GAIA meta-platform: enabling multi-energy vectors data analysis via IoT federation

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***Abstract*—Despite of the global environmental crisis with record-high CO_2 levels, urgent climate action is imperative. The EU's ambitious emission reduction targets and the goal of climate neutrality by 2050 underline the severity of the situation. The Italy case study encounters challenges aligning with these objectives, necessitating significant emission cuts despite advancements in renewable energy and reduced energy consumption. Renewable Energy Communities (RECs) emerge as vital players, focusing on local production, consumption, and management of electrical energy.**

Our research introduces the GAIA federated software meta-platform, addressing the lack of multi-energy vector management by integrating diverse Internet-of-Things (IoT) software infrastructures. It simplifies the development of multi-energy vector services by amalgamating data from federated simple vector IoT infrastructures. GAIA aims to bridge the information gap on resource consumption and interconnections, benefiting RECs citizens and service providers. The platform enhances transparency, facilitating informed decision-making for REC stakeholders and it provides new opportunities and perspectives.

***Index Terms*—Internet of Things, Federated IoT Meta-Platform, Multi-Energy Vectors Management, Renewable Energy Communities, Climate Change**

I. Introduction

In recent years, an increasingly alarming global scenario has been emerging concerning the health of our planet. In June 2020, CO_2 levels reached 417.9 ppm, "marking the highest value since humans have been on Earth" [1]; this underscores the urgency of immediate actions to reduce greenhouse gas emissions and lower temperatures to contrast the climate catastrophe [2].

With this aim, the EU has set ambitious goals to reduce emissions by at least 55% by 2030, compared to 1990 levels, and to become the first climate-neutral continent by 2050 [3]. For example, in Italy within eight years, emissions must be cut by more than 24%, despite a reduced final gross energy consumption of 12% and a doubled share of renewable sources compared to the current level. Nevertheless, the electricity demand is expected to increase by 6% [4]. In this scenario, Renewable Energy Communities (RECs) will be one of the main and most effective elements in achieving the energy transition and reducing carbon emissions in the electricity sector. A REC is primarily an association composed of private and/or public entities with a common goal: i) production, ii) consumption, and iii) management of electrical energy, providing it to its members at affordable prices through the use of a local renewable energy systems. This aims to combat energy poverty and reduce CO_2 emissions and energy waste [5].

By 2050, it is estimated that 264 million European Union citizens will enter the energy market as prosumers, generating up to 45% of renewable energy. This will play a decisive role in changing the way we consume and inhabit, moving towards climate neutrality [5]. For example, currently in Italy, there exist 58 RECs, capable of providing 1239 MW of capacity and avoiding emissions equivalent to 42,854 CO_2 kg. It is projected that by 2025, Italian energy communities will number around 40,000, involving approximately 1.2 million households, 200,000 offices, and 10,000 SMEs [4].

The promotion of renewable energy sources for a transition towards a low-carbon economy is a mission achievable only through the maximization of locally produced energy or within a REC [6]. To achieve this goal, the scientific community and key market stakeholders agree that it is essential to be able to monitor detailed instantaneous consumption and production. This allows providing real-time insights to customers to properly schedule load distribution throughout the day, thereby minimizing the impact of using energy from fossil fuels. It is a significant challenge that requires substantial investments; hence, we believe that a federated meta-platform can effectively contribute in achieving these objectives, as also highlighted in the literature [6]–[8]. Indeed, GAIA recognizes the pivotal role of RECs in achieving sustainable energy practices and reducing carbon emissions. By facilitating the operation and management of these communities, GAIA contributes significantly to broader energy sector objectives. Anticipating a future where millions of European Union citizens become prosumers, actively generating renewable energy, GAIA positions itself to support and optimize this transition. Emphasizing the importance of data-driven decision-making, GAIA positions itself as an essential tool for efficient and automated data management in the multi-energy vector services sector, and not only. By addressing these various aspects, GAIA emerges as an innovative and required solution tailored to the unique context of RECs, fostering sustainability and citizen involvement in

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the energy transition.

Within this context, in our research work, we provide a comprehensive and systematic description of the GAIA federated platform, which aims to solve problems of different nature and magnitude, present in energy communities, trying to overcome the limitations found in pre-existing solutions. In detail, it aims to solve the lack of multi-energy vector management by federating different IoT software infrastructures that are dedicated to managing data and analytics of an individual energy vector. GAIA allows an easy development of multi-vector energy services by combining the heterogeneous data originally collected by the federated simple vector IoT infrastructure. Moreover, GAIA aims to fill the lack of a comprehensive provision of information about the resources consumed and their interconnections with other factors, which represents a challenge both for the citizens of RECs, who would like real and detailed information about the energy resources present on their territory and their consumption, and for the companies that wish to offer useful services to these citizens.

A fundamental element of GAIA's strategy is the integration of data from different and diversified *silos*, which act as specialized IoT service providers. A *silo* represents a service provider in the IoT domain capable of sharing raw or processed data, depending on the services offered. *Silos* provide a variety of data from sensors, devices, and IoT systems. GAIA is designed to manage this heterogeneity, ensuring the seamless integration of data from various sources, such as renewable energy sensors, consumption monitoring devices, and other intelligent devices within the REC. Therefore, the meta-platform implements standard communication protocols to interact with *silos*, facilitating the secure and efficient exchange of information. This allows access to updated and relevant data.

The rest of the paper is organized as follows. Section II presents a literature review of existing solutions. In Section III, we present the importance of efficient and automated data management in ensuring the effective operation of the meta-platform. Section IV outlines the general architecture defined for GAIA. In Section V, we discuss the critical role of data representation in the effective and unified management of information and data concerning multi-energy vector and multi-source renewable energy within Energy Communities. Section VI describes the data management mechanisms provided by the meta-platform with a primary focus on data request and retrieval. Finally, Section VII provides the concluding remarks.

II. Related Works

In recent years, different IoT platforms have been proposed for energy management [9]. However, they have limitations and they do face several challenges that require an appropriate solution. For example, an important critical issue concerns managing the complexity of heterogeneous IoT networks within a federated platform. In [10], the authors point out how the heterogeneity of IoT devices, network infrastructures, and communication protocols can lead to interoperability and integration issues, limiting the operational efficiency and scalability of platforms. It is critical to develop orchestration and standardization mechanisms to address these issues.

Security of federated IoT platforms is another critical challenge, as demonstrated in [11]. The survey conducted highlighted existing vulnerabilities in IoT devices and communication networks, such as lack of authentication, poor encryption, and inadequate security key management. These factors can lead to serious security threats, such as malware-type attacks, data theft, and network compromise. Research has emphasized the need to develop advanced security solutions, such as the integration of robust encryption, multi-factor authentication, and intrusion detection mechanisms.

Another critical issue concerns data privacy in federated IoT platforms. According to the study [12], the massive collection and processing of personal data within platforms can raise significant privacy concerns for users. Sharing and accessing data among different IoT service providers requires clear and robust data management policies, as well as the implementation of anonymization and access control mechanisms. It is important to ensure that personal data is adequately protected and that regulatory requirements, such as the General Data Protection Regulation (GDPR), are met.

Finally, the efficient management and analysis of large volumes of data generated by IoT devices is another significant challenge. As the research study [13] demonstrated, processing and extracting meaningful information from large IoT data streams requires advanced analytics approaches, such as machine learning and artificial intelligence. Scalability of data infrastructure and analytics capabilities becomes crucial to enable efficient management and timely data-driven decision-making.

The GAIA federated meta-platform we designed promotes the development of multi-energy vector services, which can only be realized by taking into account heterogeneous data from different *silos*. These services are essential to optimize the use of different available energy sources and to allow energy production and consumption to be adjusted as needed in real-time, reducing waste and increasing the overall efficiency of the energy system; they also provide greater flexibility in energy management and greater resilience to intermittent renewable energy sources. In addition, GAIA meta-platform would support more efficient, resilient, and sustainable energy management within the REC. It is emphasized that the main goal of the meta-federated platform is to obtain heterogeneous data to search, through machine learning algorithms, for new correlations among them. Consequently, GAIA will provide the perfect ground for the development of innovative multi-energy vector services offering real-time monitoring and optimization, simulation of energy strategies, maintenance management and troubleshooting, and active community involvement, thus addressing the real needs of energy community contexts. Finally, the GAIA meta-platform can be considered also as a crucial enabling technology to develop future digital twins of RECs.

III. Data source and management

The efficient and automated management of data is a crucial element for the proper functioning of the meta-platform. This management is characterized by the ability to identify data sources through intelligent mechanisms and the integration of heterogeneous data managed by different IoT software infrastructures and provided by different companies. Thus, such infrastructures often work as *silos* that manage data, devices, and services of an individual energy vector neglecting a real data fusion and a data correlation among different energy vectors. This is a high gap in the IoT research context in general, as it strongly limits the development of multi-context services and analytics that exploit heterogeneous data from the different *silos*.

For an IoT platform, storing and managing data involves collecting, storing, and organizing information from devices. This data can include a wide range of information, such as sensor readings, environmental data, device status information, and more. Data management also involves organization, security, and continuous availability. In some specific scenarios, it might be advantageous not to store data directly on the IoT platform, offering significant benefits: i) *Resource Savings*, avoiding the storage of large amounts of data can reduce costs associated with storing and maintaining storage infrastructure; ii) *Privacy and Security* in some cases, choosing not to store certain data can be a strategic decision to protect user privacy, especially when collecting such data is not strictly necessary for the system's purposes; iii) *Reduced Complexity* by eliminating the need to manage large volumes of data simplifies the operational complexity of the platform and iv) *Removed Redundancy* by avoiding data replication from data source to data storage.

The federated meta-platform GAIA, through specially developed mechanisms for creating universal interfaces, can integrate and directly draw from external data sources. The meta-platform is capable of understanding from which sources to draw the required data, ensuring a flexible and dynamic approach for information gathering. This is achieved through advanced machine learning algorithms that analyze the specific needs of the RECs and automatically identify the most relevant sources to meet these requirements. This enables targeted data collection, optimizing resource utilization, and reducing the risk of information overload with unnecessary data.

IV. GAIA Federated Meta-Platform Architecture

This Section outlines the general architecture defined for the GAIA federated meta-platform. The following Sections present the data management components, interface components towards Data Silos, and data presentation towards Data Applicants.

Through the identified components, the meta-platform is capable of fulfilling the following high-level requirements: i) allowing for the registration of data sources (i.e., Data Providers), regardless of the type and format of the provided data; and ii) enabling external entities (i.e., Data Applicants) to access heterogeneous data sources in a unified, standardized, and consistent manner.

In Figure 1, a comprehensive overview of the platform components and their interactions is provided. The general architecture is divided into two main levels: GAIA FRONTEND and GAIA CORE. The GAIA FRONTEND level encompasses all the elements necessary to manage interactions with external entities requiring access to data, as well as data providers intending to register their services on the GAIA platform. For the intrinsic functionalities of the platform, the GAIA CORE level includes all elements for internal data management, essential for modeling data providers, data structures, and semantic relationships among data sources. Furthermore, GAIA CORE provides functionalities for unifying and harmonizing data sources.

The GAIA architecture involves interaction with two main categories of external entities: *Data Providers* and *Data Applicants*. In the context of the GAIA project, Data Providers refer to any entity or organization willing to grant access to their data (or part of it) through the meta-platform. Data Providers are involved in two distinct moments: i) *Registration*, a data provider must provide a description of their data and the mechanisms for accessing it to be managed by the GAIA platform; and ii) *Querying*, when the platform needs to access the data from a specific data provider, it queries the respective *silo* through appropriate mechanisms.

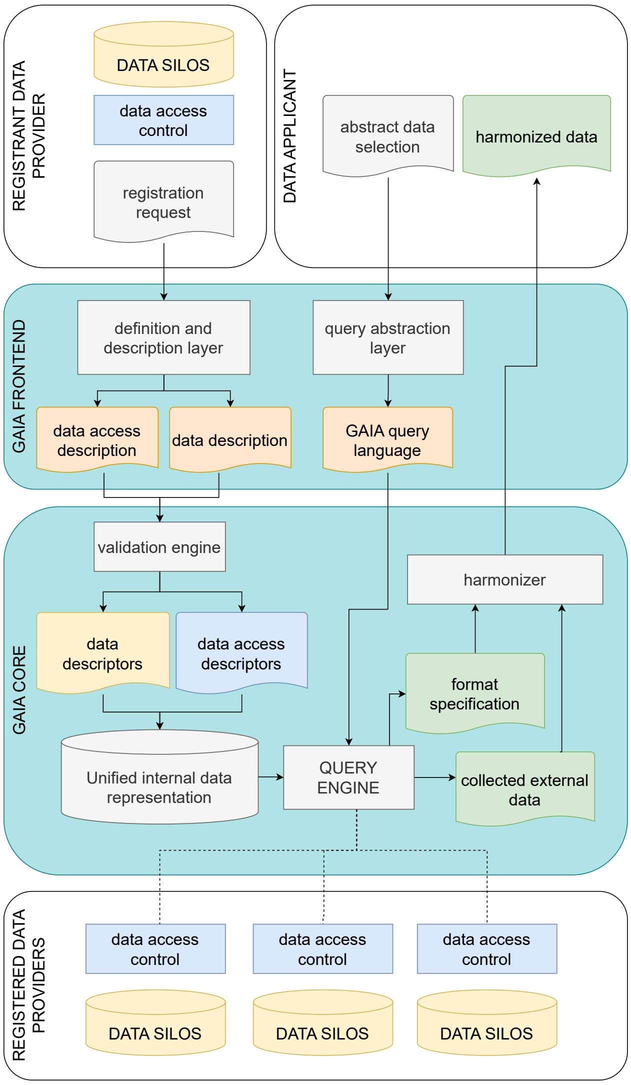

Fig. 1. Scheme of the GAIA Federated meta-platform

Data Applicants are entities, either users or automated systems, that request access to data mediated by the GAIA platform. Data Applicants are involved in the GAIA workflow as data consumers exploiting the querying mechanisms provided by the platform.

From an infrastructural perspective, the designed platform adheres to the general requirements of modern distributed systems. The components defined as entities in the architecture implement a clear and well-defined division of responsibilities. Each infrastructure element is independent and capable of carrying out its activities autonomously. This allows the platform to meet a fundamental requirement: the platform adheres to the principles of micro-services architectures, including decentralization, resilience, scalability, and separation of responsibilities.

A. Gaia Core

As shown in Figure 1, the GAIA platform is composed of a series of fundamental components that provide the meta-platform with the ability to handle a wide range of heterogeneous data from multiple *silos*. These components also enable precise and effective querying of such data and returning information to Data Applicants using a standardized format.

The components of the GAIA CORE are responsible for intelligently managing the interaction with external data sources.

1) Validation Engine: this component is the entry point to register new *silos*. It represents the interface to accept new data descriptions and validate the compliance with the meta-platform data interoperability standards. Indeed, the data registrant may be warned or, eventually, prevented from federating to the meta-platform in case of non-compliant or inaccessible data.

2) Query engine: The responsibility of directing and managing user requests is entrusted to the Query Engine.

The Query Engine, acting as a crucial pivot between the external interface and the core of the GAIA platform, plays a key role in ensuring accurate interpretation of requests made by Data Applicants. It also optimizes routing towards relevant data sources and efficiently manages connections with multiple external sources.

The Query Engine internally manages the parsing and decoding of high-level queries, identifies the proper Data Providers (and respective *silos*) to involve, generates the data retrieval strategy, and optimizes and executes the data retrieval plan.

The Query Engine allows the platform to provide a unique and standardized interface for data access, abstracting access to individual data sources and presenting them as a single centralized *silos*.

This element is the central component of the whole architecture, for this reason it is meticulously designed, engineered and implemented to minimize execution time and resource consumption.

3) Harmonizer: it aims at creating coherence and cohesion among different entities or heterogeneous data orchestrated within the meta-platform. The Harmonizer ensures that data from various sources is precise, consistent, and interoperable within the GAIA meta-platform. It internally exploits semantic methodologies to model data relationships and information affinity.

B. Gaia Frontend

The GAIA FRONTEND infrastructure layer, in Figure 1, is in charge of managing interactions with external entities, which require access to the data within the meta-platform. This layer includes all the interfaces designed to facilitate interaction between external actors (i.e., Registrant Data Providers and Data Applicants) and the GAIA CORE module. Specifically, the GAIA FRONTEND level manages and facilitates the registration of data providers on the platform, enabling them to federate to the meta-platform. Additionally, it is the system interface towards external entities intending to interact with the data and functionalities provided by the GAIA meta-platform.

1) Definition and Description Layer: this component provides all the mechanisms for new Data Providers (and their *silos*) registration on the GAIA platform

It provides a formal description for *silos* integration into the GAIA internal representation. Indeed, it facilitates the creation of internal data representation structures, instructing the platform based on the descriptions provided by Data Providers during registration.

The component defines the data schemas that new data providers must adhere to. These schemas determine the structure and characteristics of the data that providers need to supply, ensuring consistency and uniformity. Additionally, it includes a detailed description of the access mechanisms that Data Providers expose for data retrieval. This may involve specific APIs, protocols, or other communication methods.

Finally, this module defines how the entities provided by new Data Providers relate to existing entities within the system. This modeling aids in automatically deducting interactions and connections between data from different sources.

2) Query Abstraction Layer: This component provides the tools for GAIA meta-platform data access to Data Applicants. Its primary function is to handle requests from applications or other external systems, providing a harmonized and universal interface for executing necessary queries and obtaining information from the GAIA platform. Namely, it is the element that mediate the raw interaction with the Query Engine.

This component is designed to offer Data Applicants a simplified interface for querying data. Indeed, crafting raw queries in the format required by the GAIA CORE might be complex for non-expert Data Applicants.

V. Data Representation

Data representation plays a crucial role in the efficient and cohesive management of information and data related to multi-energy vector and multi-source renewable energy in RECs.

To facilitate understanding, interpretation, and interconnection of data within the meta-platform, representation formalism and standards are employed and enforced. These formal models allow for the consistent definition of relationships and concepts, promoting interoperability among diverse data sources.

The specifically engineered formalisms are: i) *Data Silos Model*: dedicated to formalizing and representing data from various Data Silos of Data Providers; ii) *Data Source Meta-model*: dedicated to formalizing cross-cutting information among various data sources; and, iii) *Data Harmonization Model*: this component formalizes a unified data representation standard for queried data results.

These formalisms are directly linked to the components of the GAIA FRONTEND architectural layer, as described earlier in Section IV-B. The introduced data representation model encompasses a set of rigorous rules, notations, and conventions, allowing for the constrained definition of a standard representation of data across various data sources. The information representation infrastructure designed for the GAIA platform is depicted in Figure 2.

A. Data Silos Model

The GAIA meta-platform exploits an internal formalism to represent data and their sources. In practice, the meta-

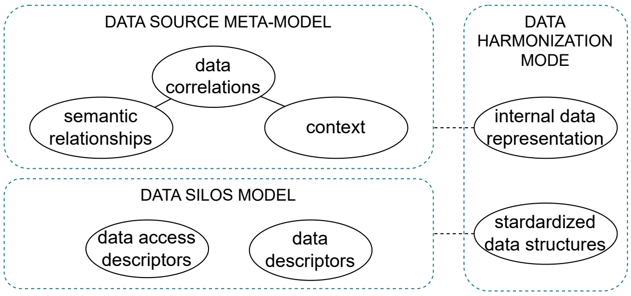

Fig. 2. The information representation designed for the GAIA platform.

platform employs an information representation structure that standardizes and uniformly defines SILOS.

For this purpose, two distinct modeling and representation elements are required, the Data Descriptor and the Data Access Descriptor.

a) Data Descriptor: it is a data structure that formally describes any type of data. Through the Data Descriptor, the platform maintains a uniform representation for: i) the data format provided by the Data Provider; ii) the provided data type (e.g., number, string, image); and, iii) the representation formalism (e.g., XML, JSON, binary).

Data Descriptors allow the platform to decouple the semantics of the data from its syntactic structure. This way, the platform can provide abstract-enough data access methods that do not depend on the original structure but rather on the semantic meaning.

b) Data Access Descriptor: it is a representation structure that models the operational modes of accessing and retrieving data from Data Provider sources. Data Access Descriptors allow for detailed descriptions of how to query the SILOS registered with the platform. In particular, this type of descriptor allows for: i) describing data access points (e.g., URLs, IP addresses); ii) specifying query methods (e.g., REST API, structured queries); and, iii) describing methodologies for refining searches (e.g., filters).

Data Descriptors and Data Access Descriptors are generated based on the definitions provided by Data Providers when registering their services with the GAIA platform.

B. Data Source Meta-model

To maintain consistency across various data sources and represent potential relationships between them, the GAIA platform constantly updates a specific representation meta-model. The data source representation meta-model is based on the models of individual sources and constructs modeling layers on them to extensively represent additional properties such as i) semantic meaning of data from various sources; ii) relationships and correlations between various Data Providers and their data; and, iii) application context information.

The data source meta-model allows the platform to expose the managed data pool uniformly from a semantic and relational perspective, rather than just from a technical data point of view.

C. Data Harmonization Model

To provide a standard for the data output to Data Applicants, the platform needs a data modeling mechanism that defines correspondences between incoming data formats and types from Data Providers and the standardized output data structures defined by the platform itself. The data harmonization model takes responsibility for defining and maintaining the correspondence between internal data representation and the standardized data structures that the GAIA platform exposes to Data Applicants.

VI. Data Access Mechanism

The meta-platform enables uniform and transparent accessibility to heterogeneous and multi-source data. For this purpose, it implements a multi-level data management flow that formalizes data request mechanisms from Data Applicants and data access to Data Providers.

This Section describes the data management mechanisms with a primary focus on data request and retrieval.

A. Data Request

Unified querying of all data mediated by the meta-platform is possible at two distinct abstraction levels, directly connected: through a direct low-level query or an abstract representation of the query.

1) GAIA Query Language: The unification of the data request formalism, and consequently, data access by Data Applicants, is implemented through the definition of a formal query language: *Gaia Query Language (GQL).*

GQL is a textual language that provides all the querying functionalities offered by modern query languages:

- Join – requesting data from different sources (Data Providers) in a single query is possible,
- Aggregation – requesting aggregated data and/or derived data by aggregating data from different sources is possible,
- Sorting – requesting data retrieval sorted by different criteria is possible,
- Filtering – restricting the number of retrieved data based on specific filtering criteria is possible.

It is important to note that Gaia Query Language provides only data access functionalities and does not include any data modification functionalities (e.g., update, delete). This behavior is explicitly imposed by the nature of the GAIA meta-platform itself: the platform never stores third-party data within its infrastructure. The meta-platform only mediates and facilitates multi-source data access.

2) Query Abstraction: This level of querying aims to simplify the drafting of queries through GQL via easier-to-use tools (e.g., visual tools). Consequently, this level of abstraction is not essential for forwarding data requests to the platform but can be very useful if the Data Applicant is a non-technically-proficient platform user.

B. Data Retrieval

The other fundamental aspect of data management for the operation of the GAIA platform is related to the modalities of retrieving the requested data from all registered data sources. These aspects of data access are managed through two specific mechanisms: Query Translation and Results Aggregation.

1) Query Translation: The first step in retrieving the requested data involves interpreting the queries to identify i) which data has been requested, ii) which Data Silos to consult, and, iii) the required output format.

All this information is deduced through the formal interpretation of queries by the Query Engine (described in Section IV-A2). Query translation aims to obtain, as a result, intermediate data and metadata necessary for the execution of data extraction directly from Data Silos. Moreover, the Query Engine is responsible for querying the individual Data Providers involved in the request. The deduction of access modes to the Silos is performed by inference from the Data Descriptors and Data Access Descriptors of each relevant Data Provider.

2) Results Aggregation: Once all requested data is collected, the platform proceeds to make them homogeneous and aggregate the information to be returned to the Data Applicant, according to the original query. This task is entrusted to the Harmonizer, which uses various resources: i) metadata extracted by the Query Parser; ii) Data Descriptors of the data coming from Data Silos; and, iii) the output format specified by the Data Applicant.

Thanks to the combination of such meta-information, the Harmonizer organizes the data to be returned to the applicant.

VII. Conclusions

This paper outlines the reasons that necessitate the development of a federated meta-platform, serving as a mediator for accessing data from heterogeneous data sources, and how such a platform can be crucial for improving energy resource management, especially in Renewable Energy Community.

The document provides the architectural framework upon which the GAIA platform is based, elucidating its fundamental elements. Methodologies enabling the centralized management of heterogeneous sources through data representation formalisms and their relationships are presented. Lastly, this paper discusses the operational flow for data access by external entities (Data Applicants) and data retrieval from accredited data sources (Data Providers).

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