EVs and other sectors for each scenario, the formulas are as follows.

$$CE_{system}=EF_g \times EI_{system}+CE_{FV} \tag{4}$$

$$CEI_{system}=\frac{CE_{system}}{P} \tag{5}$$

where CE_{system} is the carbon emissions of the whole system, EF_g is the emission factor of grid electricity, EI_{system} is the power transmission of the grid, CE_V is the carbon emissions generated by fuel vehicles, CEI_{system} is the carbon emissions intensity, P is the total power output of the system.

2.3.3 Economic impacts

In the economic impact assessment of BIPV-EV systems, this paper mainly focuses on three indicators: total cost and LCOE. The total cost considers the initial investment, operation and maintenance (O&M), and replacement, which directly affect the financial viability of the project. LCOE measures the cost per unit of electricity, the formula is as follows.

$$LCOE=\frac{Total\ Lifetime\ Costs}{Total\ Electricity\ Generation} \tag{6}$$

2.4 Data

2.4.1 Environmental characteristics of XANA

XANA is located in Hebei Province, China (38.88°N, 115.93°E), covering an area of approximately 1770km²[4]. The area is flat and receives ample sunshine, which has abundant solar energy resources and a horizontal irradiation intensity of 1,579kW/m² (Fig. 2).

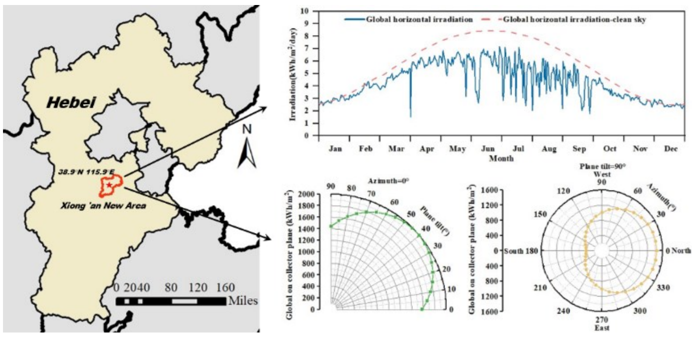

Fig. 2. Climate and solar radiation in XANA

2.4.2 Building roof & facade data of XANA

Because XANA is a newly built city, the buildings are changing rapidly, and there is a lack of GIS information and building information of the corresponding area, so the building land area and building density are used to estimate the roof area of the building[3]. The formulas for calculating the developable area of RPV are as follows.

$$BRA_i=CA_i \times BD_i \tag{7}$$

$$TBRA=\sum_{i=1}^{5} BRA_i \tag{8}$$

where BRA is the roof area of buildings, $TBRA$ is to the total area of building roofs, CA is to the development area of various types of buildings, and BD refers to building density.

In addition, on the building roofs, the installation potential for RPV and FaPV is 70% and 40%, respectively [5]. Based on these findings, further estimates were made for the building facades (Table 2).

Table 2. Estimation of short- and long-term RPV and FaPV planning in XANA (unit: km²)

Year	Rooftop	Facade				
		East	South	West	North	Total
2025	29.77	10.21	10.21	10.21	10.21	40.84
2035	40.54	13.90	13.90	13.90	13.90	55.60

2.4.3 Electricity demand forecast in XANA

Through the fitted data (Fig. 3), per capita electricity consumption is predicted to be 6,195.72 kWh/(pp·year) in 2025 and 7,781.90 kWh/(pp·year) in 2035.

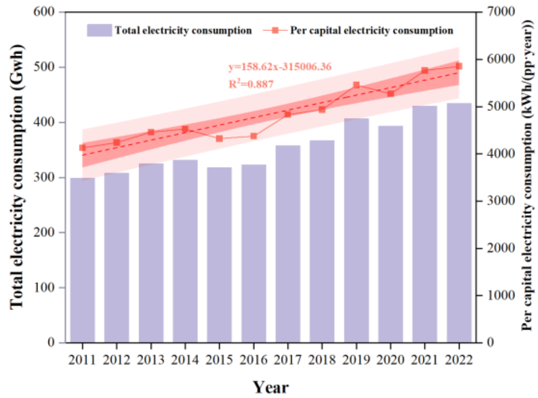

Fig. 3. Per capita electricity load in Hebei Province

Based on the characteristics of population migration in Shanghai Pudong New Area and Shenzhen Special Economic Zone, it is predicted that the population will be about 2.734 million in 2025 and about 5.128 million in 2035. Based on the above data, the electricity load will reach 16,939 GWh/year and 39,906 GWh/year in 2025 and 2035, respectively. According to the simulation of the HOMER load model, residential electricity consumption accounts for about 40% of industrial electricity consumption accounting for about 60% of the total load [6].

2.4.4 Economic parameters of the integrated system

A detailed list of the parameters and data sources is provided in Table. Moreover, the grid emission factor will reach 0.736kgCO_2/kWh in 2025 and 0.544kgCO2/kWh in

2035. The term of the project is set at 25 years, with a discount rate of 8% and an inflation rate of 2% (Table 3).

Table 3. Economic parameters of BIPV-EV system

Types	Items	2025	2035	Unit
RPV	Total area	29.77	40.54	km^2
	Cost	799.5	589.6	USD/kW
	O&M	8	8	USD/kW/year
FaPV	Total area	40.84	55.6	km^2
	Cost	1,071	790	USD/kW
	O&M	10.72	10.72	USD/kW/year
Converter	Cost	985	985	USD/kW
	O&M	101	101	USD/kW/year
Electricity	Load	16,939	39,906	GWh
	Emission factor	0.736	0.544	$kgCO_2/kWh$
	FIT	0.079	0.079	USD/kWh
	Sellback	0.06	0.06	USD/kWh
Vehicle	Number	738.2	1,384.6	1,000Car

3. RESULT

3.1 BIPV electricity generation potential

In each scenario, it is assumed that PV installations reach their maximum potential, with maximum PV capacity reaching 10.87GW by 2025 and 14.81GW by 2035 respectively. Since RPV can control its inclination value, Pvsyst simulation indicates that at an inclination angle of 40° and an azimuth angle of 0°.

Table 4 Installation angles and capacities of each side of the building

Type	Rooftop	Facade			
		North	South	East	West
Tilt (°)	40	90	90	90	90
Azimuth (°)	0	180	0	270	90
2025 (GW)	4.59	1.57	1.57	1.57	1.57
2035 (GW)	6.25	2.14	2.14	2.14	2.14
Radiation (kWh/m^2)	1,997	415	1,444	1,009	1,009

3.2 Simulation results from HOMER models

In the Base and Design scenarios, the power output of the grid and PV systems in the short-term and long-term, regardless of the threshold case (Fig. 4). With the increase of PV types, due to the mismatch between power generation and demand, there will be some surplus resold electricity, so the total power generation will gradually increase, and the proportion of PV will gradually increase. In the case of the greatest PV potential, the PV power generation in the short-term and long-term reached 12,348 GWh/year and 16,841 GWh/year, accounting for 52.4% and 36.6% of the total power generation in the short-term and long-term, respectively, indicating that the BIPV integration has good power generation potential.

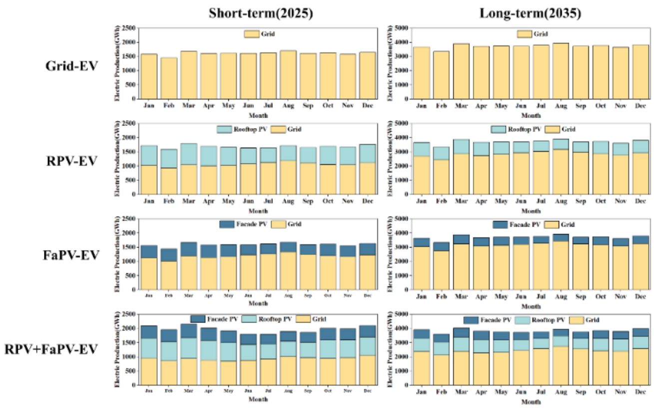

Fig. 4. Diagram of the power output of grids and PV systems in each scenario in the short- and long-term

3.2.1 Energy outputs

In 2025, the power generation of the BIPV will account for 52.37% of the power generation of the whole system when the BIPV potential is maximum, at this time, the RPV will account for 60.08% of the BIPV power generation, and the FaPV will account for 39.10%, while in 2035, the BIPV potential will only account for 36.6% of the entire system (Fig. 5).

Compared to the power generation potential of all sides of the FaPVs, it is found that in the RPV+FaPV (NEWS)-EV system, the north, south, east and west facades account for 2.03%, 7.85%, 5.32%, and 5.28% of the total power generation, respectively....

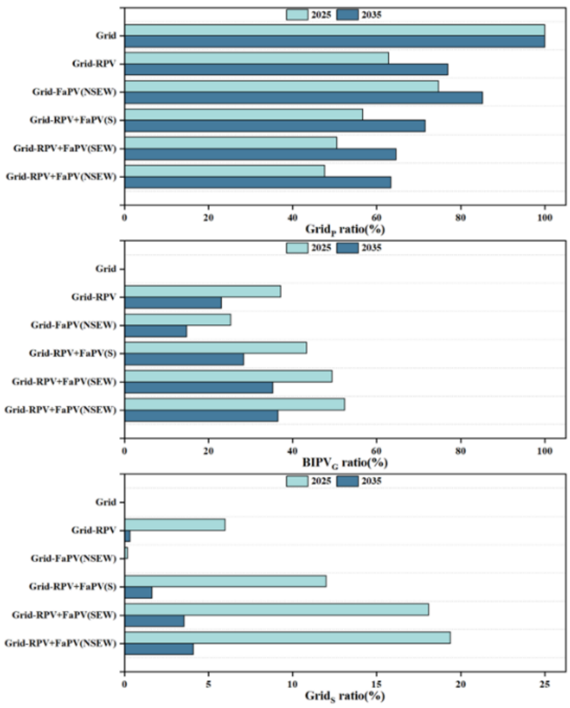

Fig. 5. Comparison of energy parameters under different scenarios

3.2.2 Environment pollutants emission

Besides effectively meeting the majority of the power demand in XANA, BIPV can also reduce carbon emissions from the Grid-BIPV power supply (Fig. 6).

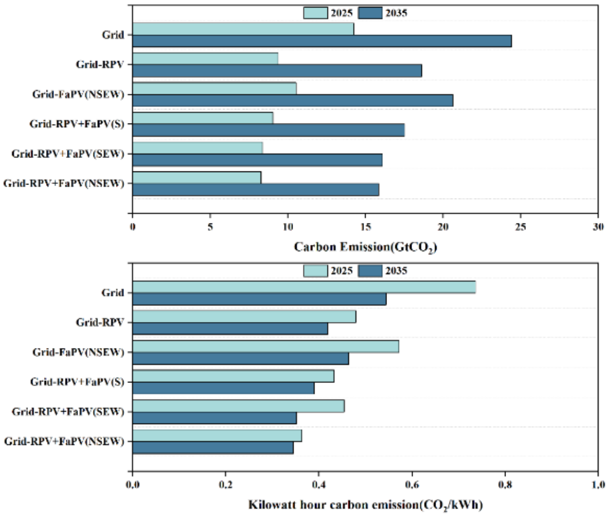

Fig. 6. Comparison of environmental parameters under different scenarios

In the base case when the EV system is operated alone, the carbon emissions of the entire system will reach 14.23 $MtCO_2$ in 2025 and 24.38 $MtCO_2$ in 2035. Moreover, the carbon emissions per kilowatt hour will decrease from 0.736$kgCO_2$/kWh to 0.350$kgCO_2$/kWh in 2025; the carbon emissions per kilowatt hour will decrease from 0.544$kgCO_2$/kWh to 0.345$kgCO_2$/kWh in 2035.

3.2.3. Economic performance of the optimal system

In the grid-only and all BIPV scenarios, the BIPV-EV system power purchase in 2025 and 2035 will be reduced, and the lowest NPC case will be Grid-RPV, saving 3.98 billion USD and 5.33 billion USD in electricity costs for XANA, respectively (Fig. 7).

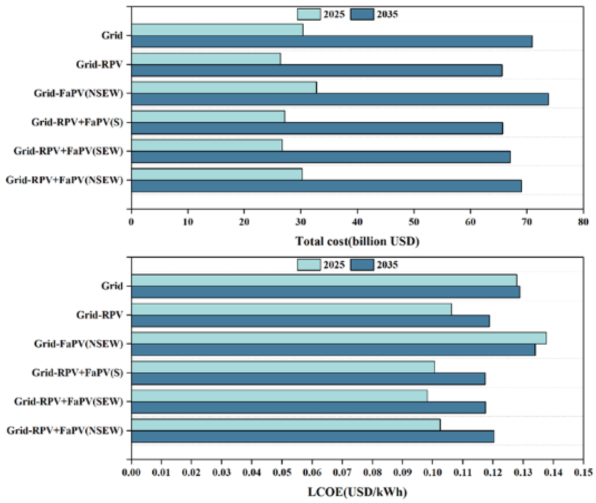

Fig. 7. Comparison of economic parameters under different scenarios

Further research on the short-term and long-term system finds that in the BIPV-EV scenario, the lowest LCOE scenarios in the near and long-term are RPV+FaPV (SE)-EV and RPV+FaPV (SW)-EV, and the LCOE reaches 0.095USD/kWh and 0.117USD/kWh, and theBIPV power generation accounts for 48.1% and 31.9%.

3.2.4 EV integration benefits

In the scenario where the potential of PV systems is greatest in the short-term and long-term, the adoption of EVs reduces the grid sale ratio by 15.38% and 30.20%, respectively (Fig. 8).

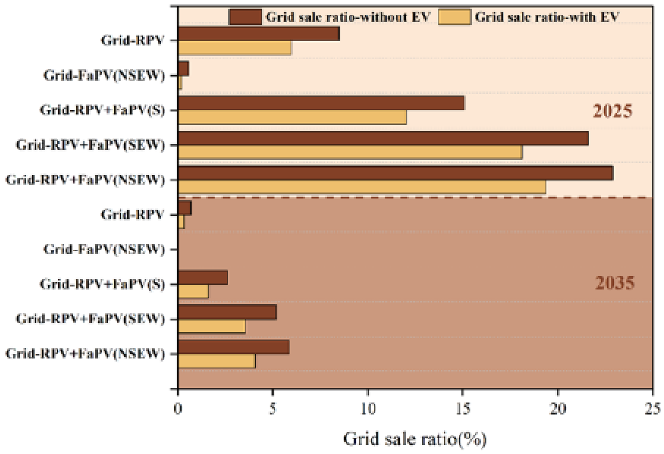

Fig. 8. Grid sale ratio with or without EV integration under different scenarios

3.3 Sensitivity analysis

Short-term and long-term LCOE sensitivity analysis reveals that LCOE is affected by grid electricity prices and BIPV costs. In 2025, when FIT+20%, the LCOE will increase by 9.70%, 8.86%, and 2.93%, respectively, in the RPV-EV system, FaPV-EV system, and RPV+FaPV-EV system. At -20%, the LCOE decreased by 9.65%, 8.93%, and 7.02%, respectively. This is because the cost of LCOE is affected by the total cost, while in XANA, where the external power demand is more than half, the LCOE rate of change is close to half of the FIT change. However, the amount of electricity sold is low, resulting in a situation where the proportion of PV power generation is low, the price of electricity resale fluctuates by ± 20%, and the LCOE is unchanged.

In terms of BIPV costs, in 2025 in RPV-EV systems, FAPV-EV systems, and RPV+FaPV-EV systems, when the FIT fluctuates by ± 20%, the LCOE fluctuates by about ±2.7%, ±4.0%, and ±6.9% respectively.

4. DISCUSSION

4.1 The advantage of the potential of BIPV assessment framework

Based on the 3E assessment framework, this research realizes the multi-scenario calculation of the system potential. In addition, the HOMER model can also analyze the power systems of other renewable energy sources as well as primary energy sources such as coal power, so the framework is suitable for integrated power system assessment of multiple energy sources at the city level, analyzing the economic potential and energy potential.

4.2 New Perspectives for Green City Development: BIPV Integration

The implementation of vehicle electrification will be accompanied by an increase in the city's power load, and the government of XANA has been focusing on building a green new urban area. so green power consumption needs to be considered. In the future, the population of XANA will surge, and the number of buildings will increase simultaneously, and the effective use of BIPVs is a new direction for the development of smart cities. The development and construction of BIPVs need to consider the economic focus of the city.

4.3 The potential status of the electricity market in BIPV-EV systems

With the construction of BIPV-EV system, renewable energy sources have a high proportion of electricity penetration into the power grid. A high proportion of renewable energy systems will exacerbate the uncertainty of power supply and output, i.e., the mismatch between production and demand. therefore, all regions should dynamically grasp the implementation of the time-of-use electricity price mechanism, and evaluate the implementation effect in depth according to the changes in the power system's electricity load characteristics and the consumption of new energy[7].

5. CONCLUSION

To explore the technical and economic potential of BIPV, this study takes XANA in Hebei Province, China as an example to evaluate the potential of BIPV and EV integration systems under multiple scenarios. The results highlight the important contribution of BIPV to the overall energy mix, with both RPV and FaPV having good energy environment economic potential, and having good absorption capacity for electricity demand for residential industrial use and EV battery charging.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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