Digital Twins for Cross-Domain Interoperability Supporting Hybrid Energy Storage System Optimisation

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***Abstract*—There is an urgent need to leverage the flexibility of hybrid energy storage assets to support the integration of increasing renewable energy resources into the electrical grid without incurring significant network upgrade costs. To address this, a Digital Twin (DT)-based approach is proposed that utilises Asset Administration Shell (AAS) data models and standardised APIs to abstract and securely share comprehensive asset data and permit distributed control of permissible asset states. This approach ensures interoperability, enabling energy assets to efficiently participate in flexibility services by dynamically adjusting their operational behaviour in response to grid needs. The AAS-based Connected Hybrid Energy Storage System (CHESS) Node is introduced to aggregate multiple energy assets—such as electric vehicle (EV) charging stations, battery storage systems, flexible loads, and generation resources—within and across multiple buildings. This aggregation is achieved through *software virtualisation* using both standards based and proprietary interfaces, exposed via AAS models and coordinated through the Universal Utility Data Exchange (UUDEX) message bus protocol. Value is created by enabling distributed optimisation and forecasting tools to aggregate and coordinate multiple CHESS assets across domains through CHESS Nodes. By harnessing AAS-based DT asset representations, the solution ensures interoperability and supports the seamless deployment of CHESS Nodes across edge or cloud environments, integrating multiple assets into a unified, distributed system. This paper presents the technical solution developed in the FlexCHESS project, demonstrating CHESS nodes, supporting a digital twin ecosystem, enabling the secure abstraction, sharing, and coordination of asset data across domains. Pilot use cases and initial evaluations validate the effectiveness and potential of the proposed approach to support energy flexibility services.**

***Index Terms*—Asset administration shell, digital twin, data models, data space**

I. Introduction

The electrical energy sector is undergoing a profound digital transformation, driven by the push for decarbonisation, the proliferation of distributed renewable resources, and evolving regulatory frameworks that promote a more decentralised and interconnected infrastructure [1]. A growing number of prosumers (consumers who both produce, store and consume energy) and distributed energy resources (DERs) are reshaping traditionally one-directional grids, creating opportunities for

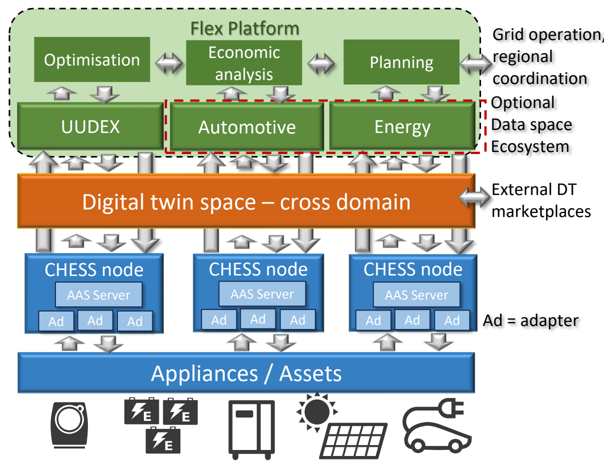


Fig. 1: Overall architectural reference framework for digital twin space supported by AAS CHESS nodes and adapters.

coordinated flexibility services to address grid stability and resilience issues that arise. Initiatives such as the EU's Energy Data Exchange Reference Architecture (DERA) [2] and the Common European Energy Data Space (CEEDS) [3] aim to support the federation of local energy data spaces. However, achieving seamless interoperability and optimised control among heterogeneous assets remains difficult [4]. Existing solutions [5], [6], [7] often operate in silos or target specific asset classes relying on different integrators, limiting the ability to exploit cross-domain synergies. Moreover, as many flexible assets are now located on the prosumer side, such as residential buildings, commercial facilities, and associated EV charging infrastructure, new methods are needed to securely abstract, share, and coordinate asset data across domains while preserving sovereignty and trust. Current fragmented approaches hinder the full utilisation of prosumer-side flexibility, highlighting the urgent need for a unified, interoperable integration framework.

A promising approach to address these challenges is the use of digital twin (DT) technology. A digital twin is a virtual representation of a physical asset capable of reflecting its real-time state and behaviour to support interoperable monitoring, analysis, and control [8]. In the energy domain, digital twins provide a unified virtual interface for managing distributed, heterogeneous DER assets, which can be on the grid-side or the prosumer-side [4]. To foster interoperability, the Asset Administration Shell (AAS) model has been adopted as a standardised DT framework, originating from Industry 4.0 [9]. The AAS defines a comprehensive set of templates describing the information model that encapsulates an asset's properties, interfaces and processes in a machine-readable form, allowing disparate systems to consistently interpret and interact with energy assets such as batteries, solar inverters, Heating Ventilation and Air Conditioning (HVAC) systems, heat pumps or EVs. By representing energy assets through AAS-based DT submodels, flexibility providers and users can exchange data related to these assets consistently across domain boundaries. Nevertheless, a clear gap remains in integrating digital twins with hybrid energy storage systems and distributed optimisation methods to fully unlock system-wide flexibility. Addressing this gap enables more resilient and efficient grid management by coordinating control strategies across all assets without requiring a centralised solution, which is not scalable or resilient.

However, establishing a DT for each asset is only part of the solution; effective cross-domain coordination and control also requires a robust, efficient and scalable data exchange mechanism between the many distributed participants involved. This mechanism must satisfy low-latency and low-overhead requirements while supporting scalability and resilience. The Universal Utility Data Exchange (UUDEX) [10] is one such mechanism, providing a flexible and secure standard for sharing data and control signals between organisations. By defining shared protocols and information models, UUDEX enables, for example, a prosumer's energy management system to cooperate with the grid operator or aggregator energy management system layers. Through such a framework, real-time status and flexibility services can be accessed by authorised stakeholders, fostering coordinated control across previously siloed systems.

Building on these enabling technologies, this paper proposes a unified coordination architecture presented in Fig. 1, developed within the EU FlexCHESS[1] project, to bridge prosumer assets with aggregator platforms and grid operators across domain boundaries. FlexCHESS combines standardised AAS-based DT models and cross-domain data exchange mechanisms to permit integration of hierarchical, distributed and decentralised control paradigms to orchestrate distributed resources for flexibility services and multi-energy optimisation. Through standardised APIs, the platform abstracts and securely shares comprehensive asset data while enabling combined hierarchical and decentralised control of permissible DER asset states based on a statistical multiplexing approach. At the core of this architecture is the CHESS Node, which represents an aggregation of multiple virtual storage assets accessed through software-based CHESS adapters. Each CHESS Node exposes its capabilities (e.g. location, type and submodels supported) and status (e.g., time-dependent available flexibility capacity) and can be monitored or adapt behaviour according to external actors in a distributed manner via the UUDEX data exchange layer. Additionally, the architecture optionally supports integration with data space connectors toward different domains, such as automotive or regional energy eco-systems. The platform leverages the DT space to enable interoperability, facilitating cross-domain asset coordination in support of flexibility services. For instance, multiple buildings' battery systems coupled with thermal storage and other building assets such as heat pumps and EV chargers can be managed as part of a single CHESS Node, making its flexibility accessible both to the local energy management system and to the external grid operator for coordination of flexibility services. By enabling such cross-domain and API level interoperability at the CHESS Node level, the paper addresses a crucial gap in existing frameworks, which have struggled to integrate different decentralised DER assets on the prosumers side.

Contributions: In summary, the paper makes three key contributions. First, it presents the design of the FlexCHESS architecture—a novel decentralised, digital twin-driven framework for cross-domain coordination of distributed energy assets. Second, it introduces the CHESS Node, enabling the seamless integration of virtual energy storage systems via corresponding CHESS adapters, using standardised interfaces and data models based on AAS templates and APIs defined in the digital twin space. The proposed approach enables scalable and cross-domain deployment of CHESS Nodes and corresponding adapters, allowing different types of CHESS assets to be controlled in a combined hierarchical and decentralised manner to support various flexibility services through a proposed prioritised statistical multiplexing paradigm and the UUDEX-based message bus. Third, a proof-of-concept implementation and case study are developed to validate the proposed approach, demonstrating how CHESS Nodes can be coordinated across domains to provide flexibility services. These contributions advance the state of the art in energy digitalisation by bridging previously siloed domains and stakeholders, thereby enabling more effective utilisation of decentralised energy assets.

The remainder of the paper is organised as follows: Sec. II introduces the concept of the DT space, including the structure and role of AAS submodels. Sec. III describes the architecture, implementation, and deployment of the CHESS node, along with the access control mechanisms and required APIs. Sec. IV presents a pilot use case and evaluates the initial results. Finally, Sec. V provides the discussion and concluding remarks.

II. Digital Twin Space

The digital twin space provides a means to abstract assets using a virtual representation and expose interfaces through the corresponding AAS APIs. These APIs allow access to asset-related submodels, which organise data into structured templates, supporting multiple views of the asset [9]. By leveraging AAS-based abstractions, a common cross-sector

[1] Available at:https://flexchess.eu/

and cross-domain method of accessing asset information is established, enabling interoperability across diverse energy and industrial systems.

The DT space can optionally interface with external data spaces, such as CEEDS and the Catena-X [11] automotive data space, to further enhance interoperability, data sovereignty, and trust among stakeholders. Designed to be domain-agnostic, the DT space provides several value-added services:

- Catalogue / DT registry: discovery of what is available and who is responsible.
- Graph database: representation of complex relationships between different asset and data sets.
- Access control: attribute-based access control (ABAC) mechanisms to enforce data access rights.
- Model and graph representations: ontology-based structuring and realisation of DT data.
- Support for different views/submodels (e.g. simulation or prototype versus twin instances)
- Mapping between different representations: facilitating interoperability between formats (e.g. DTDL [12] to AAS [9]) as described in [13].

The DT space can also leverage definitions from the IEC Common Data Dictionary (CDD) [14], which consists of concepts, classes and properties defined as data specifications within a database, to permit mapping of asset-related information across different standards and submodels. This supports semantic interoperability between sectors and enables machine-readable access to asset information.

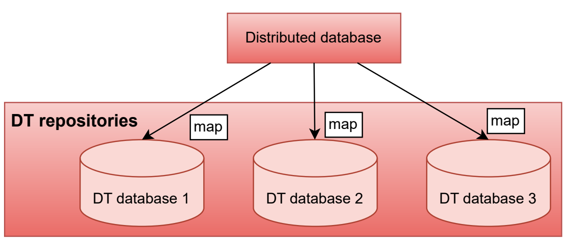


Fig. 2: Digital twin repositories within the digital twin space.

Within the DT space, submodels integrate both static asset information and real-time dynamic telemetry, enabling comprehensive monitoring, behaviour modelling, and degradation or failure prediction for hybrid energy storage systems. Real-time telemetry is critical for generating accurate behaviour models and deriving asset knowledge under varying operating environments and usage conditions. In this manner, more optimal use of the asset can be enabled by sharing this knowledge. Submodels can represent both physical assets ("digital twin instances") and simulated or prototyped assets ("digital twin prototypes"). Simulated assets, or DT prototypes, will also be used to evaluate future deployment options. To support the proposed distributed CHESS approach, the key containerised abstraction utilises real-time asset DT registries and repositories. These are exposed through standardised AAS APIs, permitting interaction with virtual asset representations (see Fig. 2), and enabling AAS registry submodel discovery based on asset location or other criteria, as well as access to submodels and DT prototypes or instances. While DT repositories can be hosted in diverse environments, the proof-of-concept implementation for this work uses Azure Digital Twins, with associated AAS submodel templates, such as the Catena-X battery passport [11] and the Smart Applications REFerence (SAREF) [15] data models for building temperature and HVAC representation. The Azure DT environment permits semantic models, defined using common data concepts and specifications, to support asset abstractions using AAS submodel templates. This ensures consistency and allows mapping of the asset data without ambiguity that can otherwise occur when different standards are being used, such as battery passports with vendor-specific data models. Additionally, the Azure DT environment is chosen for its robust support of DT data model validation and graph-based data representations, which facilitate secure collaboration between stakeholders.

In this setup, the AAS server provides a standardised type 2 API wrapper over the underlying Azure DT API, ensuring a consistent interface for accessing asset submodels and facilitating cross-domain coordination in the FlexCHESS platform. The Azure DT environment separates the DT data models, data specifications and graph instances, performing validation to ensure consistency. It also stores historical DT information for analysis and visualisation.

III. CHESS Nodes

A. Framework

CHESS Nodes perform aggregation functions by federating assets through the AAS server, which abstracts multiple assets into a single logical API endpoint. While the DT repositories can be distributed across different domains, access is unified and managed by the AAS server within each CHESS Node. To ensure consistent access control, a hash table is used to map identities across DT domains, leveraging location and other key attributes to correlate asset twins. Registration of new assets is performed through the CHESS Core API, which associates the CHESS assets with the corresponding CHESS adapter instances within the CHESS Node. The core components of a CHESS Node include:

- **CHESS Adapters:** protocol and data model mapping interfaces toward physical or virtual assets.
- **Asset Submodels:** representations of different views of assets, supporting access control and asset behaviour management.
- **AAS Server:** management of DT registries and repositories, ensuring synchronisation of DT data.
- **Core API:** registration and association of adapters with DTs, and control plane handling.

CHESS Adapters expose standardised data and control APIs that enable uniform interaction with diverse asset types. These standardised APIs support both telemetry access and localised control, independent of the underlying asset's type. Each adapter is linked to one or more asset submodels, which

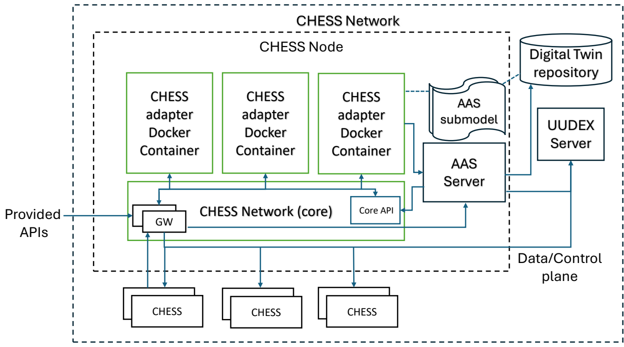


Fig. 3: CHESS Node overall interconnection architecture.

represent DER data in a structured, interoperable form and are integrated with the corresponding DT. The AAS server aggregates access to all associated assets, facilitating the registration of DTs and their association with physical assets through the Core API. This ensures that DT instances remain synchronised with the real-time state of their corresponding physical or simulated counterparts. Since FlexCHESS targets near real-time optimisation use cases, the system prioritises high-frequency twin updates to maintain fidelity. Furthermore, the Core API supports dynamic deployment of adapters and updates to asset status or scheduling, allowing for responsive coordination across domains. Inter-node collaboration is achieved through a standardised messaging architecture based on the UUDEX protocol, enabling scalable and interoperable communication across distributed CHESS Nodes.

B. Interoperability Messaging Architecture

Both the AAS aggregation server and the Core API utilise the UUDEX protocol, which is currently being standardised within IEEE P2030.103, to enable interaction between distributed CHESS Node participants in a unified manner. UUDEX protocol [10] supports data aggregation across various subjects or topics related to various assets, such as telemetry data and control commands.

Data is encapsulated in JSON-formatted messages, known as u-messages, and exchanged between CHESS Nodes via UUDEX servers residing locally on the CHESS Nodes or centrally on the Flex platform, which aggregates multiple CHESS assets and CHESS Nodes. This architecture ensures the secure, resilient, and efficient exchange of real-time status updates and control signals across distributed participants.

C. CHESS Node Deployment Environment

The implementation of the proposed solution is based on open-source components to facilitate the ease of deployment of CHESS Nodes. Each CHESS Node operates within a lightweight Kubernetes (K3S) environment, providing HTTPS /REST APIs for the associated DT Registry services via the AAS server. For integration with external data spaces, such as Catena-X, a CHESS Node can obtain a valid certificate from the Industrial Digital Twin Association (IDTA), including the required service specification profiles for simplified certification; however, this certification is not essential for operation.

The CHESS Node endpoints, offered by the data provider through the CHESS Adapters, are made accessible to data spaces via the AAS server APIs. Access to the CHESS Node AAS server endpoints requires that access tokens carry the necessary subject attributes. Therefore, an identity provider is required to issue tokens, which can correspond to different data space domains. The implementation supports this requirement by allowing each CHESS Node to host multiple API gateways (GW) or key managers, each corresponding to a different domain (see Fig. 3). This design provides the CHESS Node operator with flexibility to support interoperability across multiple data spaces by leveraging distinct gateways, which use different signed JWT token key managers. Additionally, the adapters can be dynamically registered using the CHESS Node Core API, and access control to AAS submodels is enforced within the AAS server as illustrated in Fig. 4. It is recommended that submodels conform to standard templates, although this is not strictly necessary, provided that the underlying IEC 61360 CDD data specifications [14] are used to ensure reference to relevant source definitions.

Different gateway options are supported depending on the CHESS Node scale and deployment environment. For lightweight deployments, the Envoy-based micro-gateway can be used, offering a footprint of less than 50 MB and providing high-performance open-source API gateway functionality. Alternatively, for cloud-based or larger Node deployments, the full WSO2 API Manager (APIM) resident gateway can be employed. Both approaches support advanced API traffic management and monetisation features, including subscription models, pay-per-use mechanisms, and differentiated service levels through usage throttling and quotas. In both cases, the gateways are configured using an API manager, which handles API subscriptions and access token issuance. The API manager operates in conjunction with a Keycloak server for identity and access management. To support multiple Envoy gateways per CHESS Node, different port offsets are utilised, with the default configuration using HTTPS. Furthermore, the API manager supports integration with payment platforms such as Stripe, enabling the monetisation of APIs exposed via CHESS Nodes across different data spaces.

D. Adapter Registration

Each CHESS Adapter is provided as a Docker container corresponding to a specific asset type or communication standard, and it supports the APIs required for integration into the CHESS framework. In this way, multiple CHESS assets can be registered with an adapter and associated with their corresponding DTs through the CHESS Node Core API service. The association is typically performed by scanning the asset's digital passport QR code using the registration application linked to the selected CHESS Node. Alternatively, the adapter can autonomously create the required DT instances for its associated assets. Upon successful user authentication,

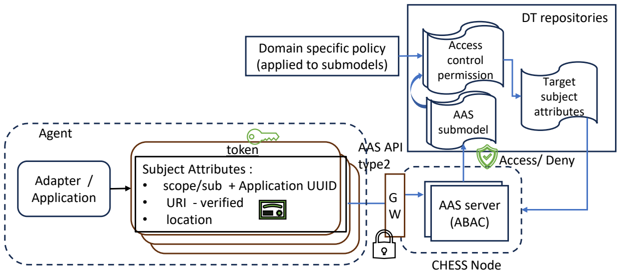


Fig. 4: AAS supported attribute-based access control.

the CHESS asset's DT is bound to the CHESS Node, and the adapter is deployed.

E. Attribute-Based Access Control

Since a CHESS Node can support multiple domains, users can choose the domain to which they authenticate. As part of the proposed solution, scenarios involving users with multiple domain associations are addressed by mapping identities across domains using common subject attributes. This mechanism enables seamless coexistence of multiple domains within a single CHESS Node without introducing additional data access overhead. To ensure data privacy and granular control across different data providers (or stakeholders), CHESS Node employs Attribute-Based Access Control (ABAC). Each AAS submodel supports different access levels, governed by subject attributes and permissions defined within the AAS data models. These attributes are evaluated against the access token presented during API interactions. The way ABAC is supported within the CHESS Node is illustrated in Fig. 4, determining access based on the token and associated subject attributes.

The access token uses OAuth2-compliant JWT bearer tokens for access control. These tokens are issued by an open-source key Manager, such as KeyCloak or other compatible key managers, and include subject attributes that uniquely identify the application and optionally the user. The scope of the issued token is either `saFlexibilityProvider`, `saFlexibilityUser` or `default` and is determined by data space-specific access policies. The token is verified at the gateway, with the embedded subject attributes such as URI, location, or other parameters, which are passed to the AAS server. These attributes are used in the ABAC process to restrict access to specific submodels, thereby enhancing fine-grained privacy and security. In particular, location is a critical attribute for enabling flexibility services in distribution networks, where control actions depend on local grid congestion or constraint conditions.

During CHESS asset registration, assigning subject attribute permissions requires the flexibility provider scope. To support this, the subject attributes of the corresponding CHESS Node are added to the asset's CHESS DT and submodels by default, with optional additional subject attributes provided in the registration command. As a result, only those authorised adapters in the CHESS Node and applications or users with the optional subject attributes are allowed to retrieve or update asset data in accordance with the access control policies. Data queries are strictly permitted only if they meet the defined access control rules.

F. Adapter REST APIs

The REST APIs exposed by the CHESS Adapters provide standardised access to DT operations. These APIs are protected by the access control framework (described in Sec. III-E) and enable initialisation, monitoring, and control of CHESS assets. The following core API operations are mandatory:

a) POST /init: The `POST /init` operation is used to initialise a CHESS asset and associate it with a corresponding adapter. This step registers the asset in the DT space and establishes the communication link. The example payload for adapter initialisation is:

```
POST /init
{
   "identifier": "test-client-adapter",
   "location": "CHESS Node 1",
   "standard": "MQTT",
   "version": "1.0",
   "topic": "CHESSNode_1_it-bess-chess1telemetry_1234
       ↪ -5678-9012",
   "id": "test-bess-chess"
}
```

b) GET /status: The `GET /status` operation retrieves the current status of all CHESS assets associated with the adapter. It provides a high-level overview of available assets and their operational states.

```
GET /status
- Retrieve the status of all CHESS assets associated with
     ↪ the adapter.
```

c) GET /status/{id}: As part of the proposed solution, the `GET /status/{id}` operation retrieves the virtual capacity profile status from a specific CHESS asset. The status structure provides a time-dependent sequence of available energy capacity values, further qualified by state identifiers such as `forceCharge` (charging energy) and `forceDischarge` (discharging energy), as shown in Fig. 5.

At a given time period t_i, the initial capacity status represents the energy stored in the asset. The capacity E_i (in Wh) indicates the amount of energy requested to be stored, retrieved, or curtailed over the time interval, and the corresponding average power is calculated as: Average Power = $E_i/(\text{Endtime} - \text{Starttime})$

This structure is conceptually similar to the "power sequence container templates" defined in IEC 63402-2-2 [16], but models virtual energy capacity rather than power. The CHESS adapters maintain estimated or actual virtual storage capacity profiles and can be dynamically controlled by issuing appropriate operational /status requests.

```
GET /status/{id}
- Retrieve the virtual energy capacity profile for a
     ↪ specific CHESS asset.
```

d) POST /status/{id}: The `POST /status/{id}` operation issues a request to set a virtual capacity operation command for a specific CHESS asset. This allows for active control of asset behaviour, including forced charging, forced

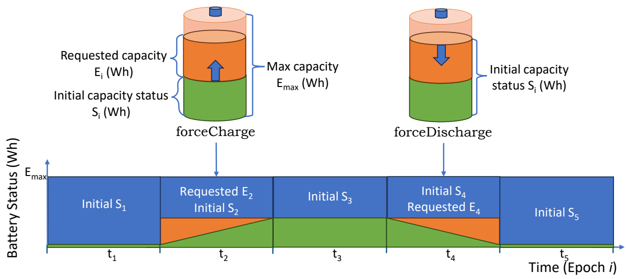


Fig. 5: Initial and requested capacity status using virtual battery status representation for energy storage.

discharging, or curtailment of available capacity. An example of a request payload to charge 10 kWh between 12:15 and 14:15 is shown below:

```
POST /status/{id}
{
    "identifier": "test-client-adapter",
    "currentStatus": "available",
    "status": [{
        "status": "forceCharge",
        "service": "all",
        "starttime": "12:15",
        "endtime": "14:15",
        "capacity": "10000",
        "recurrence": "weekdays"
    }]
}
```

This request instructs the CHESS to store 10 kWh of energy over the specified time period. Similar requests can be made for force discharge (energy retrieval) or curtailment operations.

IV. Pilot Use-Case

In the pilot use case, EV charging stations and battery energy storage systems (BESS) are optimised based on photovoltaic (PV) generation forecasts (sourced from MeteoGroup weather data, now part of DTN[2]) alongside building HVAC profiles and general load demands. The objective is to reduce the overall building peak demand during grid congestion periods, while maximising PV energy self-use through coordinated control strategies. The Flex platform orchestrates the curtailment of EV charging and the charge/discharge cycles of the BESS to alleviate grid congestion via peak shaving and load shifting, while also maximising building self-consumption and EV charging efficiency. Additionally, smart charging optimisation prioritises EV charging to minimise user impact. The benefit of using HVAC as a flexible asset is evaluated through a building simulation, avoiding the need for direct control of the existing building energy management systems. The HVAC setup consists of three refrigeration units located across three buildings, with rated capacities of 146.5 kW, 514.4 kW, and 532 kW, respectively. The PV array has a total installed peak capacity of 160 kWp. The assets operate through different cloud service environments: the EV charging station is managed by the dedicated operator adapter, HVAC and PV energy data are collected through Aveva PI™; and BESS status and control are accessed via the external FoxESS™ platform. The CHESS Node supporting this setup is also cloud-hosted, facilitating adapter-based integration with both the central Flex platform and external DT environments through the multi-building CHESS node.

a) Objective: The asset optimisation in this scenario addresses both load shifting and peak shaving using the BESS and HVAC operation, as well as EV charging state curtailment through statistical aggregation of asset behaviour. This aggregation enables the prioritisation of flexibility states, allowing the system to minimise disruption and dynamically adapt to short-term fluctuations in local PV generation, thereby maximising self-consumption. The total peak shaving and load shifting request target during each peak interval i is defined as E_i, as shown in Fig. 5, while preceding intervals E_{i-x} charging will be performed to maximise the storage of excess PV generated energy. The energy balance constraint is given by: $\sum_i E_i = 0$. In contrast, curtailment of EV charging sessions and other flexible loads can also support load shifting periods if vehicles are being charged in the corresponding epoch.

The BESS charge cycle cost is calculated based on $N_{\max}$ which represents the expected number of cycles lifetime, when operated in different State of Charge (SoC) cycle limits, derived using battery capacity fade data, which can be obtained from the digital battery passport data through digital twins. The corresponding battery degradation cost for the lifecycle stage is denoted by CS leading to the expression, derived from [17]:

$$C_{\mathrm{i}} = \frac{CS}{2.N_{\max}.(SoC_{\max,\mathrm{i}} - SoC_{\min,\mathrm{i}})}$$

The operational energy cost savings are given by the additional PV self-consumption SE_{i}, multiplied by the difference between import and export electricity prices per unit CU. Therefore, the overall flexibility benefit (FB) for epoch i is computed as :

$$\mathrm{FB_i} = \underbrace{\eta \cdot CU \cdot SE_{\mathrm{i}}}_{\text{Effective energy saving}} \underbrace{- C_{\mathrm{i}}.\sum_{j=0}^{J}(SoC_{\mathrm{j}} - SoC_{\mathrm{j\text{-}1}})}_{\text{Battery degradation cost}} \tag{1}$$

where η is the system roundtrip efficiency, E_{self} is the additional PV energy self-consumed and SoC_{j} is the state of charge of the BESS at time interval j with J intervals per epoch.

b) Priority-Based Asset Control Strategy: The proposed method for controlling assets accounts for their dynamic behaviour and availability in order to prioritise them for meeting the requested energy shift E_i. The controllable assets include HVAC, PV, EV charging stations, and BESS, all of which can be coordinated in a distributed manner to maximise overall efficiency. This coordination is supported using a statistical multiplexing approach, where asset behaviours are modelled as probabilistic processes. Each asset has a time-dependent probability of transitioning to a particular energy or power state, denoted by $p_j(s_n)$, where s_n represents a permissible control intervention state, such as discharging the battery or curtailing EV charging power to a certain level P_n.

The state transition probabilities $p_j(s_n)$ are estimated based on historical data, taking into account time-of-day patterns and

[2]https://www.meteopower.com/

distinguishing between weekday and weekend behaviour. This enables the system to make informed, adaptive decisions about which assets to activate to meet flexibility requirements with minimal disruption.

The prioritisation process first selects assets based on their geographic location and suitability for meeting the flexibility requirement, followed by evaluating the likelihood of being possible to utilise the desired controllable power state, represented by the transition probability $p_j(s_n)$. In this way, the probability of the assets being utilised at a certain time is considered the most important criterion. Additionally, a normalised estimated flexibility benefit, from (1), can be used as a weighting factor to further refine the selection.

Behaviour shaping is performed at the level of a cluster or subset of energy assets, each of which may support different prioritised permitted power states (s_n) rather than centrally controlling individual assets to meet a specific energy flexibility requirement. This approach restricts the priority states in a decentralised manner, so that curtailment of asset states only occurs when necessary, in a prioritised order. The time-dependent probabilities of state transitions model asset behaviour across different priority levels. The shaping of asset behaviour within each priority level is configured by setting a fixed transition interval or epoch T_i, along with the desired energy capacity request or limit E_i over each epoch i. The internal time resolution t_j is much smaller than the epoch (e.g., $t_j = 2$ minutes, $T_i = 2$ hours, with $T_i/t_j = 60$). The average energy flexibility estimated to be available within each epoch is given by:

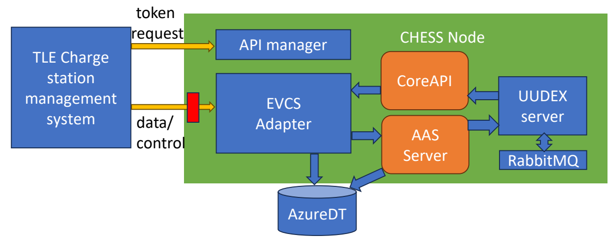
$$\sum t_j \cdot \sum P_n \cdot p_j(s_n)$$

This value may optionally be weighted by the normalised cost to order assets within their priority levels for $n = 1 \ldots N$. The activation or suppression of priority state control limits is dynamically adjusted based on whether the projected capacity meets the flexibility target for epoch i, achieved by incrementing or decrementing the priority level n.

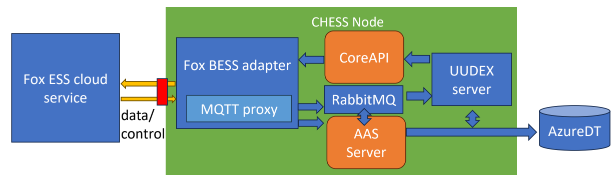
A. Smart EV Charging Coordination

Smart EV charging leverages the ability of charging stations to impose limits or constraints on the power delivered to vehicles during charging sessions, and in some cases, to support bidirectional power flow back to the grid. Rather than specifying an explicit charging power, curtailment is applied by defining a maximum controllable power threshold. Within this limit, the actual charging behaviour may still vary significantly depending on the vehicle's response.

Imposing power limits influences the charging dynamics, potentially increasing session duration or causing temporary suspension, both of which are interpreted as forms of load shifting. These effects are highly dependent on vehicle type and its internal charging logic. While optimal control would benefit from access to real-time information about the vehicle's battery state, such data is often unavailable due to privacy and security restrictions. Consequently, in the pilot use case, this information is inferred from limited observable parameters rather than being explicitly accessed, as also discussed in [18].



(a)



(b)

Fig. 6: Adapter architecture: **(a)** EV charging stations – inbound API **(b)** Battery energy storage systems – outbound APIs.

In the pilot deployment, 14 unidirectional EV charging stations are installed, all of which are Alfen NG920-61021 models[3], rated at up to 22kW. Each station supports two charging ports, allowing simultaneous charging of up to two vehicles per unit. The EV charging station adapter provides an external interface through an API gateway that connects to the charge station management system (see Fig. 6a). This interface is polled at 1.5-minute intervals to retrieve telemetry data and apply control commands. Access to the adapter is secured via tokens issued by an instance of the WSO2 API Manager (version 4.1.0, open source). Tokens are generated using client credentials for the CHESS node and with the subject attribute scope of Flexibility Provider, enabling authorised access to both telemetry and status updates and retrieving requested state constraints.

Control messages, including requested state constraints or limits, are transmitted through the AAS server's CHESS APIs and propagated to the adapters via the UUDEX messaging layer. This setup provides a secure and scalable architecture capable of supporting multiple CHESS nodes and adapters connected to different charge station management systems. To avoid naming conflicts across providers, CHESS identifiers are prefixed with a region/provider identifier. Then the CHESS identity is uniquely assigned within each provider domain. It is important to note that only two of the charging stations are actively controlled for the pilot period. Therefore, a probabilistic behaviour model is developed to simulate and assess the scalability of the control strategy across all available stations, which also depends on the vehicle types.

Charging stations serve a variety of electric vehicles with differing charging behaviours. For instance, it was observed that Renault Zoe vehicles suspend charging sessions when the requested current falls below 16 A (11 kW). As a result,

[3]https://alfen.com/en-gb/ev-charging/business/eve-double-pro-line

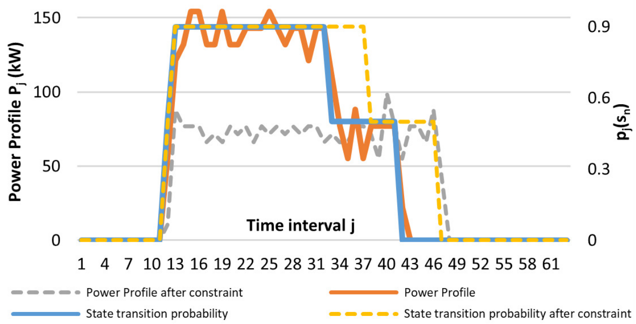


Fig. 7: Statistical multiplexing of EV power profiles using state transition with aggregation and curtailment of sessions.

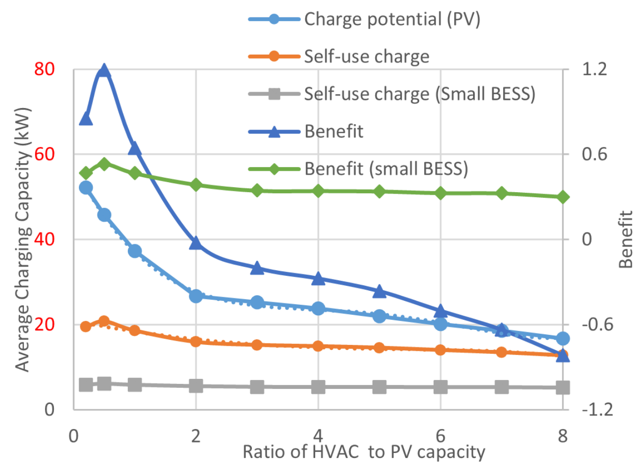


Fig. 8: BESS Cycle Charge and self-use Benefit (FB) for different HVAC and PV Capacities for Weather in Summer.

distinct control states are defined for each asset to reflect these behavioural variations, which are aggregated as illustrated in Fig. 7, along with the corresponding state transition probabilities estimated from historical session data and predictions.

Imposing current limits on charging sessions extends the charge session duration, thereby reducing peak power demand while still delivering a similar total energy capacity. The aggregated load behaviour is represented as the combined behaviour of all individual assets. Depending on the activated priority state level n, control actions will apply a power cap across active sessions when necessary. This approach enables load shifting only when required to meet the energy flexibility target E_i for each epoch i. An example illustrating the behaviour under a specific usage schedule—along with both curtailed and uncurtailed state transition probabilities derived through the statistical multiplexing process, the result of which is shown in Fig.7.

B. Battery Energy Storage System (BESS) Integration

The BESS selected for deployment in the pilot is a FoxESS™ H3 Hybrid Pro 3 inverter and battery system. The configuration consists of a 30 kW Fox H3-Pro-30.0 inverter paired with a 28.2 kWh ECS4100-H7 battery pack, along with a 4G dongle to enable cloud connectivity. The BESS asset adapters follow a similar integration approach to that of the EV charging stations (see Fig. 6b), with MQTT used for retrieving telemetry data. However, instead of direct control through the adapter, status control requests are issued via the external FoxESS cloud service, which exposes the necessary APIs. As a result, DT updates do not occur directly from the adapter instance. Instead, updates are routed through a RabbitMQ broker and synchronised with the AAS server, as illustrated in Fig. 6b. This architecture allows the BESS to participate in coordinated flexibility operations within the CHESS framework while maintaining integration with its native cloud management platform.

Among the flexibility options, the BESS discharge states have the highest control priority and predictability, followed by EV charging curtailment to 11 kW, and finally the 0 kW curtailment or suspension state. The five defined energy control or constraint state levels—including the BESS—are prioritised as follows: $n = 1$ (BESS 2 kW discharge), $n = 2$ (BESS 4 kW discharge), $n = 3$ (BESS 6 kW discharge), $n = 4$ (EV 11 kW curtailment), and $n = 5$ (EV 0 kW curtailment or suspension). These states can be selectively activated in each period j in prioritised order to meet the energy flexibility target E_i.

Conversely, during preceding time intervals, the $n = 0$ state—representing BESS force charging—is activated to meet the target E_{i-x}. The opportunity for PV self-consumption arises from the time-lagged relationship between solar irradiance and HVAC cooling demand, caused by the building's thermal inertia. As long as $x > 0$, the BESS can be charged ahead of peak building demand periods, utilising the available capacity as illustrated in Fig. 8. This potential is primarily driven by solar irradiance and outdoor temperature.

To maximise self-consumption benefits, the BESS should not be oversized, as demonstrated in Fig. 8, based on generation estimates from real-time weather data shown in Fig. 9 (provided by MeteoGroup). Daily charge-discharge cycling enables a trade-off between local PV self-consumption and grid feed-in of excess energy. According to Equation (1), the relatively small deployed BESS (28 kWh) yields a lower peak benefit compared to a larger system, but also experiences reduced impact from HVAC and PV generation variability, resulting in more stable and higher overall utilisation. This characteristic is also applicable when coordinated with EV charging, further enhancing system resilience, peak shaving, and load shifting potential.

C. Peak Shaving and Load Shifting.

The combined peak shaving and load shifting capabilities of the smart BESS and EV charging system have been initially evaluated based on the assumptions outlined above. The main sources of uncertainty in this evaluation are the variability of PV generation and the unpredictability of EV charging sessions. To address these uncertainties, a probabilistic aggregation approach—similar to that proposed in [19]—is employed

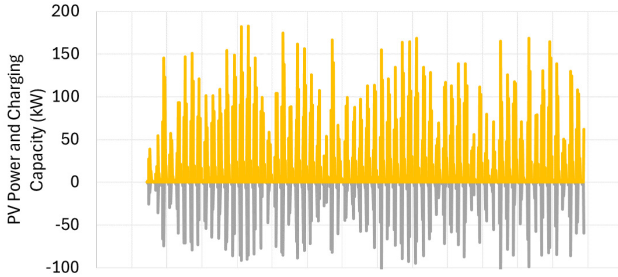


Fig. 9: PV generation (+ve) and BESS charging potential from PV (-ve) over successive epochs.

to model system behaviour across different scenarios, which are being validated in the pilot.

Four representative scenarios have been defined: (1) a weekday with clear weather, (2) a weekday with cloudy conditions, (3) a weekend with clear weather, and (4) a weekend with cloudy conditions. In the weekday scenarios, it is assumed that seven EV charging sessions are active during the peak epoch i, while only two sessions are expected on weekend days.

Weather conditions are found to have a limited impact on the overall peak shaving and load shifting capability of the combined BESS and EV system. In contrast, the number of active EV sessions significantly influences flexibility performance. To enhance control granularity the system includes HVAC as an additional flexible asset. This is achieved through smart control strategies such as pre-cooling or the integration of heat pumps and storage to enable pre-heating during winter periods.

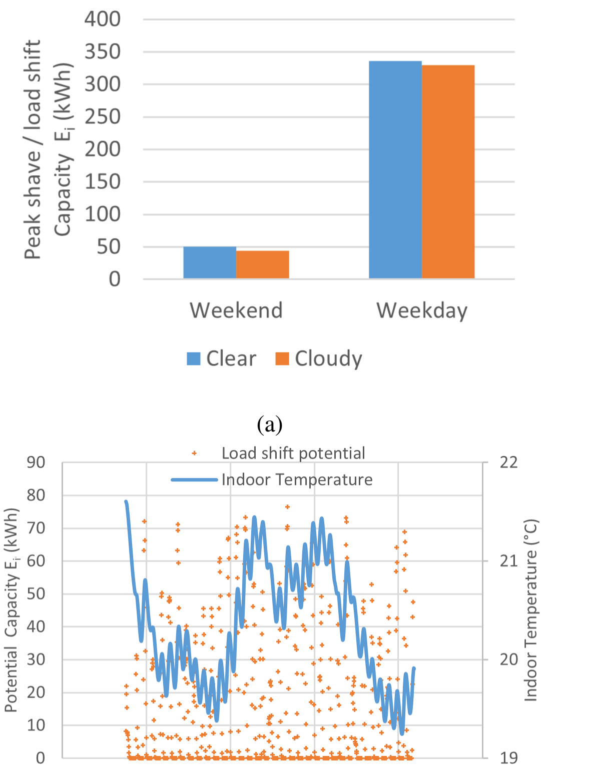
Such HVAC behaviour is modelled similarly to the BESS, with load shifting potential in the immediately preceding epoch $i-1$, denoted by E_{i-1}, and dependent on the building's thermal characteristics. This allows the integration of HVAC flexibility into the recursive discrete model and demand prediction control method, as adapted from [20]. The discrete thermal dynamics are captured in Equation 2, predicting the indoor temperature $T_r[k]$ as a function of ambient conditions and power inputs:

$$T_r[k] = (1 - 10^{-3}\alpha)T_r[k-1] + T_a[k-1] + 10^{-3}\left(\alpha\, k_{\text{sun}}\beta\, k_{\text{int}}\beta\, k_{\text{hvac}}\beta\right)\begin{pmatrix} P_{\text{sun}}[k-1] \\ P_{\text{int}}[k-1] \\ P_{\text{hvac}}[k-1] \end{pmatrix} \quad (2)$$

where, $P_{\text{hvac}} = P_{\text{heat}} - P_{\text{cool}} + P_{\text{ven}}$ and P_{hvac} represents the power consumed by the HVAC systems. The internal power generated by electrical devices is denoted by P_{int}, and the power from solar irradiance is P_{sun}.

Based on this thermal model, the required HVAC chiller power input at time t_k can be inferred using a predictive function, as shown below.

$$P_{\text{hvac}}[k] = f\left(T_r[k+1], T_r[k], T_a[k], P_{\text{sun}}[k], P_{\text{int}}[k]\right) \quad (3)$$



(a)

(b)

Fig. 10: Variation in potential capacity for **(a)** EV and BESS between weekday and weekend and **(b)** HVAC over successive periods of epochs ignoring building internal device demands.

To align thermal flexibility with energy planning, the predicted HVAC power can be translated into electrical energy flexibility using: $E_k = t_k \cdot P_{\text{hvac}}[k]$.

Acceptable indoor temperature ranges, in combination with weather forecasts, enable the derivation of a day ahead thermal flexibility profile, which can be expressed in equivalent energy terms using the above formulation.

The predicted available capacity for load shifting is estimated using the commercial building model described in [20], in combination with weather forecast data. The results indicate substantial variability in the HVAC system's potential contribution to load shifting, with available capacity reaching up to 76 kWh, as shown in Fig. 10. This flexibility can be leveraged alongside the EV and BESS capacities to enhance overall system capability. Furthermore, integrating a detailed building data model—such as the approach in [21] could improve the accuracy of these predictions.

V. Discussion and Conclusion

This paper presented a digital twin-driven approach to enable secure and interoperable coordination of flexible hybrid energy storage assets using the Asset Administration Shell (AAS) framework. The proposed architecture abstracts asset-related data—including capabilities, configuration, commercial information, control states, and operating conditions—into

AAS submodels accessible via standard APIs and templates. Fine-grained access control mechanisms are embedded to preserve data privacy and sovereignty. The integration of the UUDEX protocol further enhances the architecture by supporting the efficient distribution of data and control messages between distributed CHESS node participants. This facilitates a unified coordination mechanism across asset domains and eases integration into cross-sector data spaces—an essential requirement for enabling scalable, interoperable energy services. By combining AAS-based digital twins with UUDEX-enabled CHESS nodes, the proposed framework supports a new class of distributed flexibility services. These services allow for the coordinated participation of sovereign assets, such as EV chargers, BESS and HVAC systems, through statistical multiplexing rather than direct control. This enables scalable optimisations across multi-building, community, or regional levels while preserving local autonomy. The approach also supports full asset lifecycle optimisation, including deployment planning, operational monitoring, performance evaluation, and predictive maintenance.

Digital twins play a central role in this process by providing a standardised abstraction to simulate asset degradation, assess lifetime performance, and evaluate the integration of new assets. Furthermore, the harmonisation of multiple flexibility services through this distributed framework allows for greater value realisation and cost sharing among stakeholders, without requiring explicit real-time control. Instead, adaptive behaviour is achieved through decentralised, policy-driven orchestration mechanisms supported by UUDEX. Initial evaluations suggest that leveraging existing infrastructure, including EV charging stations, BESS, HVAC systems, and potentially heat pumps, can unlock significant opportunities for providing peak shaving and load shifting services. These early results highlight the viability of deploying such flexibility solutions without substantial additional investment in infrastructure. Ongoing work focuses on validating the proposed approach in real-world pilot sites, with plans to scale up to larger trials. These efforts aim to confirm the scalability and effectiveness of the framework across diverse deployments and to align with the forthcoming IDTA Energy Flexibility submodel template [9]. The open-source CHESS Node reference implementation will be made available[4], providing a foundation for overcoming the limitation for widespread adoption, which is the mass development and deployment of appropriate CHESS adapters for supporting large scale distributed CHESS coordination through CHESS nodes.

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[4]https://github.com/Tim-222/CHESSNode

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