

## APPLIED RESEARCH

# Building Virtual Power Plants With Dataspaces for Faster Integration of Distributed Energy Resources

MANUEL WICKERT<sup>1</sup>, DARIO KLAPP<sup>1</sup>, AND OLIVER HOHLFELD<sup>2</sup>

<sup>1</sup>Fraunhofer Institute for Energy Economics and Energy System Technology (Fraunhofer IEE), 34117 Kassel, Germany

<sup>2</sup>Distributed Systems Group, University of Kassel, 34121 Kassel, Germany

Corresponding author: Manuel Wickert (manuel.wickert@iee.fraunhofer.de)

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**ABSTRACT** Integrating new distributed energy resources (DERs) into commercial virtual power plants (CVPPs) remains a technically complex and time-consuming task. This complexity poses a critical barrier, as DER portfolios frequently change due to expiring contracts or shifting marketing strategies, which require repeated establishment of secure, protocol-specific communication channels. In this paper, we propose a dataspace-based approach that systematically addresses these recurring integration challenges by mapping them onto reusable technical concepts. Our solution builds on existing dataspace technologies, including standardized interface descriptions, automated access control, and structured discovery workflows, to simplify and accelerate the onboarding process. We present a practical implementation and evaluate it using real-world integration data from two CVPPs, comprising more than 400 integration cases. The analysis shows that 11.5% of DERs required more than one month for onboarding, while expert assessment indicates that dataspace-based integration could reduce effort by up to 80%. These results demonstrate that our approach significantly improves the scalability and flexibility of CVPP operations, thereby supporting faster DER onboarding in increasingly dynamic and decentralized energy markets.

**INDEX TERMS** Virtual power plant, VPP, energy, dataspace.

## I. INTRODUCTION

Virtual power plants (VPPs) are a well-established concept for efficiently integrating large numbers of distributed energy resources (DERs) into an energy system. According to Saboori et al. [1], Plancke et al. [2], and Lerch et al. [3], a VPP typically consists of an energy management system (EMS), a communication infrastructure, and a set of DERs that interact based on a defined operating strategy. By aggregating diverse DERs under a centralized EMS, VPPs enable grid operators and energy traders to monitor and manage an entire portfolio of assets as a unified entity. This aggregation requires a reliable communication infrastructure between the EMS and each DER. Despite a large body of work on energy management algorithms [4], [5], the question of how such communication connections can be

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established efficiently and repeatedly in practice remains largely unresolved.

Issues arising from the technical complexity of establishing communication channels between energy management software and DERs become particularly apparent in the context of commercial virtual power plants. In such settings, the composition of the DER portfolio frequently changes due to fixed contract durations between DER operators and energy traders. Consequently, VPP operators must regularly onboard new DERs and establish communication with their energy management systems. Despite more than a decade of applied research on VPPs in Europe [6], these integration processes remain technically complex and time-consuming.

## A. PRACTICAL CHALLENGES

But why is this process complex, especially in environments where the same steps must be repeated regularly? Drawing on

our practical experience from applied research and real-world VPP implementations, we identify three key factors that contribute to this complexity:

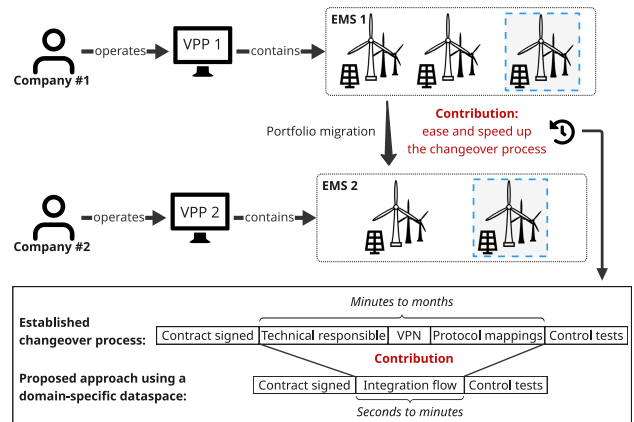
- 1) **Finding technical contacts.** Establishing a connection requires coordinated actions on both sides: the EMS software of the VPP operator and the DER. For example, in many cases a VPN connection must be established, requiring the exchange of certificates. This process typically begins with identifying a technically responsible contact person. While this is usually straightforward for large wind farm operators, it can be challenging for smaller power plants, which often lack dedicated technical personnel for such tasks.
- 2) **Building a secure connection.** Many common field protocols such as IEC 61850, IEC 60870-5-104, and Modbus TCP do not provide integrated access control or encryption [7], [8], [9]. Therefore, secure communication is typically achieved using VPN tunnels. In practice, DER communication interfaces are not accessible from the public internet. Instead, access is generally limited to the on-site internal network of the DER. To enable remote connectivity, a VPN tunnel must be established that allows the EMS to securely access the DER's local network. The underlying network technologies vary widely, including 4G/5G mobile networks, DSL, and satellite links, each introducing its own technical constraints.
- 3) **Interfacing with the correct protocol.** DERs use a variety of protocols depending on their technology. For instance, OPC XML-DA and IEC 61400-25 are common in wind farms, whereas PV plants often rely on Modbus TCP (SunSpec). These protocols typically require custom mapping of registers or identifiers to specific monitoring and control signals. Consequently, these mappings must be shared, configured, and thoroughly validated before communication begins.

## B. RESEARCH GAP

The integration workflow described above reveals a fundamental missing technical layer: a generic, standards-based broker that can automate the discovery, authentication, and protocol-translation steps required for each DER onboarding and changeover. In its absence, VPP operators must rely on manual, case-by-case engineering effort to locate technical contacts, establish secure VPN tunnels, and map heterogeneous field-protocols. This ad-hoc approach not only hampers interoperability across the increasingly heterogeneous DER portfolios, but also unnecessarily prolongs integration times for DER switch-overs. The general need for better integration of (energy) systems is highlighted by the recent proposal for establishing a new ACM SIG (SIGDX) [10] on digital transformation of industrial infrastructures.

## C. CONTRIBUTION

In this paper, we aim at closing the integration gap by introducing a dataspace design that implements the



**FIGURE 1.** Transition of a DER (marked blue) from one VPP portfolio to another. The upper row shows the established manual changeover process that requires several coordination steps and can cause considerable delays. The lower row sketches our contribution, in which the integration flow based on dataspace technologies significantly accelerates such changeover processes.

long-missing broker functionality to ease DER integration. By embedding automated access-control, interface discovery and protocol mediation into a domain-specific dataspace, the proposed domain-specific dataspace architecture eliminates the manual, error-prone steps that currently dominate integration workflows. This approach is tailored to the needs of commercial VPPs and streamlines DER integration by enabling automated access control and interface discovery, thereby reducing complexity and improving operational efficiency, as shown in Figure 1. We demonstrate how the dataspace components can be assembled to support swift, secure onboarding of heterogeneous DERs in a prototype.

Empirical insights from a proprietary data set of >400 real-world onboarding events and a focused interview with a senior VPP practitioner confirms the practical relevance and applicability of the approach. The quantitative analysis reveals that current integration cycles are prolonged by manual contact-finding, VPN provisioning and protocol mapping, while the qualitative assessment indicates that the broker could reduce integration effort. These results substantiate the broker as the long-missing solution for interoperable, low-effort DER integration and chart a clear path toward resilient, data-driven VPP ecosystems.

Our main contributions are as follows:

- A dataspace-based integration concept that eases and speeds up the DER changeover process in commercial VPPs, reducing manual effort and migration time by up to 80% compared to current practice.
- An end-to-end VPP architecture that demonstrates how dataspace technologies enable secure, automated, and scalable DER onboarding and control.
- A minimal set of dataspace building blocks and corresponding integration patterns that need to be implemented to satisfy the domain-specific requirements of VPP changeovers.

## II. RELATED WORK

Research on VPPs has grown notably over the past decade.

### A. ALGORITHMIC AND ECONOMIC CHALLENGES

Most existing work focuses on algorithmic and economic aspects, including optimization strategies [4], [5], [11], forecasting models [12], or VPP participation in electricity markets [13]. These studies provide valuable insights into VPP operation, but they rarely examine how communication links to DERs are actually established in practice. As a result, the technical and organizational steps required to connect a DER to a central EMS remain insufficiently addressed in the literature.

### B. PROTOCOL INTEROPERABILITY

Among the works that consider the creation of DER connectivity at all, most center on protocol interoperability. Several studies emphasize that the absence of standardized, vendor-independent interfaces increases integration effort and creates long-term maintenance challenges. Nwauka et al. [14] identify protocol heterogeneity as a major obstacle for VPP development and argue that harmonized interfaces such as VHPready or DERMS middleware could simplify integration. Similarly, Dande et al. [15] present a protocol conversion approach that mitigates compatibility issues between legacy systems. Reviews of IEC 61850 or OPC-based solutions [16] reach comparable conclusions and highlight the difficulties of integrating field protocols from different manufacturers. These works advance the understanding of protocol-level interoperability, but they do not analyze the overall onboarding workflow in which such protocols must be configured, validated, and tested.

### C. ONBOARDING CHALLENGES: FEW STUDIES

Practical onboarding challenges are discussed in a few studies. Reports from US aggregation pilots summarized by NREL [17] show that DER integration often fails due to organizational factors, such as missing technical contacts, unclear responsibilities, and limited support capacities at smaller installations. John [18] describes cases where technicians repeatedly travelled on-site to restart communication devices, which illustrates how non-technical barriers contribute to delays. These findings align with anecdotal evidence from VPP operators, but the available literature offers no systematic examination of how these organizational constraints interact with protocol-level challenges during onboarding.

### D. SECURITY ASPECTS

Security concerns have been analyzed more broadly. Several works point out that commonly used field protocols such as Modbus TCP or IEC 60870-5-104 lack built-in authentication and encryption mechanisms [19], [20]. To mitigate these shortcomings, many VPP deployments rely on VPN tunnels and firewall-based network restrictions. Demonstration projects such as Heimgaertner et al. [21] confirm that these measures are effective but increase configuration complexity,

especially if DERs communicate via mobile networks or other non-dedicated links.

While security research provides mainly encryption mechanism for legacy protocols, it does not explicitly address how these risks affect integration time or onboarding processes.

### E. RESEARCH GAP

Overall, current research provides insights into specific fragments of the integration challenge: protocol-level interoperability, organizational constraints in pilot projects, and security limitations of field communication. However, we identified three major gaps: First, there is no study that jointly examines these technical and organizational factors as part of an onboarding workflow for commercial VPPs. Second, existing work does not quantify the practical impact of protocol diversity and organizational coordination on integration duration. Third, the literature does not explore architectural approaches that could systematically reduce onboarding effort.

### F. DATASPACE IN OTHER FIELDS

Recently, dataspace have been proposed as a generic concept for sovereign and interoperable data exchange. The German Energy Agency emphasizes their relevance for overcoming communication barriers in the energy sector [22], [23]. Several initiatives, including CEEDS and energy data-X, aim to establish decentralized infrastructures for secure data sharing across organizations. While these projects demonstrate the conceptual potential of dataspace, to the best of our knowledge, no existing work investigates how dataspace technologies can support the practical onboarding and migration of DERs in commercial VPPs.

### G. POSITIONING OF THIS WORK

We address these gaps by analyzing real-world integration data, identifying recurring obstacles in DER onboarding, and demonstrating how dataspace can be used to accelerate and standardize the process.

## III. REQUIREMENTS FOR INTEGRATING DERs INTO VPPs

We begin by discussing the requirements for the integration of DERs into VPPs. We identified four typical cases in which DER integration becomes necessary:

- 1) **New power plant:** When a new DER is commissioned, integration into a VPP is often required to enable market access. In Germany, for example, all newly built DERs with an installed capacity greater than 25 kW are, since 2025, no longer eligible for fixed feed-in tariffs and must sell their electricity on the energy market [24]. Because individual DERs are typically too small to participate in trading directly, they are aggregated into a VPP operated by an energy trader. The trader pays the DER operator a mutually agreed price per kilowatt-hour produced and profits from the spread between the purchase price and the market price. To enable this, the trader must establish a connection

between the newly built DER and the EMS of their VPP.

- 2) **Changing energy traders:** Marketing agreements between DER operators and energy traders have fixed durations. When an agreement expires, for example at the end of the calendar year, plant operators check whether they can obtain better conditions from other traders and consequently choose to switch their energy trader. Resulting in the DER being removed from its previous VPP and paired with the EMS of the new trader's VPP.
- 3) **Changing marketing type:** If a DER previously operated under a fixed feed-in tariff or Power Purchase Agreement (PPA) switches to direct marketing, for example because the subsidy period ends or the PPA expires, it must be integrated into a VPP to enable market participation.
- 4) **Software change:** Although this case is relatively rare, it may occur when an energy trader decides to switch to a different VPP software that better meets operational or cost requirements. In such cases, all connected DERs must migrate from the old EMS to that of the new VPP platform.

The second scenario is the most common, as it recurs regularly for operational DERs. Therefore, we use it as the basis for deriving the integration requirements.

From a legal perspective, operators of German energy plants above a certain size are required to comply with direct marketing regulations, as stipulated in §10b of the Renewable Energy Sources Act (EEG) [24]. Following the 2023 amendment to the EEG, all decentralized energy plants with an installed capacity above 25 kW must be equipped with technical facilities that enable direct marketing. The law requires that authorized parties be granted the ability to access the plant's current feed-in power and to remotely adjust it if necessary. According to §52 EEG [24], proof that such monitoring and control is technically possible must be submitted to the grid operator within one month after the start of energy trading. If this proof is not submitted in time, a penalty of €10 per kilowatt of installed capacity is imposed for each month of delay. Based on these legal provisions, we derive two specific requirements:

**Requirement 1 (Integration by a Specific Date):** Each DER must be integrated into a VPP by a clearly defined date, which typically marks the start of its marketing period. In most cases, this is January 1, as trading contracts are often aligned with the calendar year. Depending on the context, other fixed dates may apply. A fixed date is important because the DER must remain connected to the previous VPP until the existing marketing agreement expires and the new one becomes effective. Only then can the transition take place. Therefore, the new setup must be activated precisely on the scheduled date to ensure uninterrupted operation and control.

**Requirement 2 (Fast Integration):** One month is the maximum period allowed for the integration of a DER without incurring penalties. From a trading perspective, timely

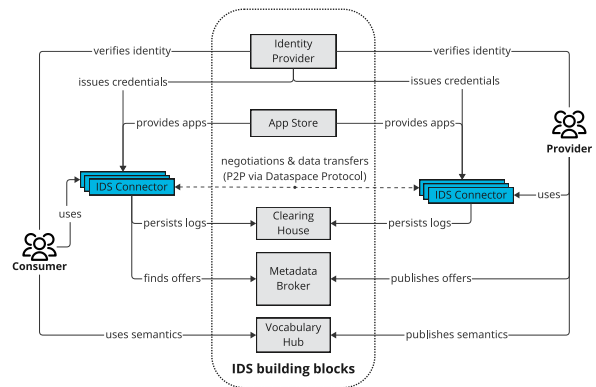


FIGURE 2. System architecture of the International Data Spaces (Adapted from IDSA RAM 4.0).

availability of monitoring data is also essential for achieving favorable results. Therefore, the integration process should be completed as early as possible.

From a technical perspective, VPP operators often work with DERs installed several years ago. The IT interfaces used to connect these DERs to an EMS are typically defined by manufacturers. Consequently, VPP operators must frequently handle legacy systems during integration processes.

**Requirement 3 (Legacy Interface Support):** VPPs must support DER interfaces that rely on traditional field protocols. Some of these interfaces were defined in the 1990s and use 16-bit registers such as Modbus TCP or IEC 60870-5-104. Despite their age, these interfaces remain widespread in practice and must therefore be supported.

In addition to the functional requirements, we also derive non-functional requirements related to cybersecurity. VPPs are classified as critical infrastructure once they aggregate at least 104 MW of installed capacity [25], which represents a relatively small portfolio for an energy trader. Therefore, it is essential to ensure the availability and integrity of DER control interfaces and the authenticity of control signals. For practical reasons, the confidentiality of measurement data should also be taken into account. Based on these considerations, we derive the following requirements:

**Requirement 4 (Access Control):** To protect the control and monitoring data of a DER, we require that access to its interface be restricted. Therefore, an appropriate access control mechanism must be implemented to prevent unauthorized access to monitoring and control functions.

**Requirement 5 (Interface Availability):** Control interfaces must provide a high level of availability to ensure reliable operation within critical infrastructure environments.

**Requirement 6 (Secure Communication):** A trader's business secrets, such as control strategies, could potentially be inferred from the DER monitoring data and control signals. Therefore, this information must be kept confidential.

#### IV. A BRIEF INTRODUCTION ON DATASPACES

Dataspaces have emerged as a central topic in discussions on cross-organizational data exchange, particularly in the

automotive sector. A dataspace is defined as a federated and decentralized infrastructure that enables participants to autonomously provide and exchange data and digital services. All members of a dataspace adhere to a common set of rules, processes, and technical standards, which together ensure secure, sovereign, and interoperable data sharing [26].

Unlike traditional architectures, such as data lakes or data hubs, dataspaces do not require central data storage. Instead, data always remains under the control of the original provider. The provider alone determines which participants may access specific data and under which rights, obligations, or restrictions this access is granted [27].

To access data within a dataspace, consumers must meet the access conditions specified by the provider and agree to associated usage policies. This agreement is formalized through a contract, which serves as a prerequisite for any data exchange between participants [28].

The International Data Spaces Association (IDSA) has further developed this concept and aims to establish International Data Spaces (IDS) as a global standard for sovereign data exchange [29]. The IDS Reference Architecture Model (IDS-RAM) provides the foundational framework, defining the necessary components and processes for implementing dataspace in practice. Figure 2 provides an overview of these components and their interactions in the dataspace.

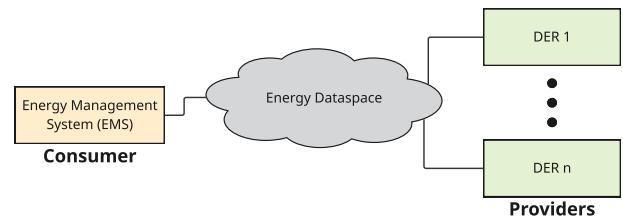
The core of this architecture is the *IDS Connector*, a software system that represents a participant within the dataspace. The connector publishes data offerings, negotiates contracts with other connectors, and provides a standardized interface for initiating data transfers.

Beyond the *IDS Connector*, the IDS-RAM [30] specifies additional components that collectively support trust, interoperability, and scalability. The *Metadata Broker* allows participants to publish and discover data offerings in a standardized manner, making data assets visible and searchable throughout the dataspace. The *Clearing House* serves as a neutral logging service that records transactions between participants to ensure transparency, traceability, and accountability.

Identity and permission management is handled by the *Identity Provider*, which authenticates and authorizes participants, verifies their trustworthiness, and issues the credentials necessary for secure communication. The *App Store* enables the deployment and reuse of data-driven services and applications, which can be executed within a connector or across the dataspace ecosystem. To ensure semantic interoperability, the *Vocabulary Hub* provides access to shared vocabularies, ontologies, and data models, allowing data to be interpreted correctly across different systems and domains.

## V. SYSTEM DESIGN FOR DER INTEGRATION USING DATASPACE TECHNOLOGIES

We now introduce the design of our dataspace-based integration concept, with the goal to ease and speed up the DER changeover process in commercial VPPs. We later show, that this design can reduce the manual effort and migration



**FIGURE 3.** An EMS (consumer) connects to multiple DERs (providers) using the energy dataspace.

time by up to 80% compared to current practice. Our design addresses the core research gap identified: migration is manually complex without a standardized platform that eases this process. To address this challenge, we propose a dataspace that acts as a broker between the EMS and the DERs, in contrast to conventional one-to-one communication channels. This design facilitates secure and straightforward discovery and integration of DERs into an EMS. Moreover, it enables the provision of meta-information for each DER or communication link by DER operators.

It is evident that usage and access policies form an integral component of the dataspace architecture. Consequently, the proposed approach allows for a precise and detailed definition of visibility and access concepts, including the discovery of DERs. The design outlined here provides a communication infrastructure that supports dynamic reconfiguration and aggregation of DERs within the energy sector. This has the potential to enable more dynamic VPP compositions than current VPP implementations.

As the dataspace is used as the central communication infrastructure, both EMS operators and DER operators become participants within the dataspace. Following the established paradigm in VPP architectures, DER operators expose monitoring and control interfaces, while EMS operators consume these interfaces to integrate and operate DERs within the VPP. Although communication between DERs and EMS is inherently bidirectional, the proposed design consistently models DERs as providers and EMS as consumers of control and monitoring interfaces (see Figure 3).

### A. DER INTEGRATION

The first step involves making the monitoring and control interface of a DER available to other market participants. To do that, we expose the monitoring and control interface of a DER as a *data offer* within the dataspace. The *data offer* serves as an abstraction layer between the EMS and the physical asset and encapsulates integration-relevant metadata describing the DER interface. By modeling DER interfaces in this way, such metadata can be defined, reused, and updated independently of when and under which conditions the interface is accessed.

The *data offer* is described using a common *vocabulary*, enabling machine-to-machine communication and allowing

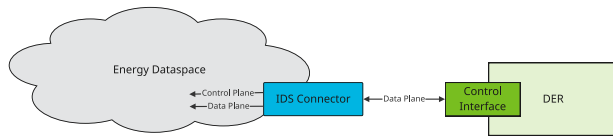


FIGURE 4. Connector as a gateway to the DER control interface.

participants to efficiently query the properties of available offers in a structured manner. For a DER interface, the *data offer* includes all relevant connection details, such as the used protocol, URL, data mapping, and technical contact information. This structured description reduces manual coordination effort and supports early preparation of the EMS integration.

To make DER integration points discoverable within the dataspace, data offers are published to a *metadata broker*. The broker enables controlled discovery of DER interfaces by authorized EMS operators based on predefined attributes and access constraints, allowing them to obtain the required integration information without prior bilateral coordination.

The identity infrastructure of the dataspace ensures that all participants are uniquely identified and can be unambiguously referenced when creating data offers. Depending on the chosen identity and trust model, identities may either be managed centrally by a trusted authority or be represented using self-sovereign identities (SSI). Both approaches facilitate access control, while the concrete choice of an identity model is treated as an implementation decision.

To enable continuous monitoring and control, the dataspace concept of a non-finite data source is applied. In this setup, the *IDS connector* functions as a gateway or proxy that enables API-based access to the DER interface, as illustrated in Figure 4. The connector provides a control plane to manage interactions such as contract negotiation and a data plane that enables access to the DER interface once a contract has been successfully established.

### B. EMS INTEGRATION

An energy trader participates in the dataspace by operating an EMS that connects via an *IDS connector*. This EMS, which may also be operated by a service provider on behalf of the trader, can use the *metadata broker* to discover new DERs for potential integration. Once a suitable *data offer* has been identified, the EMS initiates a negotiation process with the DER's *IDS connector* to establish a data contract. Both parties must agree to the terms in order to finalize the agreement. After the contract has been successfully concluded, the EMS accesses the DER interface via its *IDS connector* as shown in Figure 5.

### C. INTEGRATION TO A SPECIFIC DATE

As outlined in requirement 1, the integration of DERs by a specific date is critical, as marketing contracts and regulatory obligations typically become effective at predefined points in

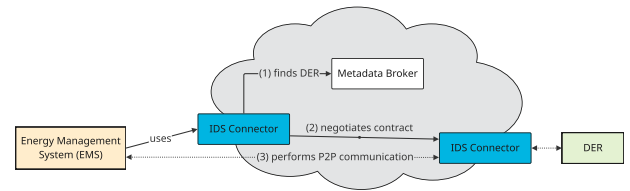


FIGURE 5. EMS leveraging the dataspace to find and integrate a DER.

time. To meet this requirement, the system design employs the dataspace concept of *policies* [30], which are defined by the data provider or asset owner and enforced by the corresponding IDS connectors.

Policies specify the conditions under which a requesting participant may access a given data offer, including temporal constraints. To ensure interoperability policies are expressed in a standardized, machine-readable format. Both the Dataspace Protocol [31] and the draft international standard ISO/IEC DIS 20151 [32] reuse the Open Digital Rights Language (ODRL) [33] to formally define such rules.

Listing 1 illustrates how time-based access constraints can be expressed using ODRL. In the example, access to a DER control interface is permitted only within a predefined validity period, corresponding to the contractual marketing window of the asset. By associating such policies with a data offer, DER operators can prepare integrations in advance while ensuring that actual interface access becomes possible only at the intended point in time.

### D. ACCESS CONTROL

In addition to temporal constraints, policies are used to enforce access control as required by requirement 4. By referencing a participant identifier in a policy, DER operators can restrict the audience authorized to use a given DER interface. If a policy specifies that the requesting party must possess a particular identity, access can be limited to a single participant. This mechanism is illustrated in Listing 1.

The policy shown there is evaluated by the provider's connector during contract negotiation and permits only the participant identified as ID-1234 to perform the `use` action for the linked data offer. By combining temporal constraints and identity-based conditions, the policy models that energy trader's exclusive right to access the DER control interface during the defined period.

### E. FAST INTEGRATION

In addition to integration by a specific date and access control, fast integration of DERs is essential to enable trading and avoid penalties, as stated in requirement 2. To support this, the proposed design enables the early and controlled exchange of metadata during DER onboarding.

Integration-relevant information is contained in the *data offer* and can be processed automatically by the EMS. While access to the DER interface itself remains restricted

```

{
  "@context": "http://www.w3.org/ns/odrl.jsonld",
  "@type": "Set",
  "permission": [
    {
      "action": "use",
      "constraint": [
        {
          "leftOperand": "dateTime",
          "operator": "gteq",
          "rightOperand": "2025-01-01T00:00:00Z"
        },
        {
          "leftOperand": "dateTime",
          "operator": "lteq",
          "rightOperand": "2025-12-31T23:59:59Z"
        },
        {
          "leftOperand": "identity",
          "operator": "eq",
          "rightOperand": "ID-1234"
        }
      ]
    }
  ],
  "prohibition": [],
  "obligation": []
}

```

**Listing 1.** Example ODRL policy expressing identity- and time-based constraints for the use action. Access is permitted only to the participant with the identifier ID-1234 and only within the defined validity period from January 1 to December 31, 2025.

by policies, metadata visibility can be granted at earlier interaction stages using catalog scoping policies. This allows authorized energy traders to access relevant integration information before interface access is permitted.

Offer creation, metadata description, offer discovery, contract negotiation, and interface access are explicitly decoupled steps in the integration process. DER operators first create a data offer that includes both access details and technical metadata and make it visible only to the intended energy trader, enabling early technical preparation.

As a result, EMS configuration can begin weeks or even months before the actual start of marketing. Contract negotiation between IDS connectors is performed fully automatically and typically takes only a few seconds. Once the policy-defined conditions are met, an access token is issued and accepted by the provider's connector, allowing the EMS to establish an authorized connection automatically on the specified date.

#### F. LEGACY INTERFACE CONTROL

To support legacy interfaces in accordance with requirement 3, the design uses IDS connectors as gateways (see Figure 4). This approach allows legacy interfaces to remain in use while access control and secure communication are handled by the IDS connector. In this way, systems that rely on existing industrial protocols can be integrated into the dataspace without replacing the local infrastructure. However, it should be noted that some connector implementations only support HTTP-based protocols natively. Non-HTTP

protocols therefore require either additional mechanisms within the connector or external bridging components.

#### G. SECURE COMMUNICATION AND AVAILABILITY

The IDS Reference Architecture Model [30] includes a dedicated security perspective that addresses requirement 6. The design is based on secure communication using the current Transport Layer Security (TLS) standard. The identity provider acts as a certificate authority, issuing valid certificates to dataspace participants. Verification of these certificates depends on the selected identity model.

In addition to secure communication, availability as defined in requirement 5 is a critical aspect. The availability of DER interfaces is influenced by many factors, not all of which can be addressed by the communication concept of the VPP. A prominent threat in this context is distributed denial-of-service (DDoS) attacks [34], [35], which can even be executed without technical expertise [36]. In current systems, such risks are mitigated by exposing legacy interfaces only through VPN tunnels. In our design, the gateway functionality of the IDS connector serves a similar purpose: the legacy interface is not directly reachable from the dataspace and can only be accessed via the IDS connector, which acts as a controlled gateway.

As with VPN-based setups, an attack targeting the IDS connector may block access to the DER interface, but it cannot directly compromise the DER controller. In the event of a successful attack, the connector shuts down the communication path, thereby isolating the DER and preventing unauthorized access.

#### VI. IMPLEMENTATION AND DEMONSTRATOR

To validate the feasibility of the proposed concept, we implemented the core elements presented in the design section. Our demonstrator illustrates how VPP and DER operators can benefit from the technologies used in dataspaces.

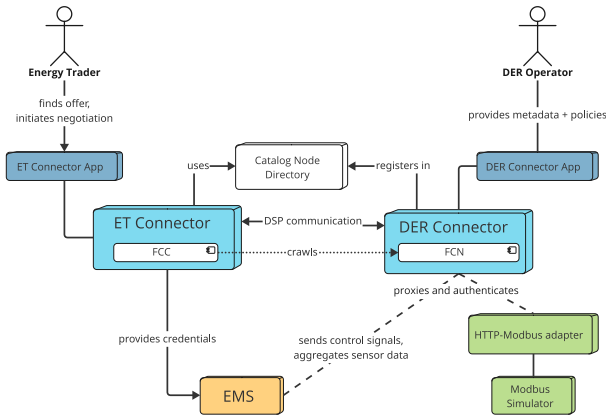
We showcase the migration of a DER between the portfolios of two energy traders. For this purpose, our demonstrator sets up a small-scale dataspace consisting of 3 participants:

- **Energy Trader #1:** a VPP operator with an EMS,
- **Energy Trader #2:** a second VPP operator with a separate EMS,
- **A DER operator,** who provides access to a wind turbine interface.

The evaluation scenario realizes a typical plant changeover, as shown in Figure 1. It begins with the DER being part of Energy Trader #1's VPP portfolio and then being transferred to Energy Trader #2.

#### A. TECHNOLOGIES AND ARCHITECTURE

Each participant in the scenario is provided with its own connector instance and assigned a unique identity. We decided to use the Eclipse Dataspace Components (EDC) [37] framework to prototype the demonstrator, as it offers



**FIGURE 6. Simplified system architecture of the demonstrator for the changeover scenario with three participants. Each box represents an independent system. For clarity, the systems operated by the two energy traders (ET Connector App, ET Connector, and EMS) are only shown once.**

a modular and extensible implementation that closely aligns with the theoretical concepts defined by the IDSA.

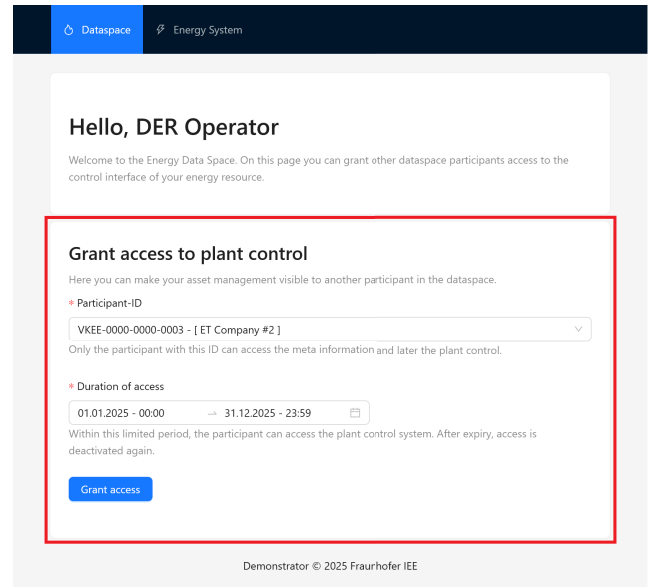
In addition to a full-featured *IDS connector* implementation, the EDC framework also provides a modular solution for metadata management called the *Federated Catalog*. This component was used to realize the metadata brokering functionality mentioned in our design section.

Unlike centralized catalog architectures, where participants must publish and update their data offers in a global *metadata broker* accessible to all, the Federated Catalog in our implementation follows a decentralized approach. Each data provider—here, the DER operator—runs a local *Federated Catalog Node (FCN)* alongside its connector. All FCNs are registered in a shared *Catalog Node Directory*, which is used by consumer-side participants to identify available sources for data offers.

Discovery of data offers is performed by the *Federated Catalog Crawler (FCC)* embedded in each consuming connector i.e., those operated by the energy traders. A key advantage of this setup is that all catalog requests issued by an FCC include the identity of the querying participant. This allows the catalog node to evaluate whether metadata should be disclosed at all, enabling access control already at the level of metadata discovery. Consequently, sensitive information such as technical contact details or control interface mappings is only visible to authorized VPP operators.

Figure 6 provides a simplified schematic view of the demonstrator system landscape. In addition to the connectors and the catalog node directory, two web applications are implemented that serve as graphical user interfaces: the *DER Connector App* for the DER operator and the *ET Connector App* for the energy trader. For clarity, both energy traders and their associated components are represented using the same elements in the figure. In the actual implementation, each trader operates a separate set of service instances.

The *DER Connector App* provides the operator with a convenient interface to define and manage relevant metadata



**FIGURE 7. The screenshot shows how a DER operator can grant temporary access to a plant interface. By choosing the participant’s identity and access time frame, the app creates a policy that restricts interface control to the authorized trader for that period.**

about their energy asset, such as interface type, protocol, and the contact information of the technical responsible person. It communicates with the control plane of the associated DER Connector and enables the operator to configure fine-grained access to the asset’s interface for other dataspace participants by applying time- and identity-based policies.

The *ET Connector App* is used by the energy trader to interact with their own connector instance. It provides a user-friendly interface to browse the data catalog, which is populated by the FCC deployed alongside their respective ET Connector. This feature allows traders to access data offers for Distributed Energy Resource (DER) interfaces provided by asset owners. It also supports contract negotiations and facilitates the integration of the asset into the trader’s Energy Management System (EMS) once an agreement is reached.

Last but not least, we include an *Emulator* to simulate a real-world energy asset. It exposes a Modbus TCP interface that resembles those commonly used in wind and solar installations. Since the EDC does not natively support Modbus, we introduce an *HTTP-Modbus adapter* that bridges the gap between the connector’s HTTP-based data plane and the binary field protocol expected by the emulator.

To represent the *identity provider*, the demonstrator uses a mock implementation from the EDC framework to illustrate a centralized identity provider. It assigns identities to participants and ensures their consistent use in catalog queries and contract negotiations. Although self-sovereign identity approaches could in principle be applied, we rely on a centralized identity management approach for the demonstrator, as the additional complexity of SSI-based solutions offers limited practical benefits for our DER changeover use case.

1) INTEGRATION FLOW

The integration flow demonstrates how a DER is discovered, contracted, and technically integrated into the EMS of an energy trader using the components described above.

a: DER OPERATOR

The demonstrator scenario starts with the DER currently being integrated into the EMS of Energy Trader #1. Towards the end of the month, the asset is scheduled to switch to the portfolio of Energy Trader #2. To prepare this transition, the DER operator uses the *DER Connector App*.

For demonstration purposes, we pre-filled the asset’s metadata, including an OpenAPI specification for the REST interface of the HTTP-Modbus adapter. We also added placeholder contact details and basic plant characteristics.

With this information configured, the operator uses the form shown in Figure 7 to define access rights. In this form, the operator selects the identity of the new energy trader and specifies a time window for access. This grants the selected participant visibility of the data offer and, later, access to the control interface strictly limited to the defined period.

b: ENERGY TRADER

The energy trader begins the integration process by browsing the local catalog through the *ET Connector App*. This catalog is continuously updated by the FCC component, which collects offers from all registered nodes.

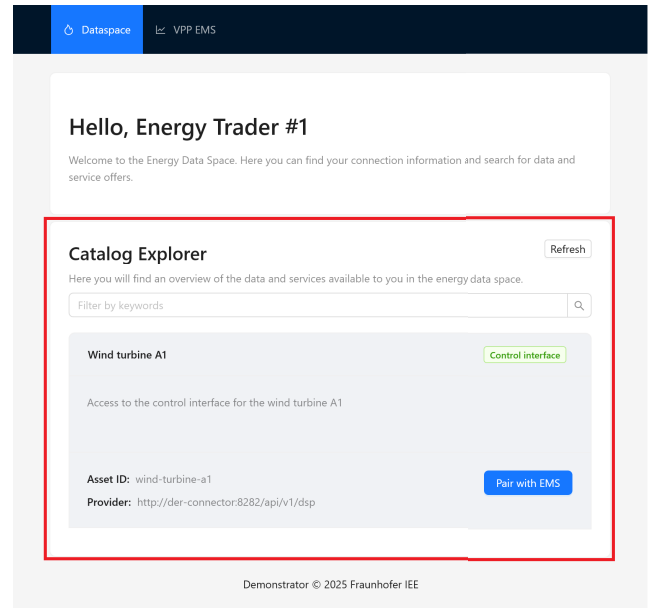
As shown in Figure 8, the offer published by the DER operator becomes visible in the trader’s view, but only because the identity of the energy trader was explicitly authorized for access. In contrast, this offer would remain hidden for other participants not listed in the access policy.

The trader can now initiate the integration process by clicking the *Integrate* button. This opens a detailed view of the selected offer, where the provided metadata, such as interface type, supported protocols, register mappings, and technical contact information, can be inspected. These details are provided by the DER operator as part of the data offer.

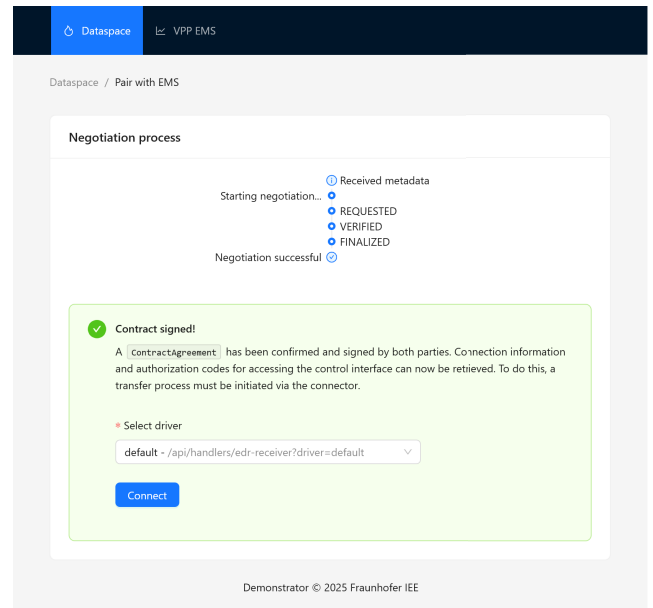
After reviewing the metadata, the trader initiates a contract negotiation between the connector systems. This negotiation is handled automatically using the Dataspace Protocol [31] and results in a formal agreement, provided that all conditions defined by the DER operator are satisfied.

After the negotiation is successfully completed, the ET Connector receives a signed contract agreement from the DER Connector. This agreement grants access to the DER interface during the defined period, based on the conditions specified in the policy. The negotiation is fully automated and typically completed within a few seconds, provided that the participant identity and time constraints are met.

Figure 9 shows the confirmation screen displayed after successful completion of the negotiation. The signed contract agreement is indicated, and the trader can now select the EMS driver that should handle the integration. By clicking the Connect button, the transfer process is initiated. The



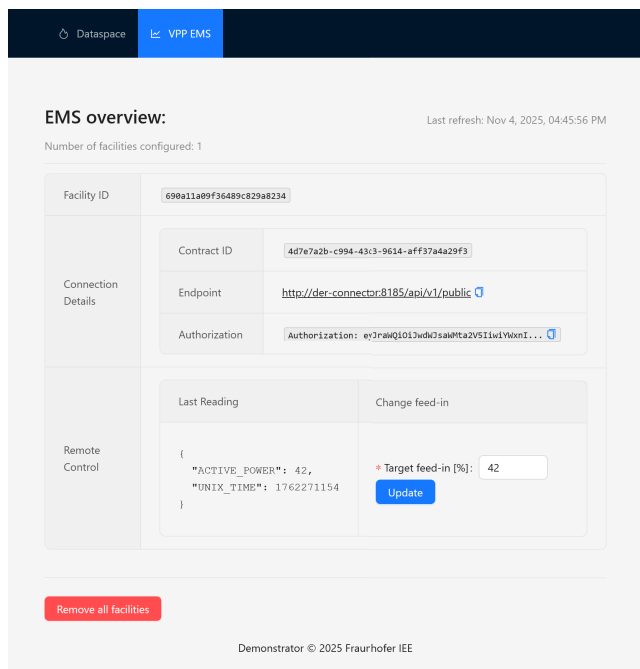
**FIGURE 8.** The energy trader can browse offers made available in the energy dataspace. In this example, access to the control interface of *Wind turbine A1* is visible because the trader’s identity has been authorized by the DER operator. Offers not explicitly shared remain hidden from view, demonstrating policy-based metadata filtering.



**FIGURE 9.** The screenshot shows the negotiation result after access terms have been verified and confirmed. The trader can now start the connection setup by selecting the EMS driver, establishing authorized communication with the DER interface.

DER Connector then provides the required credentials to the designated EMS endpoint, enabling a secure connection. The EMS uses the received access token to authenticate itself when accessing the data source.

All requests to the data source are routed through the DER Connector, which verifies the validity of the access



**FIGURE 10.** The EMS allows the trader to issue control commands such as limiting the active power output. The target feed-in is specified in percent and securely transmitted via the DER Connector, which verifies authorization and enforces policy constraints.

token. If, for example, the time window defined in the contract agreement expires, the token becomes invalid and the DER Connector denies further access. As long as the token remains valid, the EMS can retrieve operational data and issue commands such as active power limits to control the DER.

The demonstrator repository, available on GitHub at <https://github.com/FraunhoferIEE/vpp-dataspace-demo>, includes a rudimentary EMS and a Modbus simulator that emulates the DER control interface. Figure 10 shows the EMS view within the ET Connector App, which allows the energy trader to set the target feed-in power of connected DERs. The command is sent to the API specified by the provider, converted into a Modbus message, and written to the simulator. During the next data aggregation cycle, the EMS reads these values from the corresponding registers and incorporates them into the monitoring view.

## VII. EVALUATION

The proposed dataspace-based integration approach aims to reduce the effort and duration of DER changeovers between VPPs by streamlining technical onboarding processes and reducing manual coordination.

### A. EVALUATION METHODOLOGY & DATA SETS

To assess its potential impact under real-world conditions, the evaluation focuses on two complementary research questions:

- (1) how long DER integrations currently take in practice and which factors contribute to extended integration durations, and

- (2) to what extent the proposed approach could reduce integration effort under real operational conditions.

To answer these questions, the evaluation combines a quantitative analysis of historical onboarding data from productive VPPs with a qualitative expert-based assessment supported by the demonstrator presented in Section VI.

### 1) EMPIRICAL EVALUATION OF REAL-WORLD DER INTEGRATION

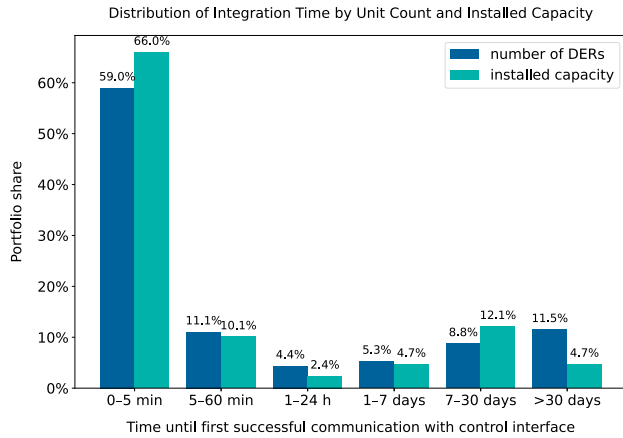
To empirically analyze and quantify integration durations and characteristics, we evaluate a data set supplied by two commercial VPP operators that covers more than 400 DER onboarding and changeover cases. The data were obtained by extracting metadata from the operators’ energy-management systems (EMS), in particular system logs and timestamps recorded during the DER onboarding and changeover processes. Because the available timestamps capture only system-level events, the measured durations should be interpreted as a lower bound for the actual organizational and technical integration effort.

*Acquiring such a data set is exceptionally challenging.* The detailed operational logs required for this study are not publicly released by VPP operators, owing to commercial confidentiality and data-privacy considerations. Consequently, the data set is effectively unavailable to the broader research community. Our ability to work with it stems from long-standing, direct contacts with the two VPPs, which granted us privileged access under a strict non-disclosure agreement. This collaboration not only enabled the empirical grounding of our work in real-world VPP characteristics, but also underscores the strategic value of industry-research partnerships for obtaining high-quality, otherwise inaccessible data.

### 2) EXPERT INTERVIEW

To complement the empirical perspective with a qualitative view on the integration process, we conducted a semi-structured interview with a senior practitioner who is directly responsible for the onboarding and changeover procedures at multiple energy traders. The interviewee was identified through our industry contact. Obtaining dedicated time from such a specialist is notoriously difficult, which underscores the value of this insight. While a single interview cannot be claimed to be statistically generalizable, it provides rich, context-specific observations that illuminate the quantitative findings.

*Evaluation procedure.* After presenting the dataspace-based integration flow using the demonstrator, the expert assessed expected impacts on integration effort, operational risk, and scalability in comparison to established workflows. This qualitative assessment contextualizes the quantitative results and enables the estimation of efficiency gains that cannot be derived from log data alone.



**FIGURE 11.** Distribution of integration durations grouped into six time clusters, shown separately by number of DERs and by installed capacity. Each cluster represents the time elapsed until the first successful communication with the control interface.

**B. QUANTITATIVE VIEW: EMPIRICAL EVALUATION OF REAL-WORLD DER INTEGRATION**

The analyzed data set comprises more than 400 DER onboarding and changeover cases extracted from two commercial VPPs operated by German energy traders. Both VPPs use the same EMS software platform and are of comparable size, ensuring consistent data structures and logging semantics across a similar observation period from 2020 to mid-2025. The data set includes timestamps for DER registration in the EMS and for the first successful communication with the DER control interface.

**1) FINDING 1: A NON-NEGLIGIBLE SHARE OF DERs EXPERIENCES LONG INTEGRATION DURATIONS**

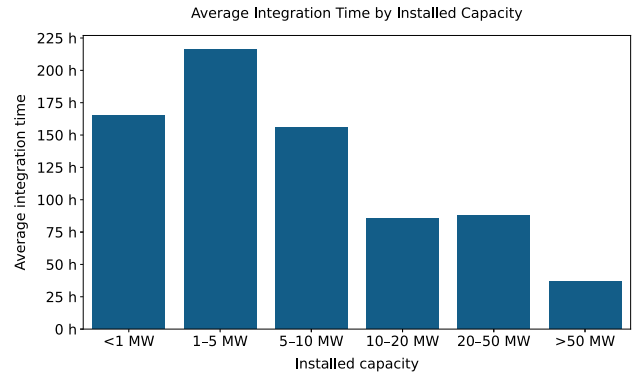
Figure 11 shows the distribution of integration durations grouped into six time-based clusters. While the majority of DERs are integrated within minutes or hours, a substantial fraction requires considerably more time. About 20% of DERs require more than one week to achieve first operational connectivity, and 11.5% take longer than one month.

These results indicate that prolonged integration durations are not isolated exceptions but occur systematically in productive VPP operations.

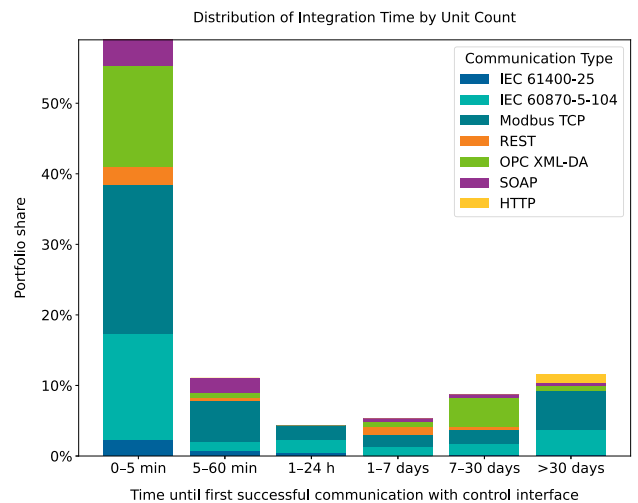
**2) FINDING 2: SMALLER DERs TEND TO REQUIRE DISPROPORTIONATELY MORE INTEGRATION EFFORT**

An analysis by installed capacity reveals a clear inverse relationship between DER size and integration duration. As shown in Figure 12, smaller units exhibit significantly higher average integration times than larger installations.

Although DERs below 10 MW represent roughly half of the data set, they account for a disproportionate share of long integration durations. This indicates that integration effort does not scale linearly with plant size and that small DERs are particularly affected by inefficient onboarding processes.



**FIGURE 12.** Average integration duration grouped by installed capacity. Each bar shows the mean time between system registration and first successful communication for DERs within the same capacity range.



**FIGURE 13.** Share of communication protocol types across six integration time clusters. The figure links observed integration durations to the underlying interface technologies.

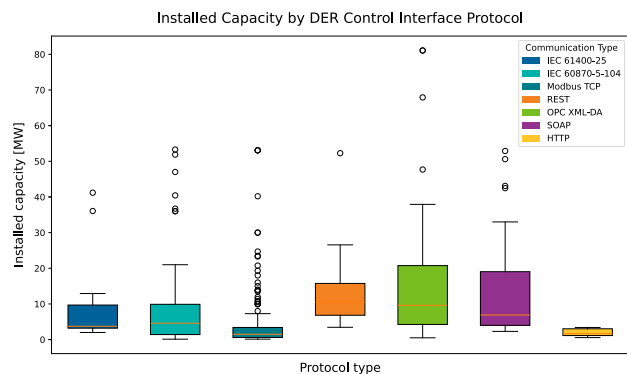
**3) FINDING 3: FIELD-LEVEL COMMUNICATION PROTOCOLS ARE ASSOCIATED WITH EXTENDED SETUP TIMES**

To further explain prolonged integration durations, integration times were analyzed across different communication protocols. Figure 13 shows that DERs requiring more than one month to integrate predominantly rely on field-level protocols such as Modbus TCP and IEC 60870-5-104.

These protocols typically require manual, device-specific configuration and lack standardized interface descriptions, which increases integration effort. In contrast, DERs using higher-level protocols such as OPC XML-DA or SOAP, for which predefined mappings are often available, tend to achieve connectivity faster.

**4) INTERDEPENDENCY BETWEEN DER SIZE AND PROTOCOL CHOICE**

Protocol choice and DER size are not independent factors. Figure 14 illustrates that DERs using field-level protocols



**FIGURE 14.** Distribution of installed capacities of DERs grouped by communication protocol. Each box indicates the range and median capacity within a protocol group, with circles marking outliers.

are smaller on average than those relying on higher-level interfaces. This interdependency suggests that prolonged integration times for small DERs result from a combination of limited standardization, fragmented documentation, and increased manual coordination effort.

Overall, the quantitative analysis shows that while fast integration is technically feasible, a substantial subset of DERs, particularly small installations using field-level protocols, faces significant onboarding delays. Since the analyzed timestamps capture only the time until first connectivity, the actual organizational effort associated with these cases is likely underestimated.

### C. QUALITATIVE VIEW: EXPERT INTERVIEW

To contextualize the quantitative findings, we conducted an expert interview with a practitioner responsible for DER onboarding and portfolio transitions at multiple energy traders.

#### 1) FINDING 4: SMALL DERs DOMINATE OPERATIONAL EFFORT DESPITE LIMITED CAPACITY CONTRIBUTION

The expert confirmed that small DERs are disproportionately resource-intensive to integrate due to unclear technical responsibilities, fragmented documentation, and manual coordination requirements. This observation aligns with the quantitative findings and explains why small installations account for a large share of prolonged integration cases despite their limited contribution to total installed capacity.

#### 2) FINDING 5: INTEGRATION EFFORT CREATES ECONOMIC AND OPERATIONAL RISKS

For the 2024/25 turnover period, the expert reported responsibility for integrating approximately 50 DERs, resulting in an estimated annual personnel effort of 2.5 person-months. The concentrated workload during contract renewal periods was described as a significant operational risk, particularly with regard to regulatory deadlines for proof-of-control.

Delayed integration increases the likelihood of penalties and reduces the economic viability of onboarding small

DERs, effectively creating a lower size threshold below which integration is no longer financially attractive.

### D. EXPERT-BASED PROJECTION OF INTEGRATION EFFORT REDUCTION

Based on the demonstrator and the expert assessment, the proposed integration approach has the potential to substantially reduce DER onboarding effort. After reviewing the demonstrated integration flow and comparing it with established onboarding practices, the expert estimated that the annual personnel effort required for DER onboarding could be reduced by up to 80%, assuming that the majority of DER integrations performed during a typical contract turnover period could be carried out using the demonstrated workflow.

This estimate is grounded in the expert's operational context, in which a large share of the portfolio is renewed annually and dozens of DERs must be onboarded or transferred within a short time frame. The projected reduction primarily results from the elimination of manual coordination steps, the earlier availability of interface metadata, and the automated enforcement of time- and identity-based access rights. In particular, the ability to prepare technical integration steps well in advance of the contractual switch date was identified as a decisive advantage over current VPN-based workflows.

By lowering integration effort, the proposed approach may shift the economic break-even point for small DERs and enable their scalable participation in VPPs. The expert further highlighted improved transparency of technical documentation, reduced operational risk during contract turnover periods, and increased scalability of portfolio management as additional benefits.

### E. LIMITATIONS

The evaluation is subject to several limitations. It is based on operational data from two commercial VPPs using the same EMS software platform and on a single expert interview. This limits statistical generalizability and may bias the results toward the specific technical and organizational context of the analyzed portfolios. However, access to comparable operational data sets from productive VPP environments is typically restricted due to confidentiality constraints.

In addition, the quantitative analysis captures only system-level timestamps and therefore reflects a lower bound of the actual integration effort. Organizational coordination steps, contractual dependencies, and parallel activities are not explicitly represented in the available data.

The results should therefore be interpreted as indicative of structural challenges in DER onboarding rather than as representative of the entire market. Nevertheless, the observed patterns are consistent with the expert's experience across multiple organizations and over several years, suggesting that the identified issues are not limited to individual traders or platforms.

## VIII. DISCUSSION

The discussion is structured by the following questions:

- Should dataspace technologies be used for monitoring and controlling DERs?
- Are dataspace technologies a good choice for building a virtual power plant?
- What does a minimal viable dataspace setup look like?
- What needs to be considered when building an energy dataspace?
- Will the smart meter rollout in Germany make the use of dataspace technologies for VPPs superfluous?

### A. SHOULD DATASPACE TECHNOLOGIES BE USED FOR MONITORING AND CONTROLLING DERs?

Dataspaces are a relatively new concept for sovereign data exchange between different companies. Since virtual power plants aggregate assets from multiple entities, they inherently require cross-company data exchange. Our work demonstrates how dataspace technologies can be used to build a virtual power plant. Although early dataspace use cases primarily focused on static data exchange, our approach shows that continuous, bidirectional, real-time data exchange is feasible.

Nevertheless, one might argue that dataspaces are not ideally suited for the monitoring and control of DERs, as semantic web concepts and shared vocabularies tend to be more intuitive for static data assets. In our implementation, we do not define or enforce a domain-specific vocabulary or ontology through a Vocabulary Hub to annotate data offers. Instead, interface descriptions are provided using OpenAPI [38] specifications, which are widely adopted for documenting modern web interfaces. The metadata modeled using dataspace vocabulary is limited to providing contact information for technical responsibilities.

Although applying dataspace concepts to DER monitoring and control may seem unconventional, the IDS Reference Architecture [30] already supports continuous data sources as first-class assets. Recent work by Karagiannis et al. [39] further shows that dataspace architectures are increasingly used for IoT-based, real-time energy data management, indicating that such scenarios align well with current developments in energy dataspaces. With our demonstrator, we have now shown exemplarily that this concept also works for DER control in practice. We therefore consider the application of dataspaces to DER monitoring and control, analogous to IoT device integration, to be a valid and promising approach.

### B. ARE DATASPACE TECHNOLOGIES A GOOD CHOICE FOR BUILDING A VIRTUAL POWER PLANT?

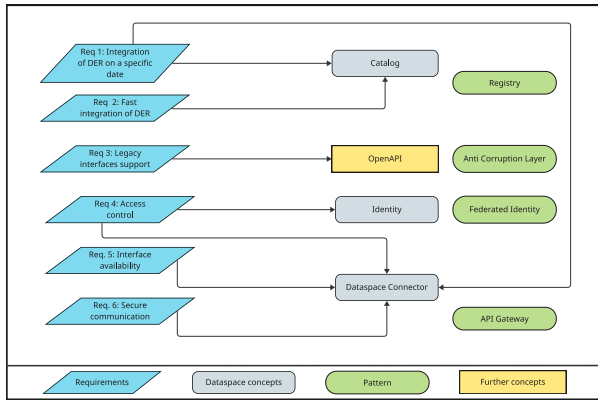
There are many concepts and studies focused on building virtual power plants. Here, we focused on DER integration and changeover processes and how these processes could be improved by building a virtual power plant using dataspace technologies. Accordingly, we defined requirements and identified dataspace concepts that meet these requirements.

Through an expert interview, we were able to evaluate that such an implementation could significantly improve the efficiency of power plant integration and changeover. However, the used EDC technology stack is still very complex and requires expert knowledge of dataspace concepts and implementation details. The discussion is still in progress, so one cannot assume that it could be easily used by companies in the energy domain with limited dataspace knowledge. There are other implementation stacks for the dataspace concept.

In previous years, the IDSA regularly published connector reports that compared more than twenty connector implementations and assessed their maturity using technology readiness levels. These reports consistently rated the Eclipse Dataspace Components as one of the most advanced implementations [40]. In the most recent edition [41], published in October 2025, the TRL metric has been removed and replaced by the Dataspace Protocol conformance test (DSP TCK). According to this updated report, only four connector implementations (including the EDC connector) have successfully passed the DSP TCK test suite, which is now the central criterion for assessing connector maturity and interoperability. This shift shows that protocol compliance has replaced earlier TRL based assessments. Despite these improvements, there is still a lack of dataspace stacks that are easy to use and suitable for broad deployment, especially for organizations without prior dataspace expertise.

This confirms that dataspace technology has reached a baseline level of technical maturity. However, the remaining complexity of current implementations makes it necessary to evaluate simpler architectural options. Since dataspaces, especially the EDC implementation, use common internet standards such as REST, JSON-LD, and ODRL, there are alternatives that may be less complex depending on the use case. Rather than comparing individual implementations, we therefore focus on the architectural patterns that meet our requirements and that are realised by the corresponding IDS building blocks.

Figure 15 shows the requirements, the identified patterns, and the used dataspace concepts. The requirements 4, 5, 6, and 1 were met by the dataspace connector. The connector itself provides a gateway function and hides the DER interface from public access; it ensures a TLS handshake before starting a connection and only provides access to dataspace participants with the correct identity. By protecting the DER interface, it supports the availability of the DER's interface itself, because only authorized participants get access. However, protecting interface access alone is not sufficient to guarantee availability. The gateway itself should also provide further features to ensure availability, because if the gateway is not available, dataspace participants cannot access the interface. Advanced concepts to improve connector availability are not analyzed in this work. The dataspace connector also supports the integration of power plants on a specific date by checking these conditions as part of the contract between connectors and only providing access



**FIGURE 15.** Mapping of integration requirements to architectural patterns and dataspace concepts, highlighting alternative implementations.

if the specified date is reached. For the defined use case, we use the connector as an advanced (*API Gateway*) [42]. Therefore, alternative API gateway implementations capable of verifying particular dates and authorizing specific identities may offer a more straightforward solution.

Besides the connector implementation, requirement 4 is met by the identity concept of the dataspace. Each dataspace participant, such as a trader, has an identity. This identity is used to identify participants and to grant or deny access to the DER interface to a specific energy trader. Since the dataspace concept itself is based on *federated identities* [43], each federated identity implementation could be appropriate as long as it allows identities across organizations.

Requirement 1 and 2 are met by the catalog system of the dataspace. The catalog supports energy traders in finding all DER connectors that have been shared with them. For this use case, the catalog acts as a *Registry* [42] which respects policies such as visibility. As with other concepts, different implementations of such a registry may exist.

The legacy interface support (requirement 3) could not be directly mapped to an existing dataspace concept. It might be possible to use dataspace vocabulary to describe the DER interface. However, for this requirement, using existing industry standards like OpenAPI is more obvious. As already mentioned, using OpenAPI for legacy protocols like Modbus TCP requires implementing a protocol translator or *Anticorruption Layer* [44].

As a result of the analysis above, alternative implementations exist that meet the defined requirements. The identified *integration patterns* can be implemented with little dataspace-specific overhead. When focusing only on DER integration and migration between VPPs, such a tailored solution may be simpler and easier to apply.

This is not surprising, since dataspace technology is designed as a generic framework for cross-domain data exchange. The effort involved in onboarding and initial setup is relatively high [45], and building a dataspace is usually justified only when multiple use cases are addressed.

Thus, dataspace can be valuable for VPPs. In the energy domain, several dataspace-based ecosystems are emerging (see Section II), where legal, organizational, and technical foundations have already been established. In such contexts, DER operators and energy traders can benefit from onboarding into existing infrastructures.

In summary, a full dataspace implementation may not be justified for a single, isolated use case. However, if a dataspace already exists, using it for VPP integration is both practical and beneficial. Based on these considerations, dataspace technologies can be regarded as a viable foundation for building virtual power plants.

### C. WHAT NEEDS TO BE CONSIDERED WHEN BUILDING AN ENERGY DATASPACE?

Building a dataspace for the energy sector has far-reaching implications. Copei and Rüllicke [45] classify the barriers and challenges of dataspace implementation into three categories: organizational, socio-economic, and technical. Each of these categories is also relevant when designing and operating an energy dataspace.

From an organizational perspective, the definition of a dataspace operator and its financing model plays a central role. The operator is responsible for managing and maintaining the core infrastructure of the dataspace. Consequently, the structure of this role, including financing and governance, directly affects the participation costs and the long-term stability of the ecosystem. In the energy sector, this role could potentially be defined as part of the regulated domain and financed through grid fees. In other domains such as supply chain or manufacturing, several operator business models have been explored, yet none have proven economically sustainable so far because most dataspaces are still experimental or publicly funded [46], [47].

From a socio-economic perspective, the cost structure and incentives for participation are key factors. For the use cases discussed in this paper, even relatively low participation fees could represent barriers, particularly for small DER operators with limited financial resources. Trading companies, on the other hand, already consider communication costs in their existing business models and would benefit most from the proposed approach. As a result, they might be willing to pay recurring fees for dataspace functionalities. The design of the operator role therefore has a direct influence on the adoption speed, as a viable financing model determines how quickly infrastructure can be established and a critical mass of participants can be onboarded. The discussed VPP use case may not be ideal for a first implementation since it requires the onboarding of a large number of DER operators. According to the German Market Master Data Register [48], more than 5M plant operators were registered in October 2025. Although only a fraction of these installations exceed the current legal capacity threshold for mandatory direct marketing, this still represents a very large group that would need to be addressed and incentivized to join such a dataspace. A sufficient share of this group would have to

participate to cover a market segment that is relevant to energy traders.

From a technical perspective, the maturity of available dataspace software components strongly influences adoption potential. Most dataspace initiatives across all domains are currently based on open-source frameworks such as the Eclipse Dataspace Components [37], which are still under active development. Documentation remains highly technical and is targeted primarily at experts, which limits accessibility for smaller organizations. As a result, scaling purely open-source deployments remains challenging. Some initiatives, including Catena-X, the Mobility Dataspace, and energy-data-X, address this barrier by providing Software-as-a-Service (SaaS) connectors that reduce the technical complexity for participants. Although this approach increases the setup effort for the operator, it significantly simplifies onboarding and lowers the entry threshold for companies without dataspace expertise. Offering SaaS-based connectors is therefore recommended as a practical measure to support broader scaling in the energy sector.

In summary, the establishment and financing of a dataspace operator, the economic incentives for participants, and the technical maturity of the available software components must be carefully considered. These organizational, socio-economic, and technical factors jointly determine the cost structure, adoption speed, and scalability of an energy dataspace. A detailed overview of barriers and mitigation strategies is provided in [45].

#### D. WHAT DOES A MINIMAL VIABLE DATASPACE SETUP LOOK LIKE?

If the presented use case is to be implemented by setting up a new dataspace or by onboarding into an existing one, not all components listed in the IDS-RAM are required. For the described integration flow, only three fundamental building blocks are needed:

- 1) **Dataspace Connectors:** They serve as the technical foundation for data exchange. They enable secure access to various DER control interfaces and enforce policies governing access rights and usage conditions. Automated contract negotiation between connectors supports timely integration. A proxy mechanism facilitates the exchange of data and control commands between energy assets and different EMS platforms.
- 2) **An identity concept that establishes trust:** This can be implemented, for example, through a central identity provider ensuring that only authorized parties have access to the dataspace. Identity management is critical for securing communication and enforcing access and usage policies.
- 3) **A catalog system:** It enables efficient discovery of assets and associated metadata. This significantly reduces manual integration efforts and simplifies interactions between participants. In IDS terminology, this corresponds to the *metadata broker* component.

These components create a minimal dataspace setup for integrating and migrating DERs into virtual power plants. The remaining elements of the IDS-RAM, such as the *Vocabulary Hub* for semantic interoperability, the *App Store* for auxiliary services, or the *Clearing House* for transaction logging, may not offer immediate added value for this specific application. Nonetheless, they could coexist seamlessly within the same dataspace environment.

#### E. WILL THE SMART METER ROLLOUT IN GERMANY MAKE THE USE OF DATASPACE TECHNOLOGIES FOR VPPs SUPERFLUOUS?

The demonstrator described in Section VI illustrates how dataspace technologies can facilitate the integration of DERs. At the same time, the smart meter rollout in Germany aims to improve and secure communication with DERs. By using smart meter gateways (SMGWs) as communication units, connectivity to all DERs is intended to be unified. With an SMGW, the metering point operator becomes responsible for providing communication to the DERs. Currently, a standardized interface [49] exists for certain use cases (e.g., EnWG §14a). For energy trading, however, no such interface has yet been defined, although an extension of [49] is being discussed as a possible solution. On the DER side, EEBus is currently the de facto standard [50]. Field protocols such as Modbus TCP, OPC XML-DA, or IEC 60870-5-104, which are commonly used for controlling wind, photovoltaic, and biogas plants, are not permitted according to [51] as they lack the necessary encryption and authentication mechanisms. Therefore, integrating legacy protocols remains a challenge for controlling DERs via SMGWs.

Compared to dataspace technologies, the smart meter rollout offers advantages in establishing secure connectivity to DERs, similar to the connector-based approach. It provides a standardized communication infrastructure. Nevertheless, dataspace technologies offer additional functionalities—for example, a catalog system that enables the discovery of power plants assigned to specific traders, and connector mechanisms that allow sharing access for defined periods. It should also be considered that the smart meter rollout in Germany is ongoing, and SMGWs are currently used to control only a limited number of DERs. For future developments, integrating smart metering technology into dataspaces should be considered to combine the benefits of both approaches.

In conclusion, the smart meter rollout does not make dataspace technologies for VPPs obsolete. Rather, both approaches address different aspects of the integration challenge and should be seen as complementary.

## IX. CONCLUSION AND OUTLOOK

### A. SUMMARY

The fast and seamless integration of DERs into VPPs remains a challenge in practice. Our analysis showed that at least 11% of DERs required more than one month for integration in

the VPPs examined. We also found that the integration of smaller DERs (in terms of installed capacity) is even more time consuming than for larger ones. The reasons for this are partly organizational, such as the lack of contact persons, and partly technical, such as protocol complexity.

To address these challenges, we designed a VPP using dataspace technologies. DERs were connected to the EMS of a VPP via dataspace connectors. This allows DER operators to easily preconfigure the responsible trader in advance and thereby simplifies and accelerates the entire changeover process. Traders can prepare integrations ahead of time and thus automate routine transitions. The dataspace concept also enables the discovery of technical interfaces through a metadata broker and the description of relevant metadata, such as technical responsibilities, using a common vocabulary.

To demonstrate the design, we built a demonstrator based on Eclipse Dataspace Components, which is available on GitHub. The demonstrator was used both to practically evaluate the theoretical concept and to assess whether such a solution could accelerate integration in expert discussions.

As a result, we found that dataspace technologies can improve the onboarding and changeover processes for DERs. It is possible to build a virtual power plant based on dataspace principles. However, we encountered significant technical complexity during implementation and believe that the technology still needs to be simplified. We also demonstrated that a minimal dataspace is sufficient for the use case examined. Overall, we discussed whether dataspace technologies are an appropriate choice as a technology stack and concluded that, despite current complexity, they offer a promising foundation for scalable and interoperable VPP integration.

## B. FUTURE WORK

Future research should explore how standardized, machine-readable representations of energy assets can be integrated into the presented design. In particular, it would be valuable to investigate the applicability of the Asset Administration Shell (AAS), a concept already established in the automotive and manufacturing sectors, within the energy domain. Recent work demonstrates that AAS-based digital twins can support interoperable and lifecycle-oriented representations of energy systems, suggesting a promising foundation for harmonizing metadata and interface descriptions in VPP-related processes [52]. Building on these insights, future studies could assess the readiness of the energy sector for adopting machine identities and standardized asset models as part of dataspace-based integration workflows.

Another promising direction is the combination of dataspace technologies with intelligent metering systems (iMSys), for example in the context of direct marketing. Such an integration could enable unified communication infrastructures and improve regulatory compliance, particularly for small-scale DERs. From a technological perspective,

simplifying dataspace stacks remains critical to enhance usability by improving tooling, documentation, and low-code interfaces to foster broader adoption in the energy sector. Finally, extending the analysis beyond direct marketing scenarios may support the definition of a minimal, energy-specific dataspace profile that lowers entry barriers and eases deployment.

In addition to these research questions, an operational adaptation of the proposed concept requires several further steps. As discussed in Section VIII-C, the work of Copei and Rüllicke [45] provides a detailed overview of the organizational, socio-economic, and technical challenges involved in building a dataspace. For the energy sector, defining an operator model and a sustainable business model will be essential. Before such long-term structures can be established, it is advisable to begin with operative use cases that involve as few participants as possible. Once an energy dataspace is operational and a minimum number of necessary participants have joined, the use case presented in this work can be implemented and evaluated under real conditions.

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**MANUEL WICKERT** received the master's degree in computer science from the University of Paderborn. After two years in the automotive sector, he joined the Fraunhofer IWES (now IEE), in 2009. He currently leads the research focus area of energy informatics with the Fraunhofer IEE, where he develops digital solutions for the transformation of energy systems. He leads the digitization dimension within the Fraunhofer Cluster of Excellence for Integrated Energy Sys-

tems (CINES), contributing to strategic studies on the role of data and automation in the energy transition. His research interests include smart grid technologies, integration of renewable energy into power grids, and microservice architectures for virtual power plants.



**OLIVER HOHLFELD** received the Ph.D. (Dr. rer. nat.) degree from TU Berlin. He held academic positions with RWTH Aachen University, TU Berlin, and Brandenburg University of Technology. He is currently a Full Professor with the University of Kassel, where he leads the Distributed Systems Group. He is a Principal Investigator in several national research initiatives, including emergenCITY, and contributes to interdisciplinary studies on the resilience and design of digital infrastructures. His research interests include internet architectures and internet measurement.

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**DARIO KLAPP** received the B.Sc. and M.Sc. degrees in computer science from the University of Kassel, in 2020 and 2024, respectively. As part of his studies, he spent a semester abroad with Aalto University, Espoo, Finland, focusing on IT governance and IT security. He was a DevOps Specialist with an academic spin-off. He is currently a Research Associate with the Fraunhofer IEE. His professional and academic interests lie at the intersection of software engineering and process

automation, with a focus on efficient communication structures in the energy sector.