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A Comprehensive Study of Contemporary Advancements in Hybrid Renewable Energy Systems Incorporating Artificial Intelligence Methodologies.

Abstract

An extremely useable and excellent alternate power source is solar power which can really reduce or it may say cut our dependency on the non-renewable energy sources and destructive fossil fuels. Amongst all renewable energy sources, solar radiation energy source has an important role in various platforms like climate and weather extremes, photosynthesis, hydrological cycles, balancing the radiation and geographic conditions etc that is why it has very important role. Solar radiation (SR) can be anticipated with extraordinary accuracy, and it could be feasible to definitely limit the effect cost related with the advancement of solar energy. In order to predict the advancement of renewable energy frameworks, this study intends to investigate several artificial intelligence applications in relation to various basic forecast benchmark models from literature assessments. Differential conditions, massive PC power, and time requirements are among the many models that are used to regulate or predict energy framework exhibits. Machine learning techniques seem to be among the best options. With a special focus on Artificial Intelligence, the study provides an overview of broad AI philosophies related to renewable energy sources.

Keywords: Solar Radiation, Renewable Energy, AI, ML, Algorithms.

Introduction

Current decade is enriched by the invention of two important source of advancement commonly known as renewable energy and artificial intelligence. Their contribution in science is immense and effective [1-2]. With a growing global population and advancing economy and culture, it is inevitable that the need for energy will rise. Renewable energy is being assigned increased responsibility for sustaining energy demands in order to avert an energy crisis and protect the environment from pollution produced by the usage of fossil fuels. One approach to the

aforementioned issues is to employ renewable resources and technologies such as solar, wind, and geothermal. Since renewable energy systems are highly impacted by their surroundings, it is imperative to apply methodologies and simulations to predict these changes for enhanced system efficiency and energy dispensation. The energy system is vital to the development of the human society, especially in daily life, industry and transportation. Energy is a fundamental requirement, not a luxury, and is crucial for sustainable development. Most energy produced today comes from fossil fuels, which are reliable yet unsustainable because their supplies deplete quickly and significantly negatively impact the environment. Greenhouse gas (GHG) emissions from fossil fuel combustion drive climate change and global warming [1-3].Due to the intermittent nature of renewable power, the market supply of electricity is therefore becoming increasingly unpredictable. Simultaneously, more energy intensive industries and a larger workforce are creating sizable swings in energy demand. This fluctuating supply-demand mismatch has led to volatile electricity market prices. As a result, both energy consumers and energy providers can substantially benefit from improved short-term production, demand, and price forecasting. In the bigger picture, improved forecasts can lead to lower costs of renewable energy projects and therefore higher renewable energy penetration [4-6].Solar irradiation varies from location to location and is a function of different meteorological and geographical parameters and physical parameters of the atmosphere. In close areas, solar irradiation values may not be the same. And using the nearby station data for any feasibility study may lead to project failure. Physically measuring this data for all locations is practically hard, especially in developing countries, due to the costs and difficulties involved [13,14].

Artificial intelligence (AI) is picking tremendous growth in recent times which acts as human intelligence and provides effective solutions in energy sectors.AI has sub fields like machine learning and deep learning they are quite beneficial in renewable energy sectors [6-10]. It enhances hybrid renewable energy systems (HRES) through the application of machine learning techniques to scrutinize data, thereby facilitating improved forecasting, optimization, and control, which in turn augments both efficiency and reliability. Its functions encompass the anticipation of energy generation and consumption, the optimization of solar panel and wind turbine performance, the management of energy storage systems, and the provision of predictive maintenance aimed at minimizing costs and operational interruptions. Furthermore, AI promotes the development of advanced grid systems that can effectively reconcile fluctuating energy

supply with demand, ultimately contributing to a more robust and sustainable energy infrastructure. In the past, researchers developed various strategies to get around the challenges and costs of assessing global horizontal irradiation (GHI) on the ground. Empirical models and models based on artificial intelligence (AI) have received the most research attention. GHI forecasting using AI models has yielded encouraging results. ANN has been widely implemented in several worldwide regions, including Turkey, Oman, China, India, Australia, and other places, with promising results [7-9]. AI methods use huge data to develop intelligent machines capable of performing activities that would normally require intelligence of a human. Since AI techniques including deep learning (DL) and machine learning (ML) are able to address nonlinear and complex data structures, they are gaining popularity in various fields of science and technology in order to solve real-life issues.

In recent years, with the fast development of AI-driven IoT technology, the applications of deep learning technologies have been extended to various fields, such as digital twinning, computersecurity,cyberphysicalsystems,transportationsystems,andairqualityforecasting. MLalgorithms comprise artificial neural networks (ANNs), kernel and nearest-neighbour (k-NN), extreme learning machine (ELM), support vector machine (SVM), to name a few.These techniques have an advantage over statistical approaches in that they do not require any internal parameters of the solar systems [10-12].

Thisstudyaimstoreviewtheuseof MLapplicationsandtechnologiesinrenewable energy's. Therefore, a detailed review of the latest studies conducted in major applications is carried out. In addition, the view of current issues, future trends and challenges are also discussed to improve the renewable energy systems.

Literature Study:

The incorporation of AI/ML with renewable energy may provide many solutions in energy sectors including automation, data optimization, data simulation, data streaming and productivity. This section provides detailed literature study in the mentioned field comprehensively and providing the key findings with solution.

Research work	Detailed study with technologies	Key findings
Lili Zhang et.al(2022)	• This study uses the Web of Science Core Collection Database for bibliometric analysis and science mapping. • AI-related technologies (e.g., machine learning, neural networks) are applied in power systems integration, such as solar and wind forecasting, power system frequency analysis, and transient stability. Tools: VOS Viewer, Cite Space.	• AI technologies can effectively address issues like integrating renewable energy with power systems. • The study identifies research trends and collaboration patterns, highlighting the importance of future AI advancements in the field.
Ali Azawii et.al (2022)	• Overview of AI techniques applied across renewable energy sources (wind, solar, geothermal, hydro, bio, hydrogen, hybrid systems) for design, optimization, prediction, management, and regulation. • Focuses on deep learning and machine learning. Techniquesincludeneuralnetworks (NNWs).	• Deep learning and machine learning are crucial for improving renewable energy systems. • Neural networks are most prominently used in future applications. AI, combined with IoT, sensors, and drones, helps overcome data gaps, enabling more efficient renewable energy systems.
Dey S et. al (2025)	• Describes the techniques of AI, ML for building sustainable energy system .	• Innovative AI schemes like SVM,RF,kNN for energy related data storage and

		optimization
Dey S (2025)& Dey S. et.al(2022)	• Studies different algorithms for solar power plant and renewable energy extraction methods	• Different methods like innovative plant set up through the help of AI.
Trung Van Nguyen (2023)	• Explores AI algorithms and modelsfor renewable energy systems, focusing on smart grids, power forecasting, and balancing supply- demand in intermittent energy sources. • Emphasizes optimization, reliability, and cost reduction in renewable energy.	• AI helps optimize renewable energy systems, improving efficiency, reliability, and cost-effectiveness. AI models provide high prediction accuracy and help balance supply- demand. • However, challenges exist in dealing with data quality (especially for cloudy days) and training models effectively.
Hasan Alkahtani et.al(2024	• Focuses on AI technologies for forecasting energy consumption and demand. Introduces Explainable AI (XAI) for improving transparency in AImodelsusedinenergyapplications. • Techniques include machine learning (ML) and deep learning (DL).	• XAI enhances transparency and interpretability of AI models in energy applications. • The study emphasizes the importance of making AI technologies accessible and aligned with sustainability goals while focusing on optimizing operations and system maintenance.

Table 1: Literature survey on incorporation of AI/ML with renewable energy.

The key findings from the detailed literature survey have been shown in above table 1.There is huge research gap in some key areas which has been listed below:

- Research gap in proper utilization of AI/ML technologies.

- Innovative algorithm and their application should be properly designed and applied.
- Huge research gap in systematic studies of AI incorporation.
- Finding the methodologies of incorporation of these technologies.

Utility and challenges faced by renewable energy sources in recent times:

The sustainability of biological and chemical processes in nature depends on solar radiation, which is a free and highly beneficial input for the majority of industries, including heat, health, and tourism, agriculture, and energy generation. Climate data, the hydrologic cycle, sensible heat, latent heat, evaporation, ecological life, migration, and many other significant parameters are all directly impacted by changes in solar radiation. As environmental concerns have grown, solar energy systems have started to be widely used on a large scale in many countries worldwide, but only in those with greater potential for solar energy.

Solar radiation is electromagnetic waves which are received from the sun, over a wide range of wavelengths at varying intensities. The wavelength comes from the sun are between the intensity of 300 nm to 3000 nm called shortwave radiation. If the wavelength is short then frequency must be high because the wavelength and frequency is indirectly proposal to each other. Therefore, these waves come to earth with very high energy. The total energy emitted bythe sun is around 3.72X 1020 MW.The solar radiation reaches at a rate of 1,367W/m2to the upper surface of the earth. For enhancingthe qualityof lifeand forthe progress of society we need the high amount of energy but the extensive use for fossil fuel creates bad impactson the environment such as air pollution (due to combustion of carbon contained in fuel) and social and sustainability problems like the Greenhouse effect. So, to overcome the dependency on conventional fuels many researchers and some organizations are working on to get some alternative fuel, which should be a convenience to use, easy to store, also minimize the pollution and must be abundant in nature [19].

The increasing rate of energy consumption is essential for progress of our civilization and therefore main problem is how we produce energy. Extensive use of fossil fuels and nuclear energy has created bad impact on environmental, social, and sustainability problems. So, we need such energy sources that will forever and can be used without pollution. Furthermore, conventional energy systems using fossil resources, especially old ones in numerous and small scale, are found to be major contributors to atmosphere pollution and green house effect.

Renewable energies are mostly intermittent; hence, the storage of energy is essential if we are to be fully dependent on renewable sources. Batteries are currently one of the most promising technologies for these purposes. However, an effective management system is essential to determine the battery's charging and discharging pattern, which can offer a cost- effective option for battery-integrated micro grid systems. For this, a long short-term memory was proposed which showed that the real-time strategy outperforms the offline optimization strategy, reducing the operating cost by 3.3% [20].

Renewable energy comes from natural replenish able sources like sunlight and wind and is often referred to as clean energy because it doesn't cause pollution. The presently known reserves of non-renewable sources of energy like coal, gas, oil are depleting fast and the renewable energy has emerged as the more preferred alternative. Moreover, rising prices of fossil fuels, particularly natural gas and electricity, environmental concerns, energy security reasons and greater investment in clean energy have resulted in the greater generation of renewable energy globally [21].All sectors and regions have the potential to contribute by investing in renewable energy technologies and policies to reduce them.RES awareness should also cut across individuals, corporate organizations, companies, business owners, decision-makers, owners of business and personnel involved in the business of RES technology and its utilization, and the public.

Reducing our carbon footprint through lifestyle changes and behavioral patterns can greatly contribute to mitigating climate change. The environmental effect of the materials used in the building of hybrid renewable energysystems is one of their environmental problems. Alot ofthe raw materials needed for solar cells, wind generators, and energy storage devices are removed using harmful environmental practices. These materials' production and removal mayharm the ecosystem bypolluting the environment and destroyinghabitats.WindTurbine and solar panel installations can harm local environments and habitats while wind mills have been linked to birdand bat deaths. Installations forgreen energycan becarefullyplanned and managed to reduce these effects and safeguard delicate environments.There should be favourable government policies on power generation for RES that will be different from the conventional fossil fuel generating sources. These policies should Favor reduction or total exemption in taxpayment, tariff plan, low-interest loans, subsidies in RES utilization, custom dutywaivers, tax rebate to encourage people to own solar-powered plants, government-sponsored programs on RES, etc.

Research on innovations and technologies that can reduce land use and can also reduce accidentsfromrenewableenergysourcesandthe riskofresource competition,forexamplein the field of bio-energy where food for consumption competes with energy production.

The cost of acquiring the least rated capacity of renewable energy is far above the minimum wage as earned in most developing nations. Traditional energysources have a lower cost and price than renewable energies.As the production cost of renewable energy is higher than that of fossil fuels with the same technology, there are serious barriers for the commercialization and distribution in relation to renewable energy. The main reasons in high production cost of renewable energy are small scale and low production technology. Hybrid renewable energy system fundingmethods canbedifficulttounderstand,particularlyintheabsenceofamature market for these products.To support the implementation of these systems and guarantee thatthey are available to a broad variety of stakeholders, creative financing methods, such as green bonds or crowdsourcing, may be required.

Increase international cooperation and support developing countries to expand infrastructure and modernize technology for modern supply and sustainable energy services as a means of mitigating climate change and its impact. The current development of renewable energy includes the cost barriers. However, a system operation reliability and decreasing production costcan beobtainedbymeansof adeveloped market.Theinfluenceofspecialinterestsinthe conventional energyindustryis a sociopolitical issue. In order to advance their own interests, fossil fuel corporations and other energy incumbents may oppose the implementation ofgreen energy systems through legislative lobbying or direct action. This may hinder the installation of green energy technologies and impede the shift to a more sustainable energy future. It is challenging for renewable energy systems to contend on an even playing field in many nations because the regulatory climate is still geared toward promoting fossil fuels and other non-renewable energy sources. These obstacles can be overcome with the aid ofpolicies that encourage the use of renewable energy, such as feed-in prices and renewable portfolio requirements.

Oneof the major challenges of RES development in developing countries is the lack of skilled/trained manpower. RES technologyis evolvingveryfast. However skilled and trained manpower to match this pace of development is obviously lacking. The shortage ofmanpower and competency level has resulted in poor or no consideration of solar insulation, panel

efficiency, and specific consideration of the geospatial angle of installation of the panels, among others. Policy enactment and implementation are distinctive elements of the policy process. In the future, renewable energy should be developed to an industrial scale. Thus, depending on the support of policies, market share of renewable energy has to be increased. Due to variations in each source's voltage, frequency, and output characteristics, it can be difficult to combine and maximize these various technologies so that they coexist harmoniously. The sporadic and unpredictable nature of green energy sources. For instance, weather-related energy sources like solar and wind can generate electricity sporadically. The electricity infrastructure may become unstable as a result, making it challenging to satisfy demand during peak hours. Hybrid systems must incorporate energy storage technologies to both store surplus energy during periods of high production and release it during periods of low production in order to overcome this problem.

In order to have more sustainable lifestyles, barriers related to the societal and cultural patterns must be prevented, and thus desirable and more sustainable alternatives and various incentiveswillberequired.Thecurrenteconomic systemstillremainsabarriertochangedue to the existing belief in unlimited natural resources and in continuous economic growth. On the other hand, the existing construction sector is a rather conservative industry. It is well known those new and more sustainable designs, building materials and construction methods are only emerging and being implemented slowly. The other challenge for the energy efficiency of buildings is related to high costs and long payback period for renovations.

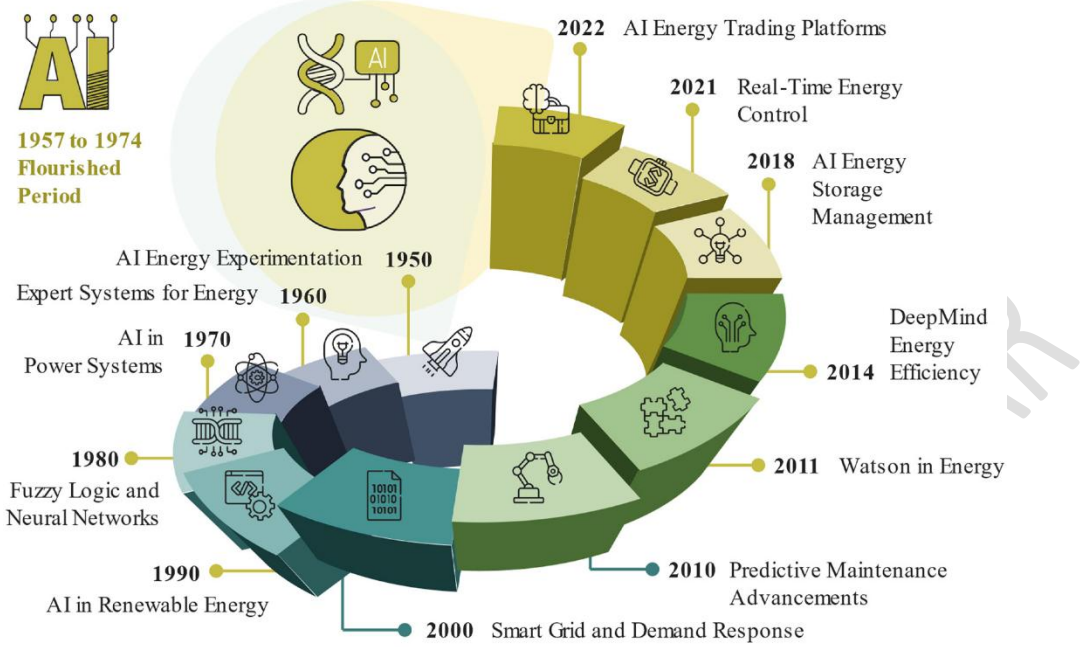

Figure 1: AI deployment in energy sector from 1950 to 2022 [22]

AI and its Systematic usage in Renewable energy Sectors:

- **Generative Artificial Intelligence:** The energy business enveloping areas like oil and gas, renewable energy, and utilities assumes basic part in driving economies and social orders all over the planet. Dynamic inside the space has generally depended on master knowledge, authentic data investigation, and complex demonstrating procedures. However, the coming of generative artificial intelligence has achieved a huge change in the business. With its capacity to dissect tremendous measures of data, create precise models, and significantly more. AI devices are turning out to be progressively fundamental for energy organizations, offering robotization for data investigation, anticipating, advancing sustainability, thus significantly more. The far and wide reception of AI isn't just a pattern however an essential shift that can encourage development and drive achievement. Generative AI can be utilized in the energy business to further develop repository recreation and demonstrating. Overwhelminglyofdata, the viability of AI in carbon control depends on the profundity and nature of available datasets. Sensors and IoT technology, which empower more exact and various measurements. Gen-AI likewise assumes a

vital part in dealing with the convergence of new data coming about becauseoftheshifttowardscleanenergy.Thisshiftisexemplifiedbythefastdevelopmentof appropriated energy resources (DERs), which aim to decentralize and confine energycreation.

- **Blockchain Technology:** Blockchain technology is changing the Renewable Energy Industry, to improve things. Blockchain technology, in this way, makes a decentralized energy sharing economy, where power can be traded between peers, settling the network. Blockchain technology will consider a safer, cost proficient, low carbon network - manufacturing a more grounded way towards a zero-carbon world. The combination of blockchain technology into the renewable energy area offers a huge number of possibilities; in any case, it likewise entails an assortment of deterrents and constraints that should be overcomes to guarantee a prosperous sending. A huge deterrent is the inborn unusualness of power dispatching frameworks, explicitly in regards to successfully dealing with the steadily changing qualities of renewable energy sources, for example, solar and wind. Moreover, the transparency innate in blockchain technology brings about protection concerns, which require careful treatment of delicate data to defend client security and stick to administrative necessities. Also, it is basic to focus on the insurance of the renewable energy foundation's respectability by guaranteeing protection from likely weaknesses and digital threats [23,24].
- **Smart Grids:** The connection between the smart grid and renewable energy spins around social occasion data. By utilizing smart grids, energy organizations can gather energy utilization data from each and every gadget on the grid, and afterward utilize this data to foster energy proficiency projects for their clients. It likewise permits energy organizations to screen energy stream and energy use in close to ongoing. Energy organizations can then decrease energy utilization through robotized request reaction frameworks which can switch off energy during top hours, bringing about energy reserve funds for property holders as well as energy organizations. Changing ordinary energy networks into Smart grids (SG) changes the energy area and further develops execution and unwavering quality. It additionally gives better administration, control, and correspondence

abilities. Smart grids are known to be cutting edge traditional grids because of the data stream capacities and two-ways power supply [25].

- **Artificial neural networks (ANNs):** It have picked up speed to where they have become famous and helpful models for order, clustering, acknowledgment, and expectation in a wide assortment of utilizations. ANNs are progressively being utilized for various applications because of their capacity and viability in taking care of various issues. They have shown to beextremely proficient when it is perplexing to separate through a mass of existing data, for instance, in the assessment of public transportation of individuals and merchandise, image acknowledgment, clinical examination, effectiveness investigation in nonlinear settings, or to change creation capabilities, among different applications. Inside the sustainable power blend, wind energy is presently viewed as the most prudent method for producing power. As of late, there has been new investigation into strategies fit for anticipating wind speed. This is vital because of the nonstop development of wind power age around the world. Inside sun powered energy, the ANN strategy has shown to be an option in contrast to conventional techniques, giving extraordinary advantages with regards to accuracy, execution, and displaying. The review demonstrates that the upside of ANN strategies over conventional methods is that they don't need information on interior framework boundaries, require less computational exertion, and proposition robust results to multivariate issues. ANNs have additionally been applied in various fields of sea, beach front, and environmental engineering [26].
- **Energy Storage Application:** Energy storage in renewable energy sources, especially in solar sources will allow progress in the energy sector, the impact of energy storage is its ability to smooth unpredictable energy generation and sustain the evolution of demand. The potent influence of every new technology is to be cost-effective so that energy storage does, and it leads to lower costs of lithium-ion batteries. With the help of the battery, power conversion system and monitoring and control systems we can built a system which can control energy system [27-29].

- **Internet of Tings (IoT):** The combination of IoT in renewable energy portion is empowering its development by and large. Uses of Internet of Things moderate a few difficulties that are restricting the acknowledgment of renewables. The osmosis of IoT in solar and wind energy frameworks alongside sensors application can build their unwavering quality much further. To augment energy creation, the vast majority of the solar boards utilize double pivot trackers. These global positioning frameworks adjust the point of solar boards and assist them with getting the most extreme solar radiation over the course of the day. IoT frameworks can be utilized to remotely direct and control these global positioning frameworks to guarantee most extreme energy creation proficiency. By utilizing investigation arrangements, the development of the sun can be followed which can then be utilized to change the point of solar boards consequently. The expense related with creating energy from these sources has diminished throughout the long term yet coordinating them with IoT can additionally decrease expenses and increment reliability. IoT frameworks can help remotely screen and manage these trackers to guarantee their ideal capability. IoT arrangements are changing the energy area, empowering practical development and the reception of renewable energy frameworks through associated arrangements. IoT improves the exactness of figures with respect to renewable energy yield. IoT works with more prominent admittance to renewable energy sources, especially in emerging countries [30-33].

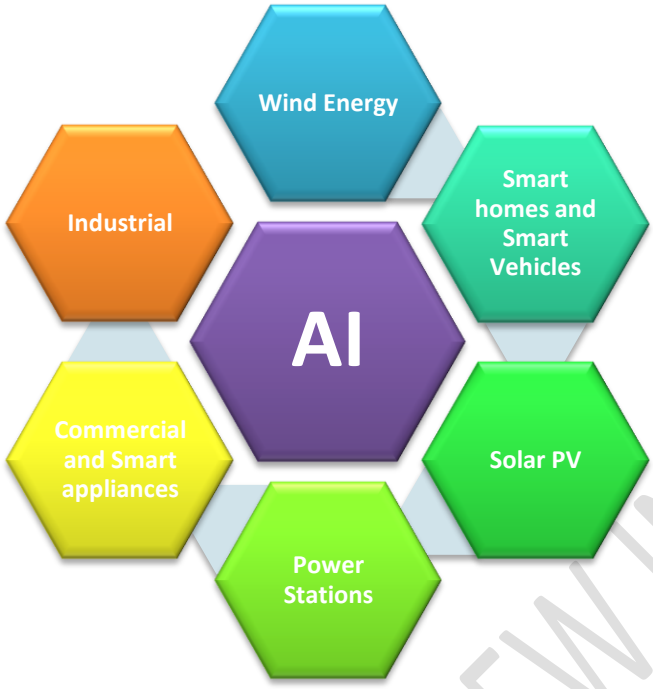

Figure 2: Applications of AI in different sectors

Conclusion

The significant job of artificial intelligence strategies and their compelling job in creating renewable energy methods is admirable in each perspective from where we can apply in different regions. Subsequent to surveying the vast majority of the procedures utilized in various regions, it is vital to zero in on the deep learning andAI strategies to further develop workinrenewable energy. Deep LearningislikewiseanexceptionallypowerfulAIprocedure broadly took on for a great many applications. It presents a high learning limit fromenormousscopedatasets, upholdsunsupervisedlearning, andhasahighspeculationcapacity. It issignificantthat, amongallAImethods,theneuralnetworks(NNWs)arecurrentlygetting the most consideration for future applications. Anticipating photovoltaic power age is basic for safeguarding framework security and organizing asset utilization.

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