SmartSPIN

Smart energy services to solve the **Sp**lit **IN**centive problem in the commercial rented sector

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List of Abbreviations

API	Application Programming Interface
ECM	Energy Conservation Measure
EPC	Energy Performance Contracting
ESCO	Energy Service Company
IPMVP	International Performance Measurement and Verification Protocol
M&V	Measurement and Verification
MEETS	Metered Energy Efficiency Transaction Structure
RDF	Resource Description Framework
SLA	Service Level Agreement
XML	Extensible Markup Language

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EXECUTIVE SUMMARY

This deliverable highlights opportunities for automating transactions that can be found in different business models for energy efficiency. The main rationale behind automating transactions is that it enhances transparency and trust among the involved parties. In general, the fewer the participants and the moving parts in a contract, the easier is for the participants to agree on it. However, business models for energy efficiency tend to become quite complex, especially when the aspiration is to adopt concepts and models that already work well for the deployment of distributed, renewable energy generation: some parties offer finance for the energy efficiency upgrades, others offer performance guarantees or monitoring and measurement services.

Automating transactions means that:

- The rules that trigger each transaction are explicitly documented and visible by all participants;
- The information that each transaction utilizes is visible by all participants;
- Transactions can take place as often as needed so as to continuously provide the participants with an updated picture of the state of their relationships. For instance, while financial transactions may take place once per month, transactions that update a record of how value is generated and allocated can take place daily or even hourly.

The examples that are presented in the deliverable are indicative, in the sense that there is more than one way to create and automate a business network. However, the benefit from presenting concrete examples is the categorization that they impose:

- **Assets**. Assets can be physical or digital, tangible or intangible. They can be owned by one or more of the participants, and they have value for one or more of the participants. A piece of equipment is an obvious asset, but automation and digitalization can make it possible to treat also performance guarantees as an asset that can be owned by participants (even fractionally) and the value of which can be tracked across time.
- **Information flows**. The main reason for automating transactions and keeping their records in a shared ledger is to bring trust and transparency to a business model. The same level of trust should characterize processes and tools that feed information into the model. Explicitly defining the information needs of a business model can help devise rules and criteria for the assessment of information trustworthiness.
- **Transactions**. Breaking up the interactions between all the involved parties into concrete transactions with specified inputs and rules makes it easier to identify sources of risk for the participants, which is necessary for devising win-win agreements between them.

Automation of transactions requires moving them on an infrastructure that allows for them to be transparent, auditable and immutable. Although the examples are technology agnostic, the underlying assumption is that the automation is achieved using *private* distributed ledgers. Such ledgers use blockchain technology so that copies of them can be distributed among multiple nodes, but are fundamentally different from permissionless and public blockchains such as Bitcoin

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or Ethereum. Private networks are invitation-only; a central entity assigns roles to participants and allows them to transact on the network. Furthermore, they do not need incentives for participants and, as a result, they do not need cryptocurrencies. Although the participants may not fully trust each other, a private business network can be operated under a set of policies that reflects the level of trust existing between participants, such as the legal agreements between them.

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1 INTRODUCTION

1.1 BUSINESS NETWORKS

A business network is a set of *participants* and *assets* that interact with each other through *transactions*. Participants act in the business network by exchanging information and value. A participant may be an organization, a device or a system (such as a monitoring system). In the case of systems, participants may exchange information through an application programming interface (API).

Business networks operate around assets, which can be physical or digital, tangible or intangible. Assets may represent payments or future payment obligations, equipment, estimations of energy savings or performance guarantees. For the particular case of equipment, one should expect that a digitalized network utilizes a digital representation (or digital twin) of a piece of equipment rather than the equipment itself.

Assets have properties that characterize them and may change over time. As an example, a piece of equipment has properties that define its state. There are at least two properties that an asset must have: (a) it must have value for one or more of the participants, and (b) there must be a relationship of ownership between the asset and a participant. An asset can be fractional, i.e. more than one participants may share its ownership. Digitalizing a business network makes it easier for participants to track the state and the value of an asset. The current state of an asset is composed of the current values of the properties that describe it, whereas its current value represents the expectation of the revenue that can be generated from it in the future (based on the revenue it has generated so far).

Transactions change the properties or the relationships of an asset. The fundamental idea behind digitalizing a business network is to enable transactions to take place in an automated way and according to predefined rules. Automation of transactions requires moving them on an infrastructure that allows for them to be transparent, auditable and immutable. It is assumed that all the participants in the business network contribute to the deployment and operation of this infrastructure, and all have access to the same record of past transactions – the inputs and results of each transaction are recorded in an immutable shared ledger, so that all participants can inspect and verify the history of their transactions. In practice, the last assumption can be relaxed through *channels*: participants can establish sub-networks where every member has visibility to a particular set of transactions, so that to preserve their privacy and confidentiality.

The set of rules that define when a transaction happens and what its results should be is called a (smart) contract. More generally, a contract reflects an agreement between two or more participants on when and how an asset should change. A smart contract is a contract that is automatically enforced or triggered.

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1.2 Structure of the Deliverable

Chapter 2 *Digitalized Transaction Models for Energy Efficiency* presents examples of automating/digitalizing the transactions between the parties involved in selected business models for energy efficiency. The details of the selected business models are provided in the SmartSPIN deliverable D2.1 “Review of existing business models for smart energy services”, which is also publicly available. In order to avoid duplication of content, this deliverable is regarded as supplementary to the D2.1 one.

The automation of a business network requires data exchange between the participants, as well as a commonly shared approach of representing this data so that it is understood by all the participants. Although any data representation approach would be valid as long as it is accepted by the participants, there are already representation schemes that specifically target building energy data. Accordingly, Chapter 3 *Protocols for Data Representation* reviews two (2) of such schemes: (a) the BuildingSync schema for energy audit data, and (b) the Brick schema for representing physical, logical, and virtual assets in buildings, the relationships between them, and the sensors and actuators that are associated with them.

Chapter 4 concludes the deliverable.

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2 DIGITALIZED TRANSACTION MODELS FOR ENERGY EFFICIENCY

2.1 Asset-Based Business Models

2.1.1 Equipment leasing with continuous commissioning

The business network that emerges from the digitalization of the equipment leasing model is summarized below:

Categories	Components	Details
Participants	Lessor	The lessor receives payments from the building user for making the equipment available, and forwards part of these payments to the ESCO for maintaining the equipment.
	ESCO	The ESCO maintains the equipment and receives a fee for this. The fee is conditional on maintaining the operational characteristics of the equipment within a predetermined, optimal range.
	Building user (tenant)	The building user leases the equipment and pays a leasing fee that depends on the equipment being maintained to operate at optimal level.
	Equipment monitoring system	The monitoring system collects operation data and compares the actual operating profile with a reference one to evaluate if the equipment operates within expected range.
Assets	Equipment	The equipment is characterized by one or more optimal operation trajectories or sequences, which reflect well-tuned and fault-free operation. The equipment is owned by the lessor.
	Payment obligations	At any given point in time, the building user owes a payment to the lessor, and the lessor owes a payment to the ESCO. Until actual invoicing and payment, the payment obligations are an intangible asset.
Information	Quality of equipment operation	The business network runs on the information about whether the equipment operates as expected. This information is generated by a process that continuously monitors the operation of the installed equipment.
Transactions	Division of payment	The payment obligations in the model are an

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Categories	Components	Details
	obligations	example of multi-party, forwarded payments: the actual amount due by the building user to the lessor includes a component that reflects payments from the lessor to the ESCO. If the equipment's operating characteristics deviate from a predetermined optimal range, this component is withheld by the building user.
	Aggregation of payment obligations	The payment obligations are aggregated and two payment amounts are calculated: (a) payment from lessor to ESCO, and (b) payment from building user to lessor.

The diagram in Figure 1 summarizes the information flows and transactions in the aforementioned business network.

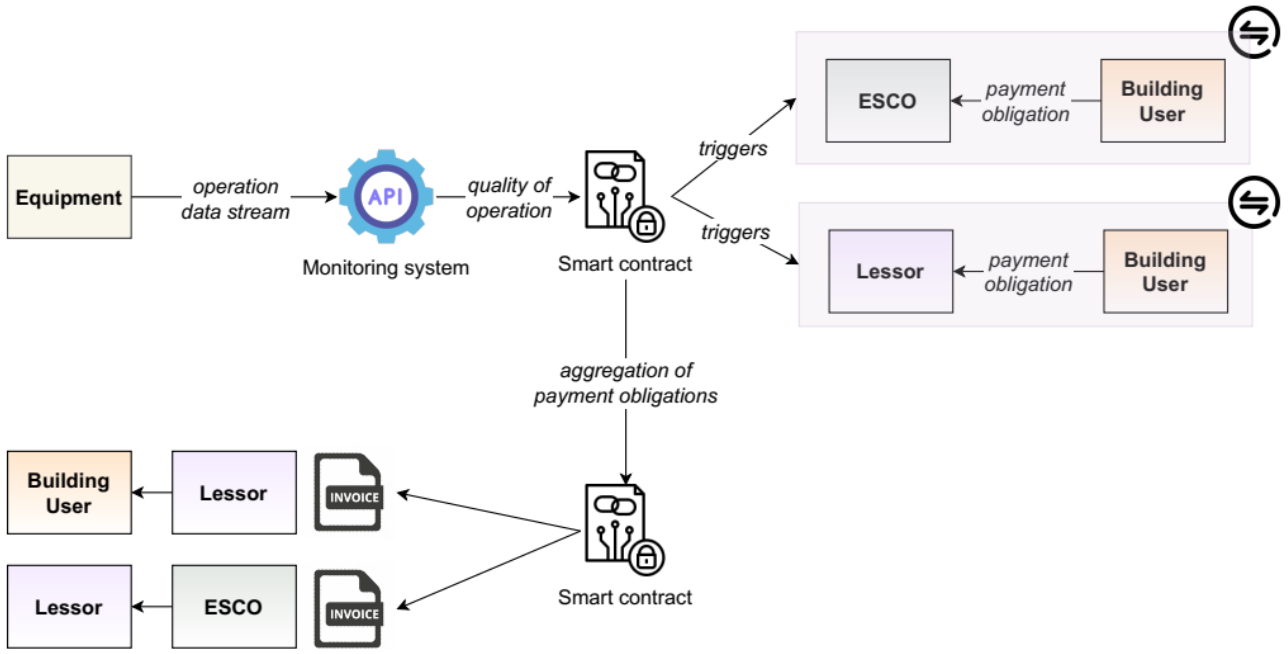

Figure 1 **Information flows and transactions in the equipment leasing with continuous commissioning model**

The quality of the equipment operation can be assessed by monitoring compliance with agreed service levels. In particular:

- A model that predicts the operation of the equipment under optimal/fine-tuned operating settings is created.

- A Service Level Agreement (SLA) is defined so as to link payments to the number of hours in a year that the equipment operated outside of the range that the aforementioned settings would entail.

A general template for monitoring SLA compliance is presented in Figure 2 and comprises the following steps:

- Collection of operation data that reflects optimal/fine-tuned operating settings;
- Construction of reference operation profiles. A simple to implement approach for this is to first linearize the observations, and then learn a linear model approximation for the equipment's behavior. One way to achieve the linearization is through a time-delay embedding transformation[1], while the identification of the linear approximation can be achieved through Dynamic Mode Decomposition[2].
- Continuous monitoring of the difference between predicted and actual operating profiles.

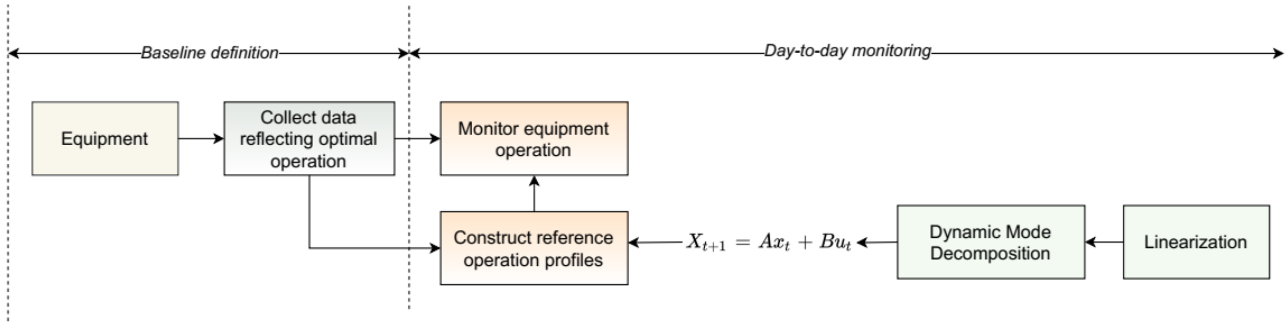

Figure 2 An approach to monitoring the quality of equipment operation

As an indicative example, the plot in Figure 3 shows a snapshot of actual and predicted operating profiles for the return air temperature of a multi-zone variable air volume air handling unit[3] using the aforementioned approach.

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[1] Takens, F. (1981) "Detecting Strange Attractors in Turbulence – Dynamical Systems and Turbulence," Lecture Notes in Mathematics 366, Springer

[2] Schmid, P. (2010) "Dynamic mode decomposition of numerical and experimental data," Journal of Fluid Mechanics, 656, 5-28, doi:10.1017/S0022112010001217

[3] Granderson, J., Lin, G., Harding, A. et al. (2020) "Building fault detection data to aid diagnostic algorithm creation and performance testing," Scientific Data 7, 65, https://doi.org/10.1038/s41597-020-0398-6

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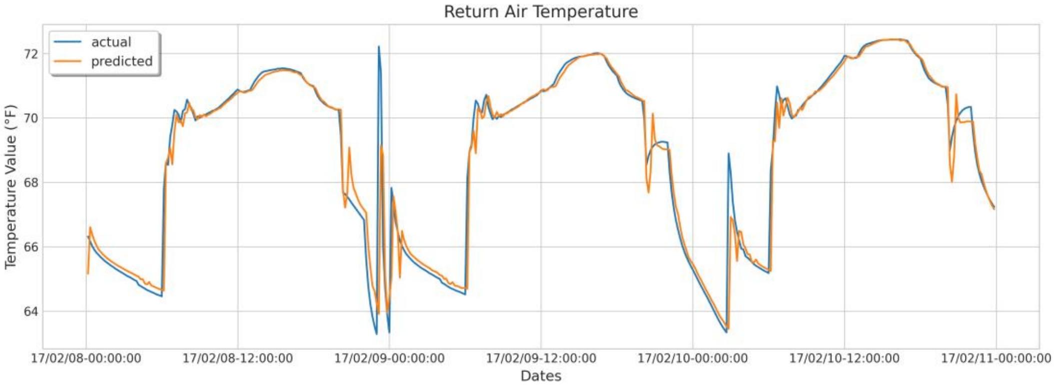

Figure 3 **Example of actual and predicted operating profiles for equipment monitoring**

2.2 Output-Based Business Models

2.2.1 Output Purchase Agreements

The business network that emerges from the digitalization of a model that extends Power Purchase Agreements (PPAs) to energy efficiency is summarized below:

Categories	Components	Details
Participants	Building owner	The assumption is that the building owner offers the space for equipment installation and the opportunity for ESCOs to generate revenue from “selling” energy efficiency to the tenants.
	Building user (tenant)	Building users buy the output of the energy efficiency intervention. In this case, the output is the difference between the actual energy consumption and the energy consumption that would have occurred had the intervention not taken place (counterfactual consumption).
	ESCO	The ESCO provides the capital for the energy efficiency upgrades and receives payments based on the value that the upgrades provide to the building users (determined as avoided energy cost).
	M&V system	The measurement and verification (M&V) system provides information on the efficiency gains and avoided energy cost due to the retrofit.
	Equipment monitoring	The monitoring system collects operation data

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Categories	Components	Details
	system	and evaluates whether the equipment operates within expected range.
Assets	Equipment	The equipment is monitored and subject to tuning/optimization if efficiency degradation is detected. The equipment is owned by the ESCO.
	Efficiency gains	The efficiency gains are estimated by the M&V process. They are an asset because they have value and an ownership relationship (the ESCO owns the gains).
	Payment obligations	At any given point in time, the building user owes a payment to the ESCO for the estimated energy efficiency gains. The ESCO may also pay a "rent" fee to the building owner for the opportunity to install the energy efficiency measures. At the conclusion of the agreement between the ESCO and the building owner, the equipment becomes property of the latter, free of debt or other financial liability. If the agreement duration between the ESCO and the building owner is not long enough, it is possible that the latter must pay a fee to the ESCO to cover the residual value of the equipment at the end of the agreement.
Information	Equipment operation data	This information is supplementary to the M&V results, and it makes it easier to identify the source of efficiency degradation that the M&V process may detect.
	Value of the agreement	This is a continuously updated signal that reflects the value of the output purchase agreement for all involved parties. The business network runs on the value of the agreement and the insights generated by the monitoring system as to which aspect any degradation in value should be attributed to.
Transactions	Division of payment obligations	Depending on the details of the agreement, part of the payment from the building user to the ESCO can be forwarded to the building owner.

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Categories	Components	Details
	Aggregation of payment obligations	The payment obligations are aggregated to a periodic payment from the building user to the ESCO.
	Update of ESCO and building owner agreement duration	The duration of the agreement is a function of the amount and direction of the payment exchange between the building owner and the ESCO.

The diagram in Figure 4 summarizes the information flows and transactions in the corresponding business network.

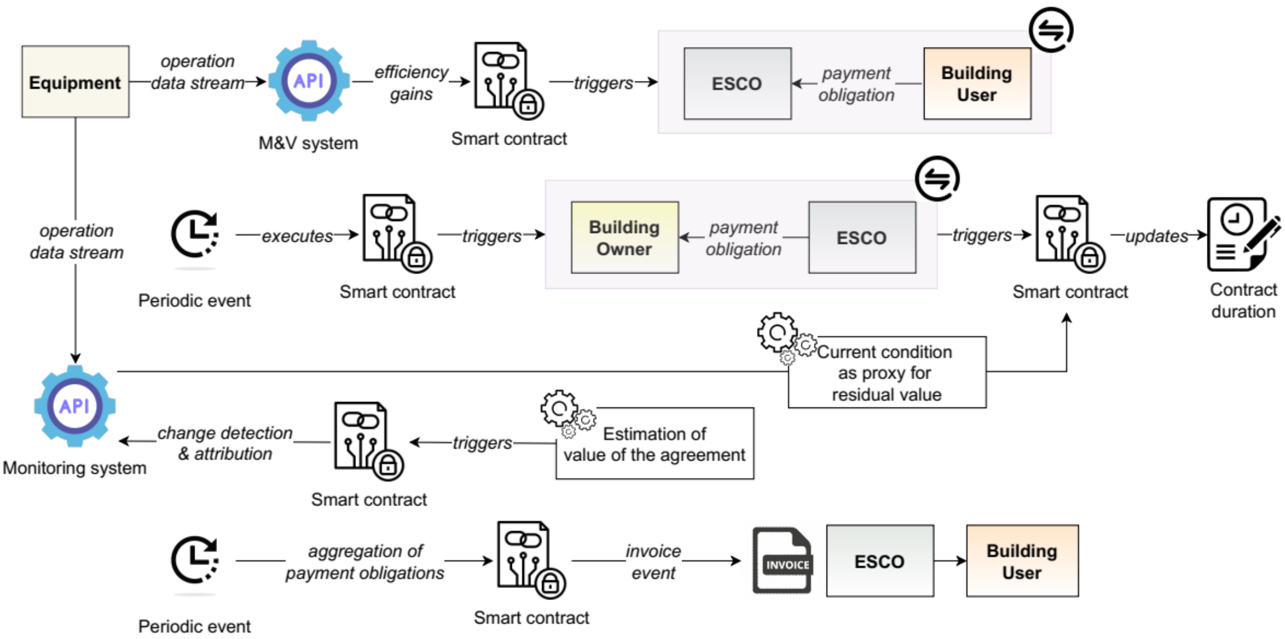

Figure 4 **Information flows and transactions in the output purchase agreement model**

The efficiency gains constitute an asset that is owned by the ESCO and consumed by the building users. The more it is used by the building users, the more value it generates. Its quantity is estimated as the part of the difference between the energy consumption before and the consumption after a retrofit can be attributed to that retrofit. There are, generally, two (2) types of quantitative approaches to support such a function:

(a) The statistical approach. In this case, a statistical model is developed so that to predict pre-retrofit consumption given a set of observable variables. Assuming that these variables remain observable after the retrofit, the model can be used to predict the counterfactual consumption.

(b) The *first-principles* approach. In this case, a simplified model of the building and/or the equipment is used.

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Irrespectively of whether the statistical, the first-principles or a combination of the two approaches is adopted, participants should trust the M&V results. In many cases, participants are more likely to trust an M&V process if it can tell them using data something about the building that they already know from experience.

The duration of the contact between the building owner and the ESCO can be updated based on two (2) parameters:

(a) The cumulative financing flows from the ESCO to the building owner. Decreasing the cumulative total of these flows should decrease the contract duration.

(b) The condition of the equipment. Unmaintained equipment has lower residual value, so it should be expected that it becomes cheaper for the building owner to buy out the ESCO's option to sell energy efficiency services or, equivalently, the contract duration should decrease.

2.2.2 Energy Performance Contracting with Guarantees

The focus of this section is on the Energy Performance Contracting (EPC) with performance guarantees model, since the assumption is that the capital for the energy efficiency upgrades is provided by the building owner. The corresponding business network is summarized below:

Categories	Components	Details
Participants	Building owner	The building owner provides the capital for the energy efficiency upgrade and receives regular payments from the ESCO.
	Building user (tenant)	Building users buy the output of an energy efficiency intervention as estimated by an M&V process.
	ESCO	The ESCO is responsible for maintaining the energy efficiency measures in place. The greater the value that is generated for the building user, the higher the ESCO's compensation is after subtracting the payments owed to the building owner.
	M&V system	The ESCO bills the building user based on the M&V system's output.
Assets	Equipment	The equipment is owned by the building owner.
	Performance guarantees	Guarantees are regarded as assets because they have value and ownership properties; they are owned by the building owner.
	Efficiency gains	The estimations of the M&V process. Gains are owned by the building owner.

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Categories	Components	Details
	Payment obligations	At any given point in time, the building user owes a payment to the ESCO for the estimated energy efficiency gains. Guarantees imply a minimum compensation for the building owner that is decoupled from the payments that are exchanged between the ESCO and the building user.
Information	Trend of efficiency gains	This information is related to tracking the evolution of the estimated efficiency gains and timely predicting if they have started to deteriorate.
Transactions	Division of payment obligations	The payment obligations of the building users to the ESCO are determined by the efficiency gains information. An *escrow account* acts as a buffer between the ESCO and the building owner. As the ESCO receives payments from the building user, a part of the payments is directed to the escrow account as collateral to ensure that the payment obligations that stem from the guarantees will be fulfilled. The escrow account is linked to the M&V information so that its minimum level adjusts according to the upgrade's performance trend.
	Aggregation of payment obligations	The payment obligations are aggregated and two payment amounts are calculated: (a) payment from building user to ESCO, and (b) payment from ESCO to building owner.

The diagram in Figure 5 summarizes the information flows and transactions in the corresponding business network.

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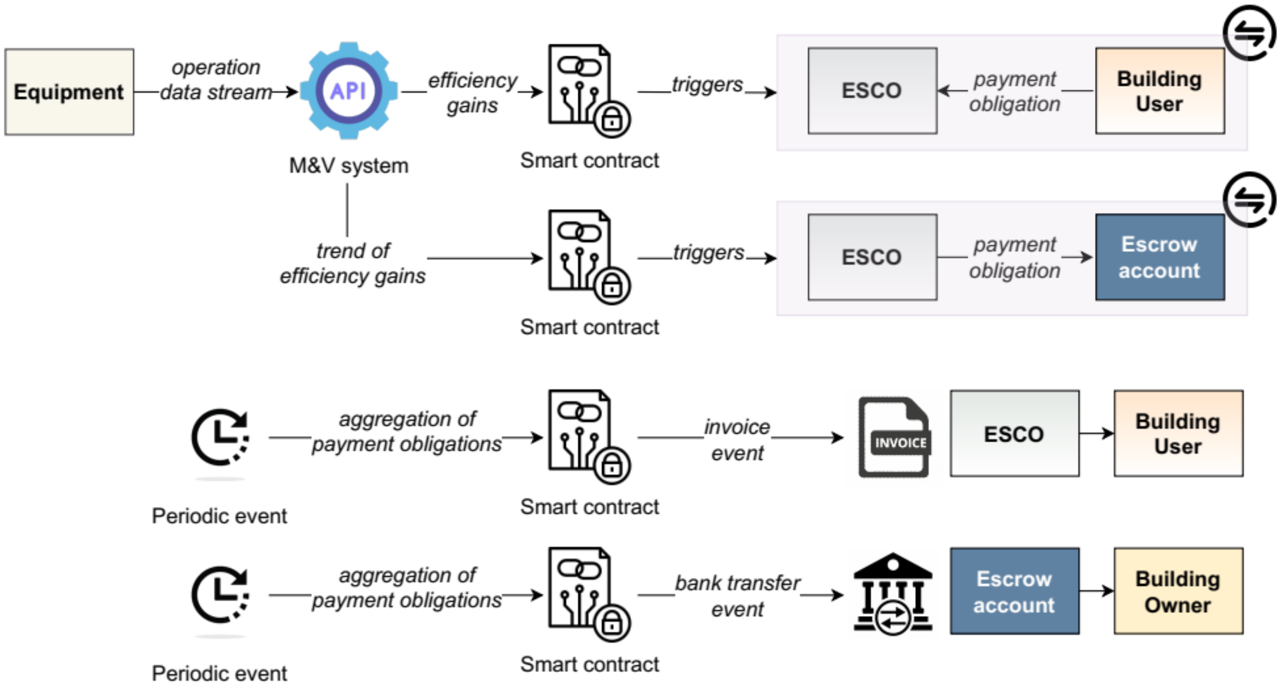

Figure 5 Information flow and transactions in the EPC with guarantees model

One way to describe this model is as if the energy efficiency measures belong to the building owner (who provides the capital for them) but are *borrowed* by the ESCOs. The ESCOs can use the measures to create value for them and the building users, but they have to also compensate the building owner. Since the only source of revenue is the payments of the building users, the escrow account exists so that to make sure that the building owner is compensated before the ESCO:

- If the retrofit project leads to far greater than expected savings, there is more value for the building users and ESCOs to share, effectively rewarding them.
- If energy efficiency performance decreases, revenue from energy cost avoidance decreases too. When this happens, a larger part of the savings' value should be passed to the building owners, effectively penalizing the ESCOs.

The escrow[4] account limits the risk of accumulating performance deficit by being linked to a smart contract that directs payments from the building users based on how much the retrofit project seems to over- or under-perform at any given time.

[4] https://www.investopedia.com/terms/e/escrow.asp

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2.2.3 The Metered Energy Efficiency Transaction Structure model

The Metered Energy Efficiency Transaction Structure (MEETS) business network is summarized below:

Categories	Components	Details
Participants	Building owner	The building owner offers the building spaces and functions for the installation of the energy efficiency measures.
	Building user (tenant)	The building user enjoys an improved indoor environment and pays the utility bill. The bill includes two main components: (a) the amount charged for actual energy consumption, and (b) the amount charged for energy efficiency gains (difference between actual and counterfactual consumption).
	Energy tenant	The energy tenant finances the energy efficiency retrofit and has the right to charge for the efficiency gains.
	ESCO	The ESCO installs the energy efficiency measures and provides performance guarantees to the energy tenant.
	Utility	The utility charges for both actual and counterfactual consumption and forwards the revenue from the counterfactual consumption payments to the energy tenant.
	M&V system	Provides the counterfactual consumption estimation for the utility's billing system.
Assets	Equipment	The equipment is owned by the energy tenant.
	Performance guarantees	Performance guarantees are owned by the energy tenant. One could envision a case where the agreement between the building owner and the energy tenant has an early exit clause that allows the former to buy out the ownership of the equipment. In this case, performance guarantees are transferred to the building owner as well.
	Efficiency gains	The estimations of the M&V process. Efficiency gains are a *fractional* asset: a part of it belongs to

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Categories	Components	Details
		the utility as compensation for utilizing its billing infrastructure, and a part belongs to the energy tenant.
	Payment obligations	At any given point in time: ▪ The building user owes a payment to the energy tenant for the estimated energy efficiency gains. ▪ The energy tenant owes a payment to the ESCO for maintaining the measures and to the building owner for providing the building spaces and functions for the installation of the measures.
Information	Utility bill	The utility bill consolidates the payment obligations for the estimated energy efficiency gains and the consumed energy.
	Trend of efficiency gains	This information is related to tracking the evolution of the estimated efficiency gains to identify if they have started to deteriorate.
Transactions	Division of payment obligations	Similarly to the EPC case, an escrow account acts as a buffer between the energy tenant and the ESCO: part of the payments from the energy tenant to the ESCO is directed to the escrow account as collateral for the performance guarantees. The escrow account is linked to the M&V information so that its minimum level adjusts according to the upgrade's performance trend. If under-performance seems probable, a larger part of the payments from the energy tenant to the ESCO should be directed to the escrow account. Since the energy tenant pays the building owner "rent" for using the building, a smart contract can be set up to directly forward part of the escrow account to the building owner. In this case, performance guarantees become a fractional asset.
	Aggregation of payment obligations	The payment obligations are aggregated, and three payment amounts are calculated: (a)

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Categories	Components	Details
		payment from building user to the energy tenant, (b) payment from the energy tenant to the ESCO, and (c) payment from the energy tenant to the building owner.

The diagram in Figure 6 summarizes the information flows and transactions in the corresponding business network.

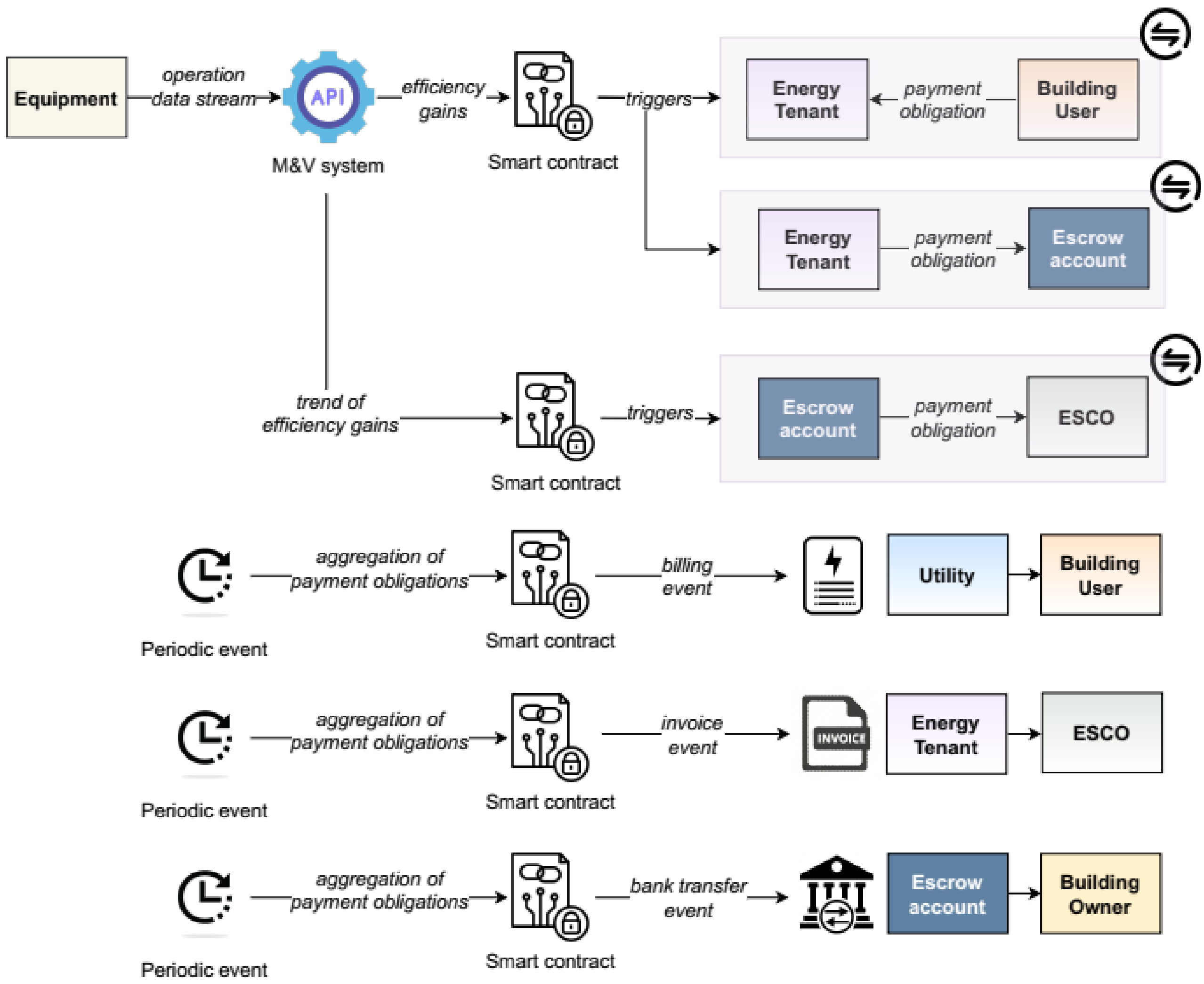

Figure 6 **Information flow and transactions in the MEETS model**

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3 PROTOCOLS FOR DATA REPRESENTATION

3.1 THE BUILDINGSYNC SCHEMA FOR ENERGY AUDIT DATA

BuildingSync[5] is a standardized XML-based schema for sharing commercial building energy audit and M&V data. The schema enables data transfer with flexible input requirements for general building characteristics, multiple-level energy audits using time-series data, and energy conservation measures (ECMs). ECMs can be associated to different levels of the facilities, sites, buildings, thermal zones, and spaces. The ECMs are defined in a structured format within the BuildingSync XML Schema such that many software packages can easily access them. The XML Schema provided by BuildingSync can in principle manage the information gathered from audit to M&V of implemented ECMs using a single technology.

The snapshot in Figure 7 presents a part of the BuildingSync hierarchy that includes fields used for describing HVAC systems.

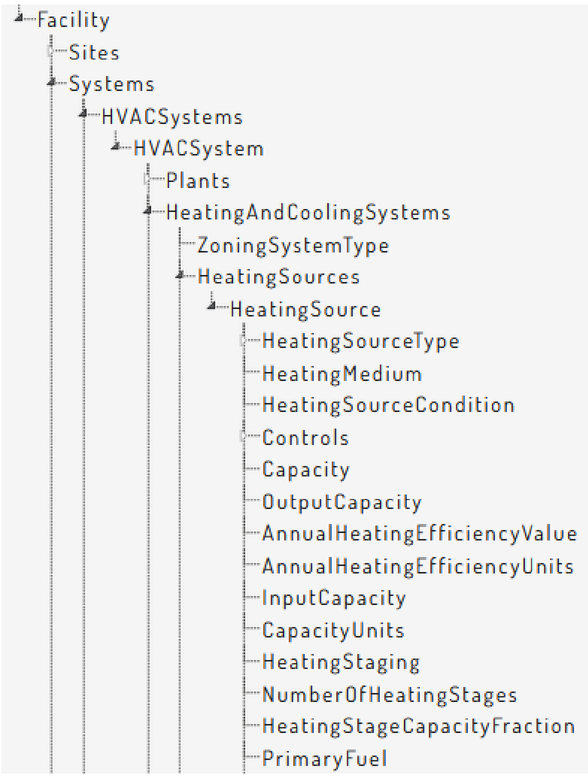

Figure 7 **The BuildingSync hierarchy of fields for HVAC systems**
(**Source**: https://buildingsync.net/dictionary/2.4.0/)

[5] https://buildingsync.net/

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The entities that compose the schema are distinguished into two categories: (a) the program(s) that financed the audit and/or the retrofit, and (b) the facility that was audited and/or upgraded. In turn, facilities are described in terms of the following components:

Components	Details
Contacts	This field includes general information about the contacts for the considered facility.
Sites	This field includes location information, such as address, climate zone, longitude, latitude, and nearby weather stations, occupancy classification[6], and the ownership status.
Systems	This field includes information on both the envelope components and the equipment that is installed in the facility. Different types of systems, such as the walls and fenestration systems that compose the envelope, or the HVAC and lighting equipment, are described by different sets of properties.
Tenants	This field includes general contact information about the tenant(s) of the considered facility.
Schedules	This field concerns the operation schedules of the different aspects of the building – occupancy schedules, heating and cooling schedules, setback strategies and so on – and the thermal zones of the building that are associated with these schedules.
Measures	This field describes the ECMs that were implemented during the respective building's upgrade. Measures are described in terms of the systems affected, the installation cost, the duration of useful life, and the applicable IPMVP M&V option[7]. ECMs supported by BuildingSync are divided into the following technology categories: chiller plant improvements, building automation systems, other HVAC, lighting improvements, chilled water / hot water / steam distribution systems, conveyance systems, other electric motors and drives, refrigeration, distributed generation, renewable energy systems, energy distribution systems, service hot water systems. Data relevant with building energy modeling (BEM) can also be leveraged[8].
Reports	This field concerns either the information gathered during an audit (audit level, date, and utility data) or generated when performing an analysis. Multiple scenarios with different ECMs applied can be included in a report along with time-series data.

[6] https://bedes.lbl.gov/bedes-online/occupancy-classification

[7] Option A: Retrofit isolation with partial measurement, Option B: Retrofit isolation with full measurement, Option C: Whole building measurement, Option D: Calibrated simulation

[8] Long, N., Fleming, K., CaraDonna, C., & Mosiman, C. (2021) "BuildingSync: A schema for commercial building energy audit data exchange," *Developments in the Built Environment*, *7*, 100054.

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BuildingSync-annotated data can support three (3) use cases:

1. **Structuring energy audit data**. The first step before an energy efficiency upgrade – and before the operation of any business network that aims at coordinating the involved parties and distributing the added value from this upgrade – is to identify retrofit opportunities. BuildingSync can be used to annotate the data from the energy audit so that it is accessible by the different participants and their information systems.

2. **Standardizing the inputs to the M&V process**. BuildingSync supports *scenarios* that enable the collection of baseline (pre-retrofit) data, as well as the explicit documentation of the energy and emission saving expectations from an intervention. To support this functionality, BuildingSync includes fields for collecting data on the energy resources that the building uses, the time series of their consumption and the meters that capture this data. Annotating the relevant data is a way to make it usable by any M&V workflow and tool that understands the BuildingSync schema (Figure 8).

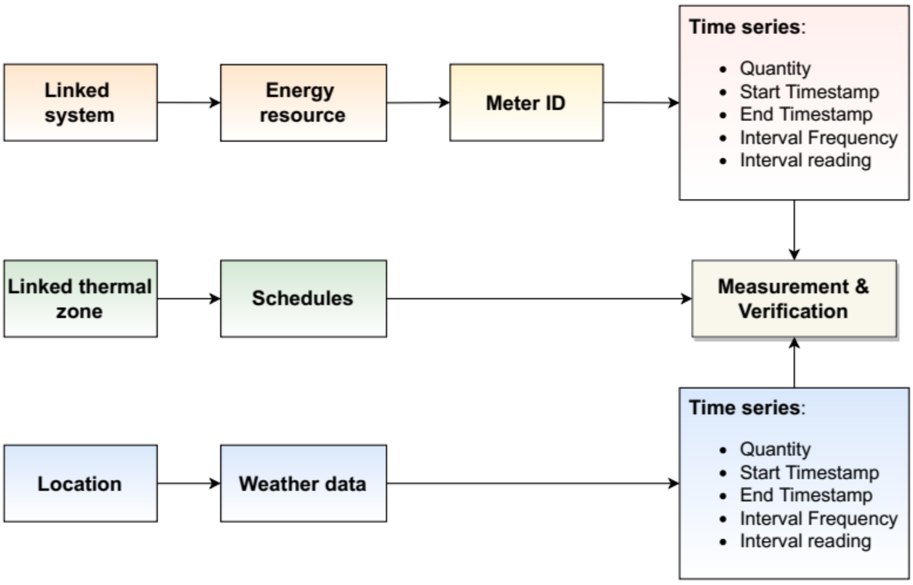

Figure 8 **Using BuildingSync constructs for M&V input**

3. **Evaluating existing and devising improved equipment control strategies**. While the envelope of a building can be unambiguously described, this is not the case for the way the equipment is used. Collecting the relevant data is much more challenging, and, even if the necessary resources were available, there are more than one sources of information to consider (e.g. functionalities of Building Management Systems, control-flow diagrams or control sequences in system manuals).

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BuildingSync-annotated data can be used as input to automated workflows that create and simulate building energy models. As an example, there are already open-source tools[9] that aim at converting BuildingSync models into EnergyPlus/OpenStudio ones. If a building energy model is available, it can be used to benchmark the building in comparison to what could be achievable – in terms of energy costs and comfort levels – by adopting high-performance sequences of operation (such as the sequences of the ASHRAE Guideline 36-2021) or other optimized control strategies.

3.2 THE BRICK SCHEMA

Brick[10] is an open-source effort to standardize descriptions of physical, logical and virtual assets in buildings, as well as the relationships between them. The main reason for adopting a standardized description of a building's assets is *interoperability*: the information systems of the participants in a business network can share and operate on a common representation of the building.

Several outcomes of research such as energy dashboards, smart control systems based on model predictive control, systems for fault diagnostics are currently not implemented in buildings because of lack of standardised methods to represent data, presence of legacy systems and issues on data exchange between system integrators and software developers. Nowadays several types of data models (sometimes called metadata) exist across the building construction, commissioning and operation applications. Examples of those are the IFC data model which is used in the construction industry and the various proprietary data models of HVAC control systems. These heterogeneous models make the software integration of multiple systems a challenging and time-consuming task. Brick is an effective tool for achieving a standardized cross-vendor representation of the various building's subsystems such as HVACs, lighting, fire, security, etc. This representation can facilitate the software integration tasks and the subsequent design process and development of energy efficiency measures, smart data analytics and intelligent controls across buildings[11].

Brick models are defined as graphs where entities are the nodes and relationships are the edges. The diagram in Figure 9 presents an example of Brick-annotated data: the data is structured as a graph that shows how the different entities are related to each other.

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[9] https://buildingsync-gem.buildingsync.net/

[10] https://brickschema.org/

[11] https://www.memoori.com/wp-content/uploads/2016/06/Brick_Schema_Whitepaper.pdf

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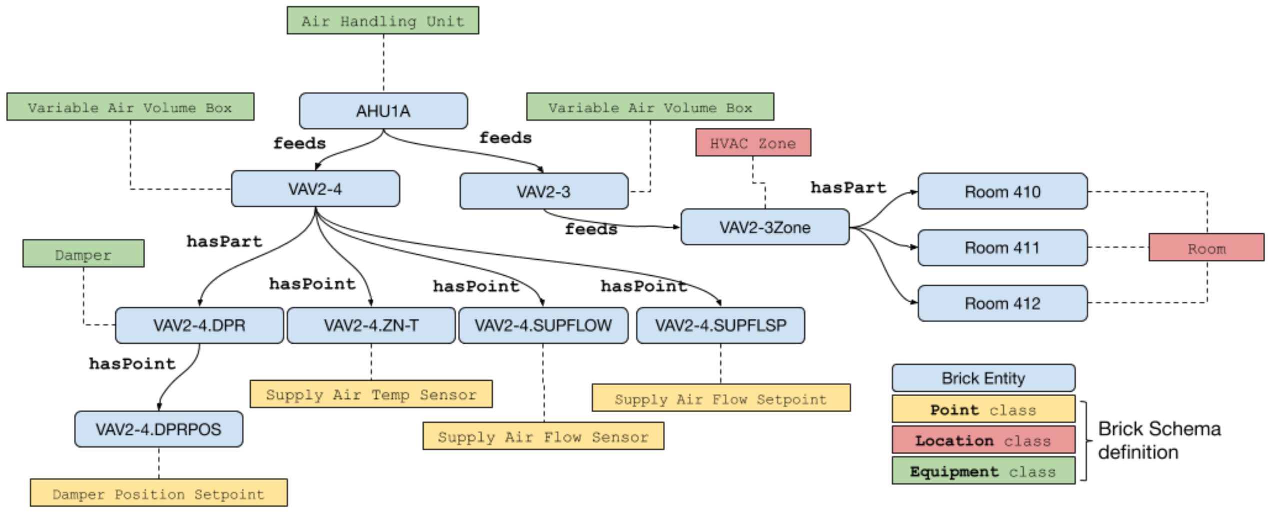

Figure 9 Example of Brick-annotated data
(**Source**: https://brickschema.org/)

The main components of the Brick schema are:

1. **Entities**. Entities are abstractions of any physical, logical or virtual item in a building:

   - Physical entities have physical presence in the building, such as pieces of equipment (mechanical equipment, electricity meters, thermostats and so on) or envelope elements, such as walls or rooms.
   - Logical entities are entities that are defined by a set of rules, such as thermal zones.
   - Virtual entities have software representations, such as sensor points that enable software tools to read the state of a physical or logical entity, and actuation points that enable software to send values to the entities.

2. **Tags**. Tags are attributes of the entities.

3. **Classes**. Classes define groups/categories of similar entities. Classes form a hierarchy, and entities are instances of one or more classes (Figure 10).

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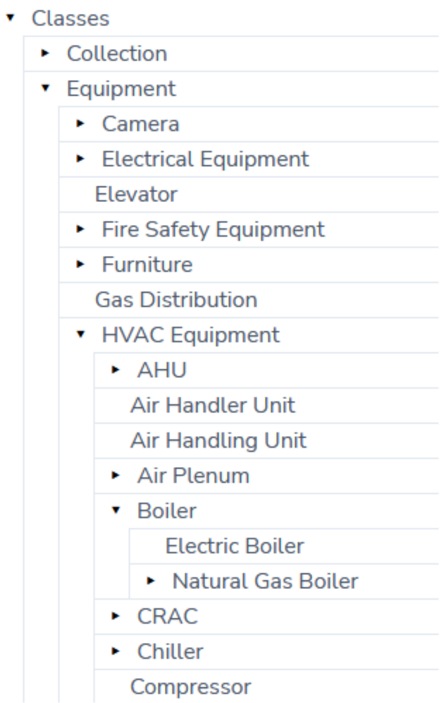

Figure 10 **The Brick hierarchy of classes for HVAC equipment**
(**Source**: https://brickschema.org/ontology/1.2/)

4. **Relationships**. Relationships define how two entities are related. The relationships in Brick support one or more of the following use cases:

- Composition. One entity may be composed of other ones, such as an HVAC system is composed by fans, reheat coils, etc., and a thermal zone is composed by rooms:

the *subject* has some component
or part identified by *object*

Subject `brick:hasPart` Object

- Topology. A relationship may define how different pieces of equipment are connected and in what order they affect some media as it flows through the building, such as air or water:

the *subject* is arranged upstream
of *object*

Subject `brick:feeds` Object

In addition, a relationship may define how spaces or rooms, or zones are connected:

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the *subject* has a location given by *object*

Subject `brick:hasLocation` Object

- Telemetry. The data sources associated or attached to various entities in the building.

the *subject* has a source of telemetry identified by *object*

Subject `brick:hasPoint` Object

Compared to prior metadata schemas such as Project Haystack[12], Brick has been designed to enable the use of complete sets of vocabularies from existing systems, uses an extensible framework of tags (keywords with minimal information), tag-sets (an entity's class composed of tags) and hierarchies (defined by tag-sets), and enables a better representation of relationships using the Resource Description Framework[13] (RDF). In Brick, an entity is a node associated with a URL[14], which enables queries based on SPARQL[15]. SPARQL provides a full set of analytic query operations for data whose schema is either embedded in the data itself or provided externally. It also provides specific graph syntax for data that can be represented as a graph[16].

Although there are many ways to structure an application that utilizes Brick-annotated data, an architecture that fits well Brick's characteristics would include:

- A graph database to store the Brick model. A Brick model is a graph data model and, as a result, it can be represented inside a graph database as a data structure built from nodes (Brick entities), relationships, and properties (Brick tags).

  This approach would also provide a way to replace RDF query languages with graph pattern matching. As an example, the following RDF query searches for all virtual meters in a Brick model of a building. Brick supports modeling virtual meters using the "brick:isVirtualMeter" property.

```
SELECT ?meter WHERE {
  ?meter rdf:type/rdfs:subClassOf* brick:Meter ;
         brick:isVirtualMeter/brick:value true .
}
```

[12] https://project-haystack.org/
[13] https://www.w3.org/RDF/
[14] https://developer.mozilla.org/en-US/docs/Learn/Common_questions/What_is_a_URL
[15] https://www.ontotext.com/knowledgehub/fundamentals/what-is-sparql
[16] https://en.wikipedia.org/wiki/SPARQL

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The graph pattern matching equivalent would be the following:

```
MATCH (meter: brick.Meter  { isVirtualMeter : true})
RETURN meter
```

- A relational or time-series database to store the telemetry data. The main classes of telemetry in Brick are:
    - *Sensors* for devices that measure one or more variables.
    - *Setpoints* that represent the value at which a desired property is set.
    - *Alarms* for signals that alert an operator to an off-normal operating condition.
    - *Commands* that represent actions that directly determine the behavior of equipment.
    - *Parameters* for settings that guide the operation of equipment and control systems.
    - *Status* that represents the current operating mode, state, or condition of an entity.

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4 CONCLUSIONS

The adoption of equipment monitoring and M&V systems enables the automation of business models for energy efficiency through the automation of information exchange and transactions between the involved parties. The result from such automation is that performance-based agreements can be used to govern not only the relationship between consumers and a service provider (only point of contact for consumers), but also between different market actors that collaborate for the provision of the integrated service. In this sense, business networks can be created by more than one linked contract that:

- translate the performance requirements of the energy retrofit service contract into performance requirements for each of the involved market parties, and
- regulate the interactions between the involved market parties by allocating the revenue that the retrofit service contract generates according to how each party contributes to it.

This approach can help in increasing the scalability of the relevant business models for energy efficiency by allowing specialized service providers to become part of a business model through bilateral performance contracts with the energy efficiency service provider (only point of contact for consumers).

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