Community-Based Convenient Hybrid Mini-Grid: Implementation Proposal and Analysis for Bangladesh

Arif Md. Waliullah Bhuiyan, Kazi Shariful Islam, Muhammad Mohsiul Haque, Md. Rejwanur Rashid Mojumdar, and Md. Mahfuzur Rahman

Abstract—**The heartiest efforts of electricity generation and extending electrification for rural population by Bangladesh Government becoming blur as it is falling short to meet urban and industrial growth. In remote areas of Bangladesh, off-grid technologies in combination with sustainable financial management promise environment-friendly access to electricity at a lower cost than conventional technologies. Such remote communities have limited resources, technical shortcomings; so training on technical issues, facilitation to proper management, methods to optimise the distribution system and load appliances can have practical benefits. This paper investigates renewable energy resources of Bangladesh and explores rural electrification opportunities using hybrid mini-grid system linked to existing and new economic opportunities.**

Index Terms—**Mini-grid Architecture, Hybrid generation's scope analysis, Community-based implementation model, Hybrid technologies and system design, Pragmatic practices**

I. Introduction

Bangladesh has enormous potential in international trade for its garments sector, jute products, shrimps, crabs and also for tourism. But the most important catalyst that influences the growth of a country, energy security, hinders those sectors to blossom. The government is facing difficulty to pace up with urban and industrial demand for last few years.

But expanding rural electrification is also vital for irrigation and the key to the prosperity and development of rural areas as well as to fulfill the GoB's vision of ensuring access to affordable and reliable electricity for all by 2020. It is well recognized that energy demand in our rural areas is increasing and supply of fossil fuel at subsidized prices is becoming an ongoing challenge for the government. Moreover, providing power without intensifying the effects of climate change is a priority for Bangladesh.

This paper aims to develop a hybrid mini-grid model for off-grid rural Bangladesh along with operation, maintenance and an appropriate tariff mechanism for sustainable power supply.

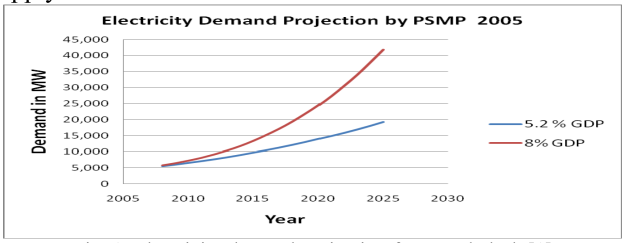

Fig. 1. Electricity demand projection for Bangladesh [1]

II. Design of Hybrid Mini-Grids

A hybrid mini-grid system usually defined as an electricity production and distribution system with a convenient combination of two or more types of electricity generating sources (wind turbines, PV panels, small hydro plants, fuel genset, biogas plants etc.). The mini-grid concept has potential applications that range from village electrification in less developed areas to "power parks" that offer ultra-reliable, high quality electrical power to high tech industrial customers. These systems can be complex, combining multiple energy sources, multiple electricity consumers, and operation in both island (stand-alone) and utility grid connected modes. [2]
The first and only attempt to establish a hybrid wind-PV system is by Sustainable Rural Energy under Local Government Engineering Department (LGED) financed by UNDP and MoEF, a 10 kW Wind-Solar Hybrid generation unit in Saint Martin Island. [3]

Hybrid Mini-grid system is usually composed of three subsystems: the production, the distribution, and demand subsystems. Each subsystem can vary greatly in its components and architecture according to the availability of resources, desired services to provide, and user characteristics.

A. Production

This subsystem determines the electricity production by hybrid system which comprises of four sections. They are generation (RETs and genset), storage (batteries), converters (convertors, rectifiers, and inverters to convert DC power to AC), and energy management systems. The subsystem connects all the components through the bus bar at the required voltage (AC/DC) for the distribution subsystem.

B. Distribution

This subsystem bears the responsibility of distributing the produced electricity to the users by means of the mini-grid. The mode of distribution (DC/AC) on the grid is the primary

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issue along with the question of building either single or three-phase grid. This decision will have a major impact on the cost of the project and will mainly determine the devices that would be used.

C. Demand Subsystem

This subsystem includes all the equipment on the end-user side of the system, such as meters, internal wiring, grounding, and the devices which will use the electricity generated by the hybrid power plant.

The design of the mini-grid directly affects the cost structure of the project and determines not only the price of the energy produced, but also the quality of the services provided to the users. The early assessment phase of any successful design must integrate an analysis of the local conditions and the rural community's needs, and maximize community involvement and support in the design considerations. Local involvement is a necessity to reduce the chances of project failure and any negative image of renewable in the region.

The system should include individual meters, or other devices to measure and limit the consumption of each user to continue power supply even when there is deficit in generation.

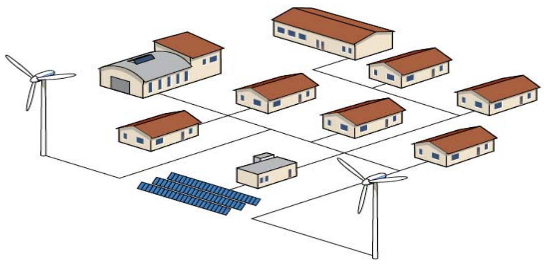

Fig. 2. Hybrid Solar-Wind mini-grid

III. Implementation Scope Analysis

A. Adjustment: Varying Natural Conditions

Renewable energies highly depend on location; so adjusting the model according to the exposure of different sources is expected prior selecting any specific method. Hydro power is scarce in context of Bangladesh, following with solar and then wind energy.

High-quality solar resource assessment accelerates technology deployment by making a positive impact on decision making and reducing uncertainty in investment decisions. GHI and DNI are the two parameters of interest for resource assessment and characterization at a particular location. GHI is defined as the total energy from sunlight, both direct and diffuse, that reaches unit area horizontal to the surface of the Earth. DNI is the amount of energy from direct sunlight that reaches unit area normal to the sun. [5]

Important assessment in recent years on solar energy resource over the country was carried out by Renewable Energy Research Center (RERC), University of Dhaka which was funded by United Nations Environment Program (UNEP) and Global Environment Facility (GEF). Based on the measured data the final map of global horizontal irradiance was produced which shows that monthly average solar global radiation in Bangladesh is around 4.255kWh/m^2/day.

According to the produced map almost half of the country fells in 4.25-4.5 kWh/m^2/day range which covers the whole western part and some of the south-eastern part that are potential for solar power generation. [4]

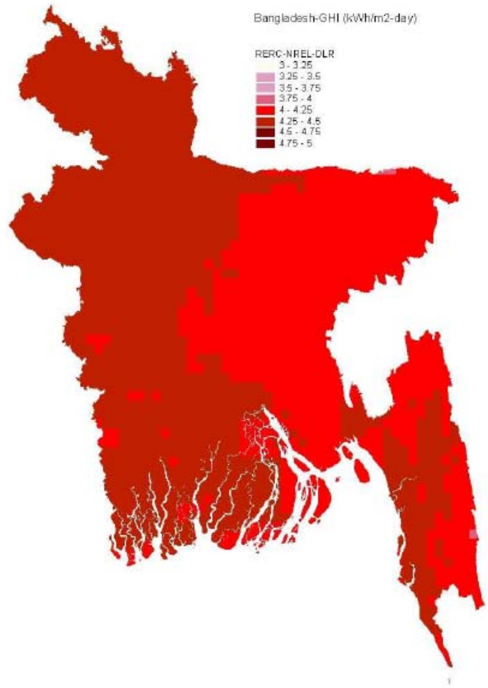

Fig. 3. Global Horizontal Irradiance (GHI) of Bangladesh [4]

The seacoast and coastal off-shore islands of Bangladesh appeared to have better wind speed than other parts. Although at the height of 20 and 30m data are at hand for different locations but data for higher height (50m) which quite often used for wind generation is not available. Detail assessment shows that the wind speed in the coastal areas goes up to 5.8 m/s. However there is a strong seasonal and diurnal variation prevails in these localities. But it is worthy to note that some of the locations have wind power density higher than 150 W/m^2 which represents a good potential for wind generation. RISOE National Laboratory, Denmark has independently assessed wind resource of Bangladesh. RISOE predicted wind energy density shows locations with power density above 200 W/m^2 over 2000 km^2 which is highly encouraging. [6]

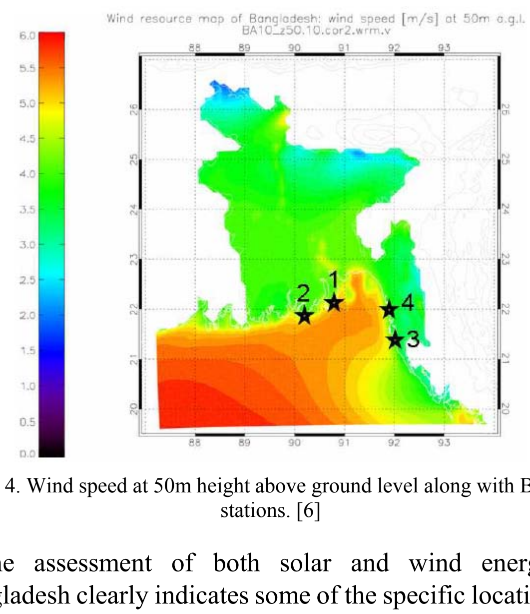

Fig. 4. Wind speed at 50m height above ground level along with BCAS stations. [6]

The assessment of both solar and wind energy of Bangladesh clearly indicates some of the specific locations as potential sites for hybrid mini-grid system. Thus most competent candidate for PV-Wind hybrid system with little doubt is lower south-eastern part of Bangladesh.

B. Estimation: Size of the Project

A cost-efficient design of a hybrid power system must precisely match the production capacity and local demand. Oversize system increases the already high capital costs, producing a surplus of electricity whereas under-size capacity results in unavailability of power, higher stress on the components and resulting dissatisfaction among end-users, which can lead to the failure of the project.

In order to install the correct production capacity, precise estimates of demand are needed. In a simplified way, the demand is equal to the number of users multiplied by the estimated average use of electricity per user. However, this approach is not really sufficient as the margin of error is quite large for a village-sized project. Instead, it is better to aggregate the estimated electricity demand of each potential user, considering domestic, public services, and economic services.

Usually the priority for most rural electricity consumers is the provision of lighting. Modern energy efficient lamps provide adequate lighting at a lower cost than paraffin lamps, but there is a wide range of other types who have poor power factor and current waveforms. There is often a trade-off between lamp cost and power quality. Unlike light other loads are need to consider carefully putting on for use to minimize power consumption. Hence total load has to measure so that project size becomes smaller in size thus lower primary cost.

TABLE I: TYPICAL LOAD PROFILE OF A FAMILY COMPRISED OF 3 HOUSEHOLDS

Load	No. of load	Wattage/ load	Hours/Day	Days/ week
Light	4	20	5	7
Fan	2	80	10	7
TV	1	60	3	7
Radio	1	10	3 (day & night)	7
Mob. Charger	1	10	5 (day)	2
CD player	1	80	2	5

So, total load= 3kWh/day (considering inverter efficiency)

Table I shows typical load profile of a 3-household comprised family. [4] The data will vary according to different loads, family size and consumption hour. While designing mini-grid, along with household level consumption other entities of community like small-scale business, hospital, mosque etc. also need to consider if only community agree.

C. Projection: Cost of Hybrid Generation

In off-grid areas diesel is consumed in large quantities for homes, rural markets and irrigation purpose. Replacing diesel by renewable resources would help lower import cost of diesel and lessen GHG emission. Although renewable technologies are more costly than conventional methods, due to unavailability of grid it remains as the main choice for rural areas. Newer technologies and improving efficiency inspire to initiate new renewable energy-based projects.

Hybrid hydro and diesel generator require less initial investment cost comparing with Hybrid PV-Wind, Hybrid Wind and Hybrid PV system. The figure below depicted the cost projection over 20 years of life cycle.

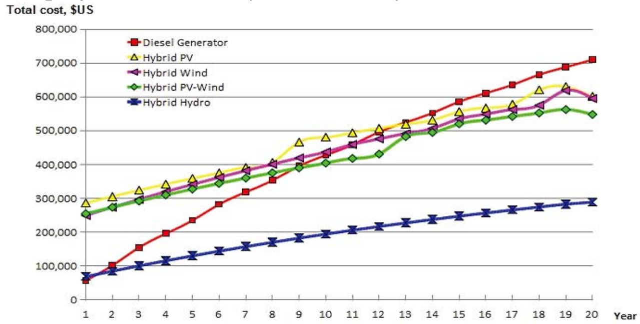

Fig. 5. Cost projection of different types of hybrid generation [7]

For many locations in Bangladesh it is found that hybrid generation using PV or wind along with diesel is cost effective. But the maintenance cost for diesel integrated system tends to high. A case study for cost of generation is shown in Table II.

TABLE II: COST COMPARISON FOR DIFFERENT GENERATION MODE [6]

Power generation	Location	Wind speed	Generation mode	Cost/kWh (tk)
100 kW	Kuakata	5.5 m/s	Diesel only	29.7
		5.5 m/s	Wind-diesel	16.3
		5.5 m/s	PV-Wind-Diesel	16.8
		5.5 m/s	PV-Wind	19.8
		5.5 m/s	Wind	24.4

This table illustrates costs for per unit generation for different modes of generation for a particular location where both solar and wind energy are adequate in context of Bangladesh. Various off-grid electricity distribution technologies (Diesel, Wind-diesel, PV-Wind, and Wind etc.) are considered for cost comparison and among all Wind-Diesel hybrid comes out as the most cost efficient technology. While cost for PV-Wind is only a little over Wind-Diesel system but it is certainly environment friendly option with less maintenance cost. It is also a potential candidate as CDM project and carbon credit earned by the project will work as a complement.

Community involvement is pivotal for building ownership as well as to minimize the cost. Community can provide labor and other necessary materials for transmission and distribution (i.e bamboo, rope etc.). Community organization can also play role to impose use of cost effective loads (i.e CFL lights) and appropriate energy usage practice which in return minimize initial investment and maintenance cost.

IV. PROPOSED CONVENIENT COMMUNITY-BASED MODEL

In many off-grid areas of Bangladesh, only a few affluent families can afford to establish a SHS whereas others regardless their earnest intension can't due to high initial investment. A community-based model with renewable energy based mini-grids could be the solution for these areas to ensure access to electricity for everybody, since interest from the private sector or utilities remain limited. As renewable sources are highly site-dependent, based on geographical location and perception and willingness to adopt any particular solution have to review prior setting up a hybrid renewable technology in community. Community-based organizations, who also happen to be consumers, will have strong interest in the quality of the service, increase self-sufficiency and self-governance, generate O&M&M scheme and offer the possibility to apply tailor made tariffs. [7]

An account with a local bank could ensure that revenues generated from the operation of the mini-grid are properly accounted for and earmarked for the intended purposes.

Through this process, the community becomes the owner and operator of the system and provides maintenance, tariff collection, and management services.

As the community will be consumers, project success thus highly depends on their satisfaction. An imposed solution will only agitate dissatisfaction and in long run project failure. That's why holding local consultation, respect local organizational structures play a vital role for future sustainability of local off-grid electrification project.

Local communities usually lack the technical skills to design, install, and maintain the systems; the business skills to develop sustainable tariff plans and additional added value to increase the outcomes; and the financing resources which often results in technical and financial failure. A community-based model, therefore, requires substantial amount of technical assistance with system design as well as training in operation and maintenance and at-least short term assistance in management support during the lifetime of the project. [7]

V. Hybrid Technologies and System Design

From the perspective of Bangladesh's rural remote areas a promising approach to meet rural energy needs is PV-wind hybrid systems using small wind turbines. The hybrid design approach also takes advantage of the differential availability of the solar resource and the wind resource, allowing each renewable resource to supplement the other, increasing the overall capacity factor.

PV-Wind hybrid systems consist of the following components:

- One or more wind turbines (common capacity ranges from 5 to 100 kW)
- PV modules (capacity varies depending on load requirement and the nature of the control unit)
- Control unit (commonly known as inverter – cum – controller)
- Storage system (typically battery banks)
- Consumer load
- Additional controllable or dump load
- Additional provision for connecting diesel generating sets [8]

The features that shape and keep operating the system are discussed briefly below:

A. *Components Coupling: AC vs. DC Bus Bar*

Larger loads (3 to 100 kW) call for more traditional AC-coupled systems with all of the flexibility inherent to a more conventional grid arrangement, but still incorporating battery storage and an optional DC bus. But for cost minimization the option for DC bus is excluded from the proposed hybrid model. This arrangement requires coupling of all generators and consumers on the AC side. Since these kind of decentralized systems are grid compatible in their power characteristics, they can be deployed so that broader interconnection to other mini-grids or the national grid is possible in future. Such a structure allows maximum electrification flexibility in initially supplying rural villages with the power for basic needs and subsequently scaling-up the rural power available through progressive interconnection. [8]

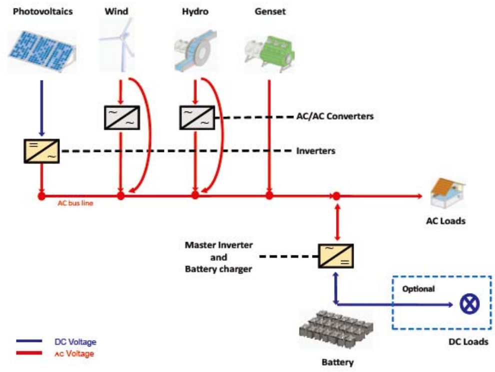

Fig. 6. AC bus bar coupled hybrid mini-grid engineering [9]

Regarding costs of installation, the difference between AC and DC bus bar is negligible for lower load application and small area coverage. For village mini-grids AC bus bar is recommendable since the efficiency is higher, the losses lower and the system is more flexible and expandable, although the wiring is more complex which could be done by professional technician. A bidirectional master inverter can be installed to control the energy supply between AC loads and battery charge.

B. *Single vs. Three-phase Distribution Line*

A three-phase distribution line has several advantages on its account. But it is likely to be more preferable for large villages where income generating services are available and where national grid connection is a possibility in future. But three-phase grid is more complex and needs more conductor lines hence more expensive. If local technology allows then it is important to know that in single-phase line the loads do not need to be balanced, and for the same size there is more surge capacity. It also reduces the costs while allowing an expansion on the generation capacity in the future. If only a few appliances in the village require three phases it can be worthwhile to invest in phase converter instead of designing a three-phase system.

The capital cost of distribution facilities is proportional to both the circuit-kilometer of distribution conductor and the rated output of the generation source. Only a low-voltage distribution network is needed when the power station output is 60 kW or less, as loss reductions will be nominal unless the distribution circuit kilometers are very large. A power station output of 100 kW may require a higher voltage network with transformers, depending on factors such as customer density and size of the mini-grid. [9]

C. *Storage Capacity*

To ensure stable power supply when renewable energy sources are unavailable battery back-up is indispensible. The frequency of periods without renewable generation, combined with the necessity to maintain a state of charge above 45%, will help determine the sizing of the battery capacity. This decision will of course have a dramatic impact on the total system costs and also a quality requirement depending on the customer's need. It is important not to reach often a full SoC between cycles and to avoid prolonged deep discharge, but this can be managed by using a diesel generator as a backup. The lifetime of batteries must be maximized as battery costs play a major role in the project costs.

Genset use ensures the quality of service when all other technologies are down or when demand is especially high. But it also increases primary and also operation cost as fuel is highly costly.

VI. Pragmatic Practices

A. Operation and Maintenance Issues

Several problems exist when it comes to the financing of renewable and mini grids. One of the main ones is the question of long-term operation and maintenance (O&M). Generation and distribution equipment must be regularly maintained to operate efficiently and comply with the lifetime expected. A good rule of thumb is that O&M costs for a power delivery system should run between 1/8 and 1/30 of capital cost on an annual basis.[7]

The lifetime of a mini-grid is considered to be around 20-30 years, but can be more than 50 years with proper maintenance. Operation and maintenance therefore have to be planned carefully in the project structure itself, as well as in the financing scheme, to be sure that the system will continue to run smoothly in long run. To ensure its own sustainability either the project has to generate sufficient cash flow or subsidies have to be smartly targeted towards long-term O&M.

As with the individual SPV and wind technologies, the key uncertainties affecting delivered generation costs revolve around expected Capacity Factor and capital cost variability. Since the hybrid systems combine two resources, the range over which Capacity Factor can vary will be smaller than with the individual technologies. A Capacity Factor in the range from 25% to 40%, with 30% as probable value is assumed. The uncertainties in projected capital costs, shown in Table III, and assume a ± 20% variation in O&M costs in order to estimate the band of generation cost estimates in the years 2010 and 2015 shown in Table IV. [8]

TABLE III: PV Wind Hybrid Power System Projected Capital Cost ($/kW)

Capacity	2010			2015		
	Min	**Probable**	**Max**	**Min**	**Probable**	**Max**
300W	4,650	5,630	6,440	3,880	5,000	5,800
100kW	4,.30	4,750	5,340	3,420	4,220	4,800

There are several options to pick from to share O&M management responsibilities, although all are linked to the question of ownership and to the distribution of responsibilities between the different stakeholders involved in a project. However, unless clear ownership, responsibilities, and risks are clearly established and transferred to community, the project is unlikely to maintain sustainable operation over an extended period of time.

TABLE IV: PV Wind Hybrid Power System Projected Generating Cost (cents/kW)

Capacity	2010			2015		
	Min	**Probable**	**Max**	**Min**	**Probable**	**Max**
300W	31.6	37.8	44.5	28.1	34.8	40.9
100kW	23.8	27.8	31.7	21.4	25.6	29.1

B. Acting on the Project Revenues: Tariff

When it comes to O&M the determination of the tariff is the main concern. A basic rule generally accepted in rural electrification planning is that, regardless of the scheme chosen, an adequate tariff structure should at least cover the running costs (O&M) to ensure the ongoing operation of a system throughout its lifetime. Moreover, tariff must also integrate replacement necessities (batteries) that generate a separate reserve fund for necessary replacements. Last but not least, tariff structures must keep a balance among sustainability, meeting rural consumers' ability and willingness to pay (affordability). Community involvement is critical for the sustainability of renewable energy mini-grids. Communities sometimes can pay up to 10–20 per cent of the capital investment of renewable energy mini-grid systems upfront in the form of labor, material, and cash contributions. [10]

Flat-fee tariffs with different categories are a good option for less wealthy end-users but the tariff rate itself should be able to supply O&M funds as well as replacement costs. Collection of any tariff also needs careful consideration.

C. Education and Capacity Building

The issues of training, capacity building, and embedding into local communities have also become central in modern rural electrification to ensure project sustainability. They are tightly linked with key questions on ownership, financing, and other factors, and have to be addressed right from the inception of the project. For instance, it is hard to avoid the question of local involvement when one talks about a business model based on a community.

At the village level, local training and the involvement of the local population are very closely linked. In every type of project, regardless of the model used, it is critical to factor in education and training of end-users. Very early on, in the assessment phase, some efforts must be made to maximize community awareness, involvement, and support, which are vital to project success. From project inception, target communities must be reached via promotional programs and regular meetings with community leaders.

Most people in rural villages are unaccustomed with the range of uses electricity can serve. This can limit the benefits that potential consumers see for themselves. Therefore, the technical education of consumers to help them to make the best out of their systems and to ensure the project sustainability is fundamental. The active participation of end-users in this educational program on operation and maintenance has to be pushed since these activities are very complex to them. It is also important to ensure that the consumers are aware of their obligations in terms of payment and maintenance and of the repercussions for failing to live up to them.

VII. CONCLUSION

Hybrid mini-grids incorporating renewable energy can be a cost-effective means of supplying affordable and reliable power to rural communities. Economic aspects of these technologies are sufficiently promising to include them in developing power generation capacity for developing countries.

Research and development efforts in solar, wind, and other renewable energy technologies are required to continue for, improving their performance, establishing techniques for accurately predicting their output. [11] However, such projects require capacity building at every point of the project chain, and with every stakeholder. Capacity building work, from project inception to the operation of the system and the organization of the local social structures, must be factored into the cost and timeframe of project development upfront in order to ensure the sustainability of the investment.

There are various models of ownership, each with its own strengths and weaknesses. Consideration as to the best form of ownership will vary from community to community and must take into account the model best suited to local stakeholders.

Some key points to observe when considering development of a hybrid micro-grid are:

Since long-term viability of the system depends on the satisfaction of its users, it is imperative to include them in planning and encourage participation from local leaders during each phase of the decision making process.

Community-run mini-grids have myriad positive impacts on the community in terms of self-governance and local buy-in into the electrification system. However, a long preparation period including technical and capacity building is imperative to compensate for the lack of skills and potential social conflicts. Local ability to deal with serious technical issues could also be a problem, thus adequate training programs must be developed.

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