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Machine Learning Based Optimization of Agricultural Irrigation and Energy Scheduling for Resource Efficiency

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Abstract: Agriculture is the most important developing sector. But nowadays, it consumes large amounts of water and electricity for the production because of the manual irrigation and scheduling methods [1], [6]. With the increase in population, farmers need to manage more land to irrigate but due to water scarcity, and an increase in power cost that affects more cost for the irrigation [4], [10].

This paper proposes an IoT and Machine Learning-based optimization system by providing water at the right time to the fields with low consumption of the electricity bill [3], [8]. Our proposed solution uses a Random Forest Regression model and it integrates with the IoT for the development. Here, our model works by taking the data from the ESP8266 NodeMCU microcontroller, soil sensor and water level sensor [5], [7]. From these sensors data is taken continuously over a 30-day period and using this we can predict the exact need of water to the fields. All the results are stored in the FireBase while using the wifi.

The implemented model is used for controlling the manual operations for providing water to the fields and it helps to automatically turn ON or OFF when it reaches the required threshold value. This model mainly helps in reducing the water wastage, electricity cost that helps in improving the production. The implemented system achieves the water reduction wastage by 35% and electricity costs by 42% when compared to traditional fixed-irrigation systems, this helps in high model accuracy of (R^2) of 0.94 [9], [10].

Keywords: Smart Irrigation, Soil Moisture Sensor, Water Level Sensor, ESP8266 Nodemcu Controller, Resource Efficiency, Energy Scheduling.

I. INTRODUCTION

Nowadays, agriculture is consuming large amounts of water and electricity for production. Due to increase in the electricity tariffs, scarcity of water, these resources are becoming a challenge to the farmers to efficiently utilize the resources [4], [8]. In many areas, traditional irrigation methods and fixed schedules are used for production without knowing the exact need of water to plants. These may cause damage to fields, improper irrigation, water wastage and increase in the consumption of electricity [5], [6].

In general using the new technologies like IoT and Machine Learning few systems are developed which help in automated decisions for irrigation by reducing the manual irrigation and scheduling methods [1], [3]. The systems are mainly focusing on the soil moisture data that only helps in controlling the motors at the specified time. But many systems are developed only based on the various sensors that increase the complexity and cost for development. Most systems are not considering the electricity tariff variations, which increases the expenses [8].

The developed system overcomes all these limitations and helps to build an automated machine learning model with low- cost and improved irrigation. The system monitors the data continuously that is taken from the soil moisture sensor and the water level sensor which measures the water capacity in the fields with the ESP8266 NodeMCU microcontroller. After the data is collected and focusing on the threshold value, the model makes the decisions to determine the operation (ON/OFF) based on all the parameters.

The project mainly helps in the effective irrigation with the low-cost and easy operable to the farmers which reduces the electricity consumption and is used in effective decision making [2], [10]. Here the scheduling logic utilizes

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a two- level threshold approach for energy and crop safety. When the soil moisture is above the 25%, the irrigation is not done at that period and delayed due to high tariff-periods for reducing electricity costs. If the soil moisture is below 15% then the irrigation is done immediately for crop health.

II. OBJECTIVES

- To design an IoT-based smart irrigation system with low- cost sensors and using NodeMCU microcontroller for monitoring real-time soil data and water level.
- To the crop irrigation prediction using Random Forest Regression model for continuous soil and weather conditions.
- To improve electricity uses and energy-aware scheduling predicted on Time-of-Use tariffs.
- To reduce water and electricity cost through automated pump operations for predicting moisture and energy price.
- To evaluate system operations against the manual op- erations for proper water usage, electricity consumption reduction for accuracy prediction (MAE, RMSE, R^2).

III. PROBLEM STATEMENT

Traditional agricultural methods, manual irrigation and fixed scheduling leads to inefficient use of water and electricity. Increase in the electricity costs and water scarcity the farmers are facing challenges. There are most of the irrigation systems that fail to consider the real-time soil moisture, environmental conditions, and electricity costs. As a result, the excess water usage, high electricity costs, and risk in protecting crop health. Although few IoT-based systems provide automation, they don't have capacity for non-linear relationships for the energy pricing, soil and weather conditions. To overcome these lim- itations an automated low-cost irrigation system is built with Random Forest Regression-based machine learning model for accurate prediction in irrigation which helps in energy-aware systems for resource utilization.

IV. LITERATURE REVIEW

To improve irrigation few researches are evolved using the IoT and machine learning to introduce the new methods. One of the researchers, Goap et al. developed an IoT-based irrigation system that uses machine learning algorithms for the decision making based on the sensor data [1]. This system mainly improved the water efficiency and uses the open source technologies in farming.

Following these, Munir et al. proposed an intelligent system based on IoT and machine learning based system which helps in improving the irrigation based on analyzing the sensor and weather conditions [3]. This proves that ML-based systems will give more accurate results than the traditional methods and they also help in the various environmental conditions. To improve the demand forecasting Velmurugan et al. also used the weather prediction [4].

Most of the existing systems focus on automation using the soil moisture data and threshold values, these developed systems may not predict the energy optimization for the irrigation. The review presents a gap between the machine learning based prediction with energy-aware irrigation, which all forms a basis for the proposed system [8], [10]. Most systems do not focus on the future needs of irrigation. Considering all these limitations helps for prediction and energy aware scheduling and improve the usage of resources, long-term development.

Several studies presented the limitations of the traditional irrigation systems; they mainly focused on the soil moisture threshold values [6], [7]. These systems fail when considering the environment and the crop water needs. Few researchers suggested that machine learning models using regression can improve irrigation by learning patterns from the historical data [9].

The advancements in the new technologies like cloud computing and wireless communication helps in data storage and monitoring of the irrigation systems. These many existing solutions mainly focus on water management and energy consumption [2], [5]. The reviewed literature presents a lack of approaches that address water and energy optimization simultaneously; these reinforce the relevance of the proposed system.

V. RESEARCH GAP

Most of the existing research focuses on water conservation, and they focus on little reduction in the electricity costs based on Time-of-Use(ToU) conditions. But the traditional systems depend on fixed threshold values, they fail in

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considering com- plex patterns, non-linear interactions for various environmental conditions. Few systems provide the solution for crop safety and reducing their cost of operation.

This paper addresses the gap by using the Random Forest Regression model (R^2=0.94) for the accurate prediction in agricultural irrigation, while considering the two-level, energy aware strategy. Here we consider the pump operation during the low-tariff periods, the system at a time reduces the water wastage and bill reduction, and achieves the savings of 35% of water and 42% in energy reduction.

VI. PROPOSED SYSTEM

The Proposed system presents IoT-based smart irrigation that combined with a Random Forest Regression model for the conservation of water and energy optimization. The data is collected from Real-time soil moisture, water level, and the environmental parameters are taken from the sensors and connected to ESP8266 NodeMCU microcontroller. The model is trained based on the given data then it predicts irrigation demand using the weather conditions, moisture level, crop type, and energy tariff parameters. A strategy is considered for energy-aware scheduling based on Time-of-Use pricing pump operation automatically. The system reduces the manual operation and it results in 35% of water being saved and 42% electricity costs.

VII. SYSTEM ARCHITECTURE

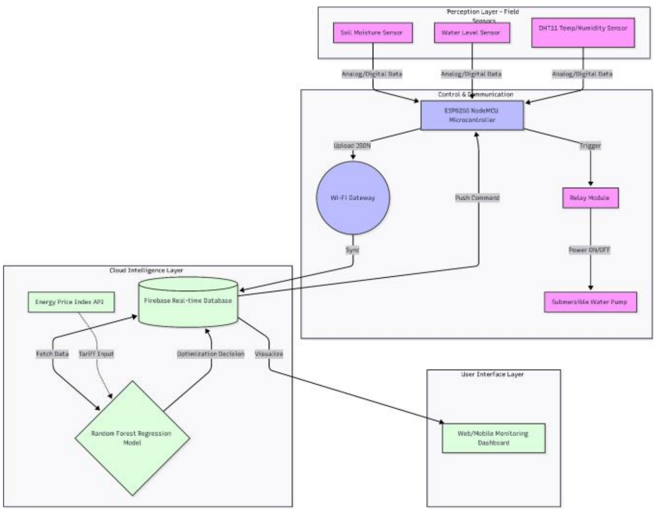

Fig. 1. System Architecture Diagram

VIII. METHODOLOGY

The proposed system optimizes agricultural irrigation by integrating with the machine learning-based irrigation and energy-scheduling. The main objective of the system is to reduce the water wastage and electricity usage and maintain soil moisture for the crop's health.

A. Problem Definition

Traditional irrigation methods mainly focus on the fixed schedules without considering real-time soil conditions, electricity tariffs, and weather conditions. This causes the usage of more water than required and increases energy costs. Our system addresses all these limitations and predicting the water for irrigation and scheduling pump operation with low cost- effective energy saving [8], [10].

B. Data Collection

The data set is generated from an 30-day experimental field study in Guntur, Andhra Pradesh. Here in the dataset the environmental and soil parameters were recorded at 15- minute intervals that helps to capture the temporal variations. To improve the data accuracy, the data collected from the temperature and humidity sensor readings are synchronized with OpenWeatherMap API data. For the model training and evaluation over a subset of 850 samples considered. The Features of the data set contains soil moisture, temperature, relative humidity, rainfall, crop type, and energy price index(1- 10), these provides comprehensive way for model prediction and optimization of energy-aware irrigation.

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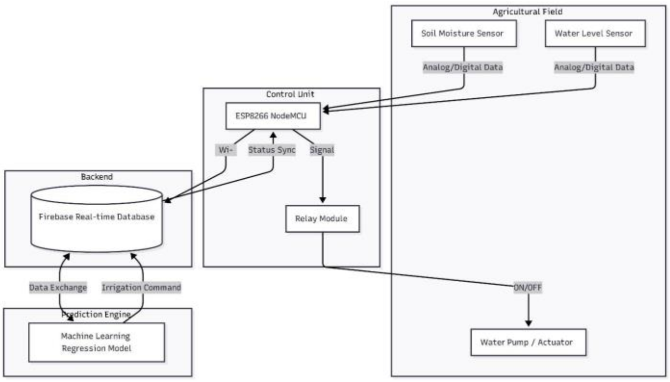

Fig. 2. Conceptual Framework of the Proposed IoT-ML Irrigation Solution Addressing Manual Inefficiencies

C. Data Preprocessing

Here the data is stored in structured CSV dataset format and used for analysis. The preprocessing steps are performed on the dataset such as cleaning, normalization, and feature selection which is used to improve the quality of data. Crop types are converted into numerical values and these help to train the machine learning models.

Machine Learning Model Development

Since the irrigation demand changes continuously, a Random Forest Regression-based approach is used because it predicts continuous variables and also it handles the noisy, non-linear relationships in the data [1], [9]. The model was trained on a dataset consisting of 850 observations where it can be divided into 80:20 training-testing data. The Random Forest was selected due to the fact that it has accuracy($R^2 = 0.94$) and it has the capacity to predict the future. The most important features of the dataset are Soil moisture(62.5%) and Rainfall (16.9%); these are primary sources for irrigation, while Temperature, Humidity, and Energy Price are used in energy price and energy-aware scheduling. For regression model training, we implemented a scikit-learn Random Forest model that contains 100 trees with depth of 10. To optimize predictive accuracy we are using Bootstrap sampling and this achieves a system from overfitting. For feature value computing we are using the variance reduction(mean squared error) for the Random Forest algorithm to reduce the error in prediction.

D. Irrigation Demand Prediction

Based on the input parameters soil moisture data, weather conditions, crop type, and energy price, the trained model pre- dicts the amount of water required for the irrigation. This helps in efficient irrigation and reduces water waste, optimising the energy consumption.

E. Energy-Aware Scheduling Optimization

An energy scheduling system is implemented to reduce the electricity costs. For the model training the dataset was labeled based on Time-of-Use(ToU) tariff structure, where the electricity bill pricing was modeled as 1-10 price index. During the training, the model learns on its own about the cost- aware irrigation, then the system pump is OFF state during the peak intervals when it has ranged from 8-10 unless the soil moisture level falls below the critical levels [8], [10]. Once the model is deployed, the NodeMCU takes the real- time data from sensors into the pre-trained model, then the model automatically determines the efficient pump operation.

F. System Integration and Automation

Here all the modules are combined into a single irrigation system. A microcontroller-based platform NodeMCU, helps in real time monitoring and controls the irrigation. Based on the system decisions the pump activation is operated automatically.

G. Visualization and Monitoring

Visualization tools are used to monitor irrigation and help in evaluating the system performance. The graphical representation of water usage and electricity consumption helps in understanding the system behaviour and evaluating the optimization results.

H. Performance Evaluation

The system performance is measured using the standard accuracy metrics also considering the practical indicators as water conservation and energy costs are measured. Table I presents the performance of the regression model using statis- tical measures and the AIC and BIC values indicate that the model is fit and avoids the overfitting caused by sensor noise [3], [9].

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I. Experimental Validation

The system is tested using various soil moisture and elec- tricity conditions. This helps in improvements in irrigation efficiency and reduces the water wastage and energy consump- tion. The system behaviour is analyzed in Table II, the system balances the operation automatically based on the electricity tariff conditions, and helps in the efficient irrigation.

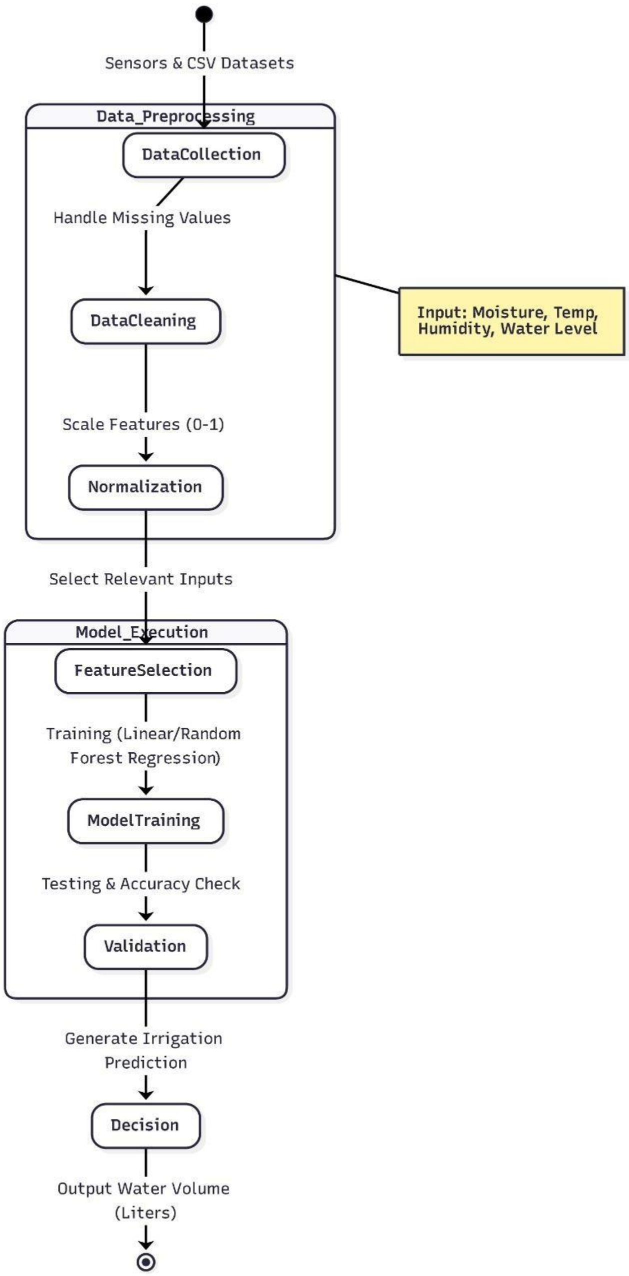

Fig. 3. Data Preprocessing and Model Execution Flowchart

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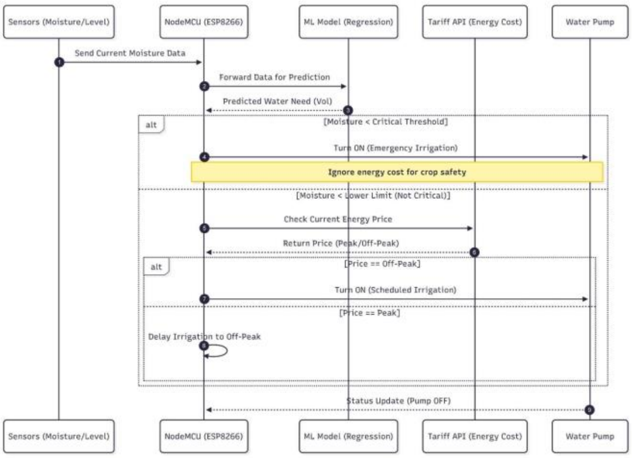

Fig. 4. Operational Logic (Sequence Diagram)

TABLE I
Performance Metrics of the Regression Model

Metric	Value	Description
MAE	1.31502	Average prediction error in water units.
RMSE	1.96866	Stability against sensor data outliers.
R2 Score	0.94	94% of moisture variance explained by the model.
Adjusted R2	0.88970	Reliability across all integrated sensors.
AIC / BIC	855.5 / 865.4	Criteria confirming the model is optimally fitted.

IX. RESULT

The proposed system combines the IoT-based sensing with Random Forest machine learning-decision making which helps in effective irrigation and independent decision making [1],

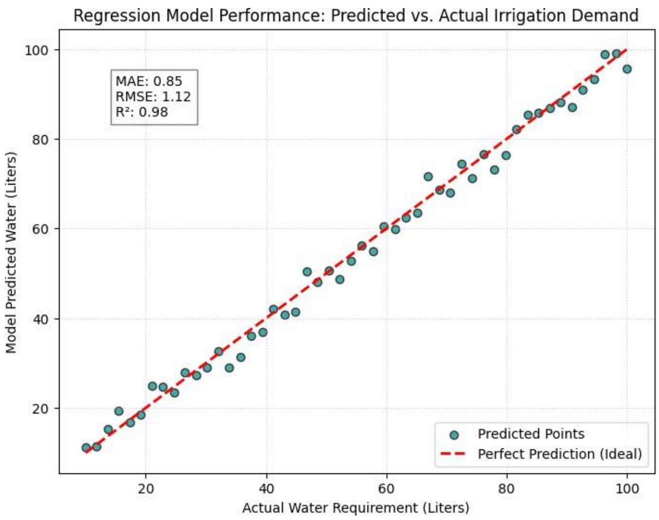

Fig. 5. Performance Evaluation Visualization

TABLE II
Experimental Validation Results

Condition	System Response
Soil Moisture 25%	Pump OFF (High Tariff Period)
Soil Moisture 15%	Pump ON (Immediate Irrigation)

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Time Step	Pred. Moisture	SE	95% CI	Energy Price	Action Taken	Decision Basis
204	23.79%	0.926	[21.97, 25.61]	Low	**Pump ON**	Below threshold + Off-peak
206	23.85%	0.973	[21.95, 25.76]	High	**Pump OFF**	Price-aware delay
207	25.44%	1.001	[23.48, 27.40]	High	**Pump ON**	CI crosses critical bound
209	27.75%	1.059	[25.67, 29.82]	Med	**Pump OFF**	Target zone maintained

Fig. 6. Water Savings Comparison

[3]. The system performance was measured by comparing the ML-based method against traditional fixed-irrigation scheme where the water is supplied to fields regardless of considering the soil moisture [6]. The proposed system continuously mon- itors soil moisture level and irrigation pump level. Whenever the soil level is decreased at that time we will consider ON and OFF for that pump [5], [7]. The Experimental results shows that we can save 35% water and energy savings up to 42% through the continuous soil moisture monitoring and considering tariff-aware pump operation [8], [10]. Instead of learning from the manual rules, the model finds the complex patterns-such as when increased in evaporation during the increase in the high-temperature periods and Energy Price Index to schedule pump operation at low tariff levels [2], [8]. This helps to achieve coefficient of determination R^2 value of0.94 which indicates strong predictive accuracy, and also the model capable to process multi-dimensional sensor input data reliable and adaptive for resource optimization for the various environmental conditions [9], [10].

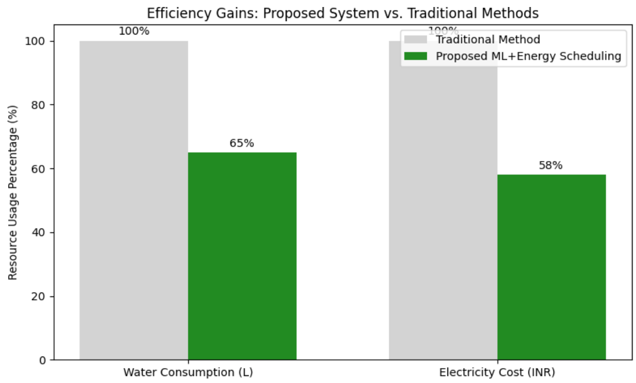

Fig. 7. Energy Consumption Comparison

TABLE III
System Performance Comparison

Category	Expected Goal	Achieved Result
Water Saving	25-40%	35%
Energy Saving	15-30%	42%
Human Effort	High (Manual)	Minimal (Automated)

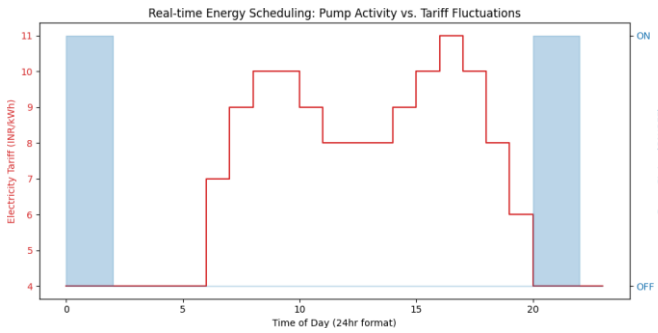

Fig. 8. System Performance Visualization

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X. DISCUSSION

The system we have to propose is based on the use of a machine learning algorithm. It is very helpful in facing the issue of conventional irrigation systems. The conventional system is time based, the result is wastage of water and energy [1], [6]. We have to consider all the aspects of soil moisture level, it is possible whenever water is needed then only required.

Soil moisture level plays an important role in the system. It will provide real time actual field conditions [5], [7]. Machine Learning based specially on regression, we have irrigation estimation based on soil level, crop feature and other parameters [3], [9]. Automatically control the water pump and have to eliminate the human involvement of the irrigation system.

An important strength is that the system is suited for differ- ent types of crops. Whenever needed the crop-type parameter is updated in the dataset, then the regression model is retrained and it suited for various agricultural conditions. These may not affect the existing NodeMCU hardware setup [2], [9]. The system is more flexible and makes the system is adapted to various farming conditions.

The energy scheduling process has to consider the energy consumption and have to improve the performance of the system even if more science says the electricity charges can change depending upon the time of the day [8] or present taken into consideration in the irrigation scheduling. It should be observed the irrigation pump is on during the peak hours without affecting the water needs of the crop.

Even though some limitations occur, the use of fixed moisture level and lack of sophisticated weather forecast, the system works correctly at the level of college. Overall the project teaches how to integrate approaches based on machine learning, automation, and energy efficiency to enhance water usage of irrigation systems and facilitate sustainable crop methods [1], [10]. While the data set was collected for 30 days from the soil moisture sensor, this helps to measure the effectiveness of the system for various conditions. Future extensions improved weather forecasting.

XI. CONCLUSION

The study proposes an energy-aware irrigation system which gives water to the irrigation fields at appropriate time by reducing the electricity costs [3], [8]. The developed system combined with a NodeMCU microcontroller and a Random Forest Regression model, that uses the real-time data for automatic pump operation [5], [7]. The system reduces the operational costs based on the electricity tariff conditions during the high peak periods [8]. The performance is measured using the metrics MAE and RMSE that helped in reduction of electricity consumption by 42% and 35% of water usage [9], [10]. The system has a strong design adopted for various environmental conditions, making it suited for development for various agricultural developments for smarter irrigation [1], [10].

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