DOCTORAL THESIS

LINKED DATA FOR ENHANCED ENERGY MANAGEMENT AT DISTRICT AND BUILDING LEVELS: AN INDICATOR-BASED METHODOLOGY

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GLOSSARY OF TERMS

Performance indicator (PI)	Performance indicator is a way to summarize pieces of performance information from available data and measure the progress towards achieving an organization's goals.
Key performance indicator (KPI)	Key performance indicator is an indicator that provides critical pieces of actionable information to ensure success and evaluates and tracks the key critical performance of an organization.
Linked Data	Linked data is a pattern of interrelated datasets using Semantic Web techniques, which extends the Web to share information in a way that can be readable by both humans and machines. Linked data enables data from different sources to be interlinked and to become more useful through semantic queries.
Ontology	Ontology is the foundation of linked data, which is a formal model that represents knowledge of a specific domain. An ontology describes the types of things (classes) that exist in the domain, the relationships between them (properties) and the logical ways those classes and properties can be used together (axioms).
RDF	Resource Description Framework (RDF) is a common format for linked data, which is a family of World Wide Web Consortium (W3C) standards for data interchange on the Web. RDF is based on the idea of making statement about resources in the form of triples (subject-predicate-object), which expresses a relationship between the resources, and identifying things using Web identifiers or HTTP URIs (Uniform Resource Identifiers).
SPARQL	SPARQL Protocol and RDF Query Language (SPARQL) is a query language for RDF data produced by W3C, which is able to retrieve and manipulate data stored in RDF format.
OWL	Web Ontology Language (OWL) is a family of knowledge representation and vocabulary description languages for authoring ontologies. OWL is built upon RDF and standardized by the W3C.

EXECUTIVE SUMMARY

Energy efficiency at both the district and building levels is an imperative for sustainable cities. The current initiatives for smart cities and communities and the growing use of distributed energy resources increasingly requires the allocation and management of energy from building to district level. An effective, integrated energy management at the district and building scales is a solution to improve multi-level energy efficiency, but such a solution is an information-driven process, which requires to exchange and analyse energy performance information and data gathered from different stakeholders. Due to the complexity of energy management at the district scale, there may be numerous potential stakeholders and a massive amount of data involved. In order to gain insights into such data for potential energy performance improvement and address stakeholders' performance goals, the problems are threefold: firstly, there is a challenge to identify and analyse stakeholders in the energy management context; secondly, it is essential to define a method to extract the key performance information and core insightful data of stakeholders' concerns; thirdly, an interoperability problem exists for exchanging and sharing the cross-domain heterogeneous data among various stakeholders.

In this thesis, a Key Performance Indicator (KPI) -based, linked data methodology is proposed to systematically support the identification and analysis of stakeholders, the extraction of key performance information and master data that underpin stakeholders' goals, the interchange of such information and data among the stakeholders, and the exploitation and analysis of the cross-domain data for multi-level energy performance improvement.

The proposed methodology has been developed in the following steps:

- Firstly, a three-task method is developed to identify stakeholders and conduct their prioritization analysis; the latter aims to find the key stakeholders who take precedence in decision making and achieving their performance goals.
- Secondly, a bi-index method is defined to select the KPIs that represent the key performance information and that measure the progress towards stakeholders' goals. KPIs are selected among a pre-list of energy performance indicators (PIs) through stakeholders' involvement, considering both their vote to PIs and their prioritization; thus, the selected KPIs can not only support stakeholders' goals but also balance their benefits.
- Thirdly, the selected KPIs are used to identify the cross-domain master data for energy performance analysis. The identified master data using KPIs ensures that the stakeholders' concerns are underpinned and avoids analysing unnecessary data.

- Fourthly, an EM-KPI ontology is developed to facilitate the exchange of key performance information and master data among different stakeholders. The ontology describes not only the multi-level KPIs but also the cross-domain master data; therefore, it supports both performance tracking and improvement analysis.
- Finally, linked data are generated using the EM-KPI ontology to realize the data interchange and exploitation. Linked data resolve the data interoperability problem and facilitate the data exploitation for performance problems identification and informed decision-making in improvement measures.

The proposed methodology has been validated through a representative case study for a small district called Villa Solar. The district was the competition site of Solar Decathlon Europe 2012. It contains 18 solar houses, which are energy prosumers aiming to achieve net zero energy buildings, and several public service buildings, which are net energy consumers. The combined features of the buildings and their connections to a smart microgrid make it one of the best cases for district-scale energy management and suitable for the context of smart cities and communities.

Buildings and microgrid in the district were equipped with energy management systems and monitored from September 17th to 28th, 2012, but initially without information exchange among different stakeholders. Through using the proposed methodology, 6 groups of key stakeholders are identified, 23 KPIs are selected and a linked dataset is generated. The generated linked dataset validates that the ontology enables to interchange the key performance information and master data among various stakeholders. The exploitation of the linked dataset helps identifying key performance problems and make better decisions for improvement, compared to the current used methodology in the district. Through stakeholders' interaction and information exchange, the district has the potential to save at least 18.24% of the energy cost. The case study demonstrates the feasibility and benefits of the proposed methodology to extract, exchange and analyse the key performance information and master data, in order to improve multi-level energy performance and enhance energy management at both district and building levels.

RESUMEN EJECUTIVO

La eficiencia energética tanto en el distrito¹ como en los edificios es indispensable para las ciudades sostenibles. Las iniciativas actuales para ciudades, comunidades inteligentes y el aumento del uso de recursos energéticos distribuidos, requieren cada vez más la asignación y gestión de energía desde el edificio individual hasta el nivel del distrito. Una gestión eficaz e integrada de la energía en las escalas del distrito y los edificios es la solución para mejorar la eficiencia energética multinivel, pero dicha solución es un proceso orientado a la información, que requiere intercambiar y analizar información sobre el rendimiento energético y los datos recopilados por las diferentes partes interesadas. Debido a la complejidad de la gestión energética a escala de distrito, puede haber numerosos interesados y una gran cantidad de datos involucrados. Con el fin de obtener información sobre estos datos, para mejorar el potencial rendimiento energético y abordar los objetivos de rendimiento de los interesados, hay que resolver tres problemas: en primer lugar, existe el desafío de identificar y analizar a las partes interesadas en el contexto de gestión energética; en segundo lugar, es esencial definir un método para extraer la información de rendimiento clave y los datos básicos y perspicaces de las inquietudes de las partes interesadas; en tercer lugar, existe un problema de interoperabilidad para intercambiar y compartir los datos heterogéneos entre dominios entre varios interesados.

En esta tesis se desarrolla una metodología de datos enlazados y basados en indicadores clave de rendimiento (KPI, por sus siglas en inglés), para proporcionar un enfoque sistemático que respalde la identificación y el análisis de los interesados, la extracción de información clave de desempeño y los datos principales que sustentan los objetivos de los interesados, el intercambio de dicha información y datos entre los interesados, y la explotación y el análisis de los datos entre dominios para la mejora del rendimiento energético multinivel. La metodología propuesta ha sido desarrollada en el siguiente orden:

- En primer lugar, se desarrolla un método de tres tareas para identificar a las partes interesadas y llevar a cabo su análisis de priorización; este último tiene como objetivo encontrar a las partes interesadas clave que tienen prioridad en la toma de decisiones y el logro de sus metas de rendimiento.
- En segundo lugar, se define un método de dos índices para seleccionar los KPIs que representan la información clave del desempeño y que miden el progreso hacia las metas de las partes interesadas. Los KPIs se seleccionan entre una lista previa de indicadores de desempeño energético (PIs, por sus siglas en inglés) a través de la participación de las partes interesadas, considerando tanto su valoración de los PIs

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¹ Distrito: Cada una de las demarcaciones en que se subdivide un territorio o una población para distribuir y ordenar el ejercicio de los derechos civiles y políticos, o de las funciones públicas, o de los servicios administrativos.

como su priorización. Por lo tanto, los KPIs seleccionados no sólo pueden apoyar los objetivos de las partes interesadas sino también equilibrar sus beneficios.

- En tercer lugar, los KPIs seleccionados se utilizan para identificar los datos predominantes para el análisis del rendimiento energético. Los datos principales identificados que usan KPIs, asegura la importancia y que las partes interesadas se sustente, evitando el análisis de datos innecesarios.
- En cuarto lugar, se desarrolla la ontología EM (gestión energética) -KPI para facilitar el intercambio de información clave de rendimiento y datos principales entre las diferentes partes interesadas. La ontología describe no sólo los KPIs de varios niveles, sino también los dominios de datos principales; por lo tanto, soporta tanto el seguimiento de rendimiento como el análisis de mejora.
- Finalmente, los datos enlazados se generan utilizando la ontología EM-KPI para facilitar el intercambio y la explotación de datos. Los datos enlazados resuelven el problema de interoperabilidad de los datos y facilitan la exploración de datos para la identificación de problemas de rendimiento y la toma de decisiones informadas en las medidas de mejora.

En este sentido, la metodología propuesta ha sido validada a través del estudio de un caso representativo, un distrito de pequeña escala llamado Villa Solar. En dicho distrito se desarrolló la competición de Solar Decathlon Europe 2012, el cual estuvo conformado por 18 casas solares, que son productores y consumidores (prosumers termino en inglés) de su energía, con el objetivo de lograr edificios con cero energía neta, el distrito también contaba con varios edificios de servicio público, que eran consumidores netos de energía. Las características combinadas de los edificios y sus conexiones a una micro red inteligente lo convierten en uno de los mejores casos para la gestión de energía a nivel de distrito, adecuado para el contexto de ciudades y comunidades inteligentes. Los edificios y la microrred en el distrito fueron monitoreados y equipados con sistemas de gestión de energía, pero inicialmente sin intercambio de información entre los diferentes interesados.

Mediante el uso de la metodología propuesta, se identificaron 6 grupos de aspectos relevantes, se seleccionaron 23 KPI y se generó un conjunto de datos enlazados entre sí. El conjunto de datos enlazados generados valida que la ontología permita intercambiar la información clave de rendimiento y los datos principales entre varias partes interesadas. La exploración del conjunto de datos enlazados ayudó a identificar los problemas clave de rendimiento y a tomar mejores decisiones de mejora, en comparación con la metodología utilizada actualmente en el distrito. A través de la interacción de las partes interesadas y el intercambio de información, el distrito tiene el potencial de ahorrar al menos el 18.24% del costo de la energía. El caso de estudio demuestra la viabilidad y los beneficios de la metodología propuesta para extraer, intercambiar y analizar la información de rendimiento y los datos principales, a fin de mejorar el rendimiento energético multinivel y la gestión de la energía tanto a nivel de distrito como de edificio.

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LIST OF ABBREVIATION

AEC	Architecture, Engineering and Construction
AMI	Advanced Metering Infrastructure
AHP	Analysis Hierarchy Process
ANP	Analysis Network Process
BEMS	Building Energy Management System
BAS	Building Automation System
BIM	Building Information Model
BMS	Building Management System
BOLD	Big and Open Linked Data
BIO	gbBuilding Information Ontology
CIS	Customer Information System
CIM	Common Information Model
CI	Comprehensive Index for KPI selection
CQ	Competency Question
CQG	Competency Question Group
DER	Distributed Energy Resource
DSM	Demand Side Management
DR	Demand Response
EM	Energy Management
EMS	Energy Management System
EU	European Union
ENRM	Environment and Natural Resource Management
EIS	Energy Information System
EEI	Energy Efficiency Index
ETI	Energy-Time consumption Index
ERO	Energy and Resource Ontology
GIS	Geographic Information System
GHG	Greenhouse Gas
HVAC	Heating, Ventilation and Air Conditioning
IoE	Internet of Energy
IEA	International Energy Agency
ICT	Information and Communications Technology
IT	Information Technology
ISO	International Standard Organization
IAQ	Indoor Air Quality
KPI	Key Performance Indicator
LDAC	Linked Data for Architecture and Construction
MG	Microgrid

MDM	Meter Data Management
MAMO	Mathematical Modelling Ontology
MV/LV	Medium Voltage/Low Voltage
NZEB	Nearly Zero Energy Building
NetZEB	Net Zero Energy Building
NetZEC	Net Zero Energy Cluster
OWL	Web Ontology Language
OM	Ontology of unit of Measure
PEMS	Prosumer based Energy Management System
PI	Performance Indicator
PO	User Behaviour and Process Information Ontology
PV	Photovoltaic
RDF	Resource Description Framework
RDFS	Resource Description Framework Schema
SHEMS	Smart Home Energy Management System
SG-BEMS	Smart Grid Building Energy Management System
SPARQL	SPARQL Protocol and RDF Query Language
SPI	Stakeholder Prioritization Index
SVI	Stakeholder Vote Index
SCADA	Supervisory Control and Data Acquisition
SSN	Semantic Sensor Network
SDE	Solar Decathlon Europe
TOU	Time of Use
URI	Uniform Resource Identifier
VPP	Virtual Power Plant

1 INTRODUCTION

1.1 THESIS CONTEXT

The energy consumption and CO₂ emissions around the world have been increasing dramatically in the last 50 years, and the growth trend is expected to continue for the foreseeable future [1]. Urban areas cover about 2% of the earth's surface, but are responsible for about 75% of the resources consumption [2]. Moreover, the current process of rapid urbanization exerts additional pressure on energy resource supplies and increases CO₂ emissions [3][4].

Urban energy planning and urbanization management will be pivotal for the achievement of sustainable cities [5]. The initiatives of smart cities and communities have the potential for large-scale energy management through the adoption of appropriate new energy technologies and ICT (information and communication technologies) [6]. In addition, the growing use of distributed energy resources in energy distribution networks increasingly requires energy management at a district scale, for the purpose of integrating energy supply and usage [7][8]. One example of it is demand-side management: this involves actions that can influence energy consumption patterns of end-users with upstream benefits for electricity distribution and transmission networks [9]. Such large-scale benefits align with the Digital Agenda for Europe², which is one of the seven pillars of the Europe 2020 Strategy. Therefore, a series of EU funded projects has been launched aiming to use ICTs to support energy management in cities, neighbourhoods and districts. These include the projects such as DoF (District of the Future)³ and COOPERATE (Control and Optimisation for Energy Positive Neighbourhoods)⁴.

Buildings are one of the three main sectors of energy consumption [10], which involve significant levels of energy end use in cities, accounting for approximately 40% of final energy consumption in the EU countries [11]. However, a considerable proportion of the existing building stock in the EU countries is either designed or operated in an inefficient

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² The Digital Agenda presented by the European Commission forms one of the seven pillars of the Europe 2020 Strategy. The Agenda proposes to better exploit the potential of ICTs in order to foster innovation, economic growth and progress. <https://ec.europa.eu/digital-single-market/en/europe-2020-strategy>

³ An EU-funded project under the topic ICT-2013.6.4 - Optimising Energy Systems in Smart Cities, with the objective to increase energy efficiency in a city district using innovative ICT approaches. For more information see: http://cordis.europa.eu/project/rcn/111353_en.html.

⁴ An EU-funded project under the topic EEB-ICT-2011.6.5 - ICT for energy-positive neighbourhoods, with the objective to develop an open, scalable neighbourhood service and management platform to progress towards energy positive neighbourhoods and achieving 2020 targets. For more information see: http://cordis.europa.eu/project/rcn/105699_en.html.

way. By improving the energy efficiency of buildings, the total energy consumption in Europe could be reduced by 5–6%, and CO₂ emissions by 5% [12].

Effective energy management is an important measure used to improve energy efficiency in buildings. A lack of energy management at the operational stage may cause the failure to achieve expected energy performance levels [13]. However, improper energy management will also cause the extra waste of energy resources and costs [14]. Through effective energy management, the recent need to improve the energy efficiency of both individual buildings and those at the district scale is another issue [15]. The energy efficiency of buildings at the district or community level offers a substantial potential in terms of contributing towards the effort to achieve sustainable cities.

A series of regulations and policies has been formulated in order to promote the application of renewable energy technologies, energy efficiency measures and smart technologies in Europe [16]. Such legislative decisions give strong drivers to implement more effective measures to promote energy innovation, improve energy efficiency and reduce CO₂ emissions at both the district and building scales.

1.2 THESIS MAIN MOTIVATIONS

Figure 1: Thesis main motivations.

The primary motivation of the thesis is to improve multi-level energy efficiency in districts and buildings using energy management, as illustrated in Figure 1. However, energy management at the district and building scales is a multi-stakeholder and cross-domain issue, which needs the interaction of various stakeholders and information from different domains. Therefore, the second motivation is to promote stakeholder engagement in energy management and the third motivation aims to address the data overload problem caused by

ICTs and extract the core information. Furthermore, the required data sources are often gathered from various stakeholders and from different domains, which are usually heterogeneous but interrelated with each other and are closely associated to different energy operations. Therefore, the fourth motivation is to exchange and exploit the cross-domain heterogeneous data among stakeholders for multi-level energy performance improvement.

The following subsections illustrate each of the motivations in detail and a summary of the key findings is presented thereafter.

1.2.1 Improve Multi-Level Energy Efficiency via Energy Management

The building sector has a big potential in energy saving and energy efficiency improvement. In EU countries, more than 50% of residential buildings were built before 1970, without complying with any energy regulation, and approximately 1/3 were built between 1970 and 1990 which corresponds to the initial implementations of energy policies [17]. Energy efficiency is a key measure to reduce energy use and CO₂ emissions in buildings.

According to the International Energy Agency (IEA)⁵ [18], if the EU energy target for 2030 (a 40% cut in greenhouse gas emissions, at least a 27% share of renewable energy and at least 27% energy savings, compared to 1990 levels) is implemented, around 16% energy for space heating in domestic buildings is expected to be reduced and 25% energy for space heating in commercial buildings could be saved. Additionally, the adoption of LEDs in lighting systems will result in more than 40% reduction in household electricity consumption for lighting per square meter. Figure 2 shows the energy saving potential in domestic and commercial buildings in the EU by 2030. It can be seen that space heating, water heating and lighting have a considerable potential in energy efficiency improvement.

Energy management at the operation and maintenance stages is an important factor that influences the actual energy performance in buildings and energy systems, such as HVAC (Heating, Ventilation and Air Conditioning) and lighting systems [19]. Building energy management always involves a range of measures to monitor, control and optimize building services and energy use. Lee and Cheng [20] reviewed 105 cases of building energy management. It has been found that, from 1976 to 2014, the energy saving effects for buildings increased from 11.39% to 16.22% annually using energy management; the highest saving effect for artificial lighting systems is up to 39.5% in average; and the saving effects for HVAC and other equipment are around 14.07% and 16.66%, respectively.

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⁵ International Energy Agency, an organization aiming to coordinate national efforts to conserve energy, develop alternative energy sources and reduce Greenhouse Gas (GHG) emissions.

Figure 2: Building energy saving potential in the EU by 2030 compared to the 2013 levels [18].

Through effective energy management, approaches that improve the energy efficiency of individual buildings with a view towards enhanced district-scale performance is an ongoing societal priority [15]. Solutions that consider the energy efficiency of buildings in the context of community or district level can significantly contribute towards sustainable and smart cities. Furthermore, the increasing use of renewable energy generation and distributed energy resources increasingly requires the implementation of energy management not only in a single building but also at a district scale, in order to attain a rational allocation of energy resources [7]. In a smart city context, buildings tend to act as prosumers, which means that they both produce and consume energy [21]. The increasing number of prosumers requires a district-scale energy management strategy that constructs an energy sharing mechanism among different buildings in order to optimize district energy supply and demand and to achieve energy balance [22].

Energy management at the district scale should consider together buildings and district energy systems (e.g., microgrid) [23]. Measures should be taken to optimize the energy performance at both the supply and demand sides [24]. Through the synergies between buildings and district energy systems, the demand-side can better manage and optimize energy use and save energy cost; meanwhile, the supply-side can gain more flexible mechanisms for power demand and supply management [24].

In any case, an integrated energy management framework for districts and buildings should be capable of providing information on appropriate energy efficient measures at any scale of implementation: from the equipment level, via the whole building and systems level, to the district level [25].

1.2.2 Promote Stakeholder Engagement in Energy Management

Integrated energy management at district and building scales is a multi-stakeholder problem. It requires exchange and analysis of energy-related information at different scales and from

different domains [26]. Usually, the information sources are gathered from various stakeholders. Hence, stakeholder engagement is a prerequisite for the integration of such information and the promotion of multi-level energy management [27]. Furthermore, distributed energy sources also belong to different stakeholders; therefore, stakeholders' involvement can further facilitate the sharing of such energy sources. The complex and dynamic features of energy management require flexible and transparent decision-making. Stakeholders' involvement in decision-making can ensure that their energy performance goals are addressed and that the various interests are balanced, thus to achieve a win-win situation [28]. As a result, energy management is actually an interactive process among various stakeholders and should enable the realization of their respective energy performance goals in order to promote their collaborative engagement.

There are different stakeholder engagement channels, including informing, consulting, involving, collaborating and/or empowering [29]. However, in order to develop an effective engagement mechanism among various stakeholders, the identification and analysis of stakeholders is a great challenge. Numerous potential stakeholders may be involved due to the complexity of energy management especially on the district scale. This undoubtedly increases the difficulties in identifying stakeholders and analysing their interests, goals, needs, potential concerns and level of influence.

Although the importance of stakeholders for the successful implementation of a project is indisputable, there is a present shortage of studies that aim to identify and analyse stakeholders related to energy management from building to district level. Stakeholder analysis and engagement are crucial to energy management because the complexity of energy operations at the district and building scales involves numerous actors. The implementation processes of energy management should take different types of stakeholders' views and needs into consideration [30]. However, the present focus of energy managers is usually technical in nature and includes specification of monitoring and control systems along with energy optimization techniques [30]. Further studies about stakeholder identification and analysis in the energy management context are needed.

1.2.3 Data Overload Problem in Energy Management

Energy managers can improve energy efficiency only when the monitoring data from different domains are available. Therefore, energy management aimed to improve multi-level energy efficiency is a complex data-driven process [26]. The integration of cross-domain information is a key to facilitate the joint energy management at district and building levels and from supply to demand sides [31].

However, with the multiple domains involved and the upward trend to use advanced ICTs, an incredible amount of energy-related data is being generated. Such energy-related data tend to grow exponentially due to the high volume, velocity and variety of data generation.

Energy managers can sometimes find themselves drowning in a big data ocean [32]. However, both opportunities and challenges exist in order to make sense of such big amount of data [33].

The big amount of energy-related data provides new analysis possibilities in data-driven decision making and draws insights in potential performance improvement in district and buildings [33]. The discovery and exploitation of the knowledge hidden within the data is extremely useful because of the economic and environmental benefits. For example, according to the National Institute of Standards and Technology (NIST) of the United States, up to \$2 trillion energy cost could be saved by 2030 with the implications of data from smart grids [34]. Hence, the expansion of data presents great opportunities for energy performance improvement and energy consumption and cost reduction. However, it is also true that energy managers may be overwhelmed by the volume and variety of data involved; the big amount of data becomes unusable without careful consideration of what data are valuable, how often to collect them and how to present the collected data [35]. It is really important to focus on the data worth collecting, the analysis worth sharing and the problems worth solving [36]. A well-designed framework for data exploitation is required by considering the pieces of information needed to support the key goals of an energy management plan [35]. Therefore, it is essential to extract the key performance information and core insightful data that underpin stakeholders' performance goals.

1.2.4 Data Interchange and Exploitation among Stakeholders

Data from different information domains are usually not standalone. They are closely related to the energy operation of buildings and energy systems, which often have a direct/indirect relationship with, or influence on, each other [37]. Modern energy management should not only consider the data generated inside the energy management systems but also other external data, such as weather, location, energy pricing, energy billing/cost, building, occupancy, user behaviour and scheduling. Energy managers should identify and use the implicit or explicit associations (i.e., connections or relationships) and correlations between multi-domain data in order to benefit from the data for developing energy efficient measures [37]. Therefore, it is essential to integrate and exchange the cross-domain data gathered from different stakeholders in order to facilitate the data exploitation and knowledge discovery.

However, energy-related data and information are usually stored in different information islands, there is little interaction between each other for effective data sharing and exchange [38]. One of the main barriers is due to the interoperability of heterogeneous data. The traditional way to share and exchange different silos of information is usually complicated, inefficient, exhaustive and sometimes costly and time-consuming.

To resolve the interoperability problem of cross-domain data, the semantic web provides a possible solution. Linked data harnesses the ethos and infrastructure of the Web to enable data sharing and reuse on a massive scale [39]. In recent years, linked data has been a subject of growing interest and applications in the building and energy fields. For example, Corry et al. [40] used linked data to access AEC (architecture, engineering and construction) data for building performance analysis. Besides, an annual workshop titled LDAC (Linked Data in Architecture and Construction) has been conducted since 2012, aiming to enhance information exchange in the AEC domain [41]. Linked data are scalable, which can not only be applied for individual buildings, but also for smart energy grids and districts.

Despite for the wide range of benefits in linked data application for energy and buildings, there are still challenges to integrate the big amount of distributed data in a coherent manner and to derive and tailor information from the data that exactly satisfies the needs of specific end users [38]. The main purpose of data interchange in integrated energy management is to enable data exploitation and to improve data driven decision-making for energy performance improvement. Therefore, the linked data generated for integrating and exploiting key performance information and core insightful data of stakeholders' concerns is emerged as a noticeable opportunity.

Ontologies are the foundation of linked data, which defines the concepts and relationships within a specific domain in a well-defined and unambiguous manner, so as to generate linked data and enable data exchange among different domains [42]. Furthermore, ontologies play a major role in solving the interoperability problem by providing a shared understanding of common domains [43]. Currently, a range of ontologies have been developed to describe different energy-related domains, aiming for different types of applications [44]. However, an ontology aiming to integrate both the key performance information and its related core data that underpin stakeholders' performance goals has not been developed to date.

1.2.5 Summary of Key Findings

The summary of the four main motivations can be depicted as the improvement of multi-level energy efficiency through engaging stakeholders and extracting, exchanging and exploiting the key performance information and core valuable data among such stakeholders.

The key findings associated with the utilization of energy management for multi-level energy performance include:

- An integrated energy management framework is required for appropriate energy efficient measures at any scale of implementation (Section 1.2.1);
- The identification and analysis of stakeholders is a great challenge due to the numerous potential stakeholders involved (Section 1.2.2);

- There is a present shortage of studies about identification and analysis of stakeholders in the energy management context (Section 1.2.2);
- It is essential to extract the key performance information and core insightful data that underpin stakeholders' performance goals (Section 1.2.3);
- The interoperability problem of heterogeneous data impedes the exchange and exploitation of cross-domain data stored in different information islands (Section 1.2.4);
- There is the need of an ontology to integrate and exploit the key performance information and the cross-domain core data for multi-level energy performance improvement (Section 1.2.4).

1.3 RESEARCH QUESTIONS

Energy management in the context of this thesis is a complex yet collaborative process, involving numerous potential stakeholders and enormous volumes of information. In order to provide an effective engagement mechanism for stakeholders and to improve informed decision-making through effective exchange and exploitation of cross-domain data from districts and buildings, three main research questions are put forward.

The three research questions are proposed based on the main motivations presented above and are stated as follows:

- **Research Question 1.** What method can be used to identify stakeholders and extract the key performance information and core valuable data of stakeholders' concerns?
- **Research Question 2.** What linked data need to be defined to interchange and exploit the key performance information and core data among various stakeholders in order to improve multi-level energy performance and address stakeholders' performance goals?
- **Research Question 3.** How much potential does the generated linked data have for improving multi-level energy performance through data interchange and informed decision-making?

1.4 RESEARCH HYPOTHESIS, ASSUMPTIONS AND RESTRICTIONS

Bearing in mind the three research questions, the hypothesis of this thesis is defined as follows:

Hypothesis. The combined use of KPIs and linked data can enable key valuable data interchange and exploitation among stakeholders and improve data driven decision-making for enhanced multi-level energy performance at the district and building scales.

Using KPIs supports extracting the key performance information and identifying the master data from big amounts of energy-related data. Furthermore, the involvement of stakeholders in the selection of KPIs can ensure that data and performance information underpin their energy performance goals.

The linked data represented using an ontology that integrates KPIs and cross-domain master data can support exchanging and exploiting insightful data and key performance information among various stakeholders. The generated linked data can help not only tracking the energy performance but also identifying the performance problems for potential improvement, enabling to achieve stakeholders' energy performance goals.

The study of this thesis is based on the following **assumptions** that are accepted as true:

- **Assumption 1.** Energy management at the district and building levels is a collaborative process involving different stakeholders;
- **Assumption 2.** The use of ICTs generates a massive amount of cross-domain data available for decision-making in energy management;
- **Assumption 3.** Stakeholders are willing to share their own data if they can benefit from the data from other stakeholders and their energy performance goals can be addressed.

Some **restrictions** define the limits of this study and allow determining future research objectives. The restrictions defined for this thesis are listed below, which delimit the research problem and allow the continuous improvement of this research.

- **Restriction 1.** The research boundary in this work is a district in a city;
- **Restriction 2.** Buildings are the main objects under study considering the district-scale energy management;
- **Restriction 3.** Among all energy types, this work focuses on electricity. Only the stakeholders, KPIs and data in relation to electricity generation, delivery and use are considered. Therefore, energy management in this thesis refers to electricity management;
- **Restriction 4.** This thesis studies energy management in its broad sense for energy performance tracking and improvement, rather than in a narrow sense which emphasizes on energy control systems.

Figure 3 shows the research boundary of the integrated energy management at district and building levels in which a group of buildings is connected to the utility grid in the district. The energy demand in the district is aggregated by buildings.

Figure 3: Research boundary of district and building energy management.

1.5 THESIS OBJECTIVES

In order to demonstrate the hypothesis, the main research objective of the thesis is defined as follows:

- **Main Objective.** To build a systematic methodology using KPIs and linked data for extracting, exchanging and exploiting the key performance information and the core data that underpin stakeholders' performance goals, thus to enhance integrated energy management through stakeholders' engagement and improve multi-level energy performance.

Furthermore, in order to achieve this main objective, the following sub-objectives are needed:

- **Sub-objective 1.** To develop a structured method to identify and prioritize stakeholders in district-scale energy management. This is aimed to decide who are the stakeholders and, moreover, who are the key stakeholders taking precedence in decision-making.
- **Sub-objective 2.** To design a quantitative method to weight, select and validate the KPIs through stakeholders' involvement. This is targeted to identify the KPIs that underpin stakeholders' performance goals and to represent the multi-level key performance information, thus helping decision-makers achieve the performance goals concerned by stakeholders.
- **Sub-objective 3.** To implement a linked data approach, based on an integrated ontology, that facilitates the integration and interchange of key performance information and core data among different stakeholders. This is aimed to generate linked data, resolve the interoperability problem of cross-domain data sharing,

facilitate data exploitation for performance improvement, and offer an engagement mechanism for various stakeholders.

1.6 THESIS STRUCTURE

Considering the research questions and objectives, the thesis overview is illustrated in Figure 4, and the rest of the thesis is structured as follows:

- **Chapter 2 (State of the Art)** deals with the state of the art in the fields of energy management for districts and buildings, performance indicators in energy management and linked data application in energy management. The open research problems that will be addressed in this thesis are identified from the state of the art.
- **Chapter 3 (Thesis Methodology)** defines: (1) the general research process of the thesis, including the relationship between the research objectives and their addressed research problems; and (2) the general framework of the systematic KPI-based linked data methodology for enhanced multi-level energy management proposed in this thesis.
- **Chapter 4 (Identification of Stakeholders and KPIs)** specifies a detailed three-task method for the identification and prioritization of stakeholders, a method used to define a pre-list of performance indicators and a bi-index method for selecting KPIs that underpin stakeholders' performance goals through stakeholders' involvement.
- **Chapter 5 (Identification of KPI-related Master Data)** presents the data typologies in energy management and illustrates the method for the identification of master data using KPIs.
- **Chapter 6 (Development of the EM-KPI Ontology)** elaborates the detailed process to develop the EM-KPI ontology for the integration of key performance information and its related master data.
- **Chapter 7 (Method for Linked Data Generation)** describes the method applied for generating linked data using the EM-KPI ontology, in order to exchange and exploit the key performance information and cross-domain master data among different stakeholders.
- **Chapter 8 (Case Study)** demonstrates the feasibility and benefits of the methodology using a case study involving a small district called Villa Solar.
- **Chapter 9 (Conclusion and Future Work)** discusses the conclusions of the thesis, the main contributions and the future work.

Figure 4: Structure and overview of the thesis.

Chapter 4 and **Chapter 5** address the first research question about the method to identify stakeholders and extract the key performance information and core data of stakeholders' concerns. **Chapter 6** and **Chapter 7** answer to the second research question about the generation of linked data to exploit and exchange the key performance information and core data among various stakeholders. **Chapter 8** is related to the third research question, aiming to demonstrate the potential of linked data to improve multi-level energy performance.

Meanwhile, **Chapter 3** involves the study regarding the main objective to build a systematic methodology using KPIs and linked data. **Chapter 4** comprises the research in relation to sub-objective 1 and sub-objective 2 for the development of methods to identify stakeholders and select KPIs that underpin stakeholders' goals. **Chapter 5**, **Chapter 6** and **Chapter 7** include the study related to sub-objective 3 for the implementation of linked data approach. Finally, **Chapter 8** aims to demonstrate the proposed methodology and verify the hypothesis.

2 STATE OF THE ART

2.1 INTRODUCTION

This chapter presents a summary of the state of the art that is relevant to this thesis. It starts out with the energy challenges for sustainable cities in Section 2.2, including the current energy poverty and rapid urbanization, the initiatives towards smart cities and communities and the policy drivers to improve energy efficiency in districts and buildings. Subsequently, the current situation and trends in relation to energy management as a measure to improve energy performance are studied in Section 2.3, focusing on the timeline of energy management, the integrated and information-driven process in energy management and the importance of stakeholders' engagement for energy management. In Section 2.4, a related study about the performance indicators for energy management is conducted, since performance indicator is a useful means by which to evaluate and track the process towards achieving stakeholders' performance goals and represent the performance information. Afterwards, Section 2.5 conducts a literature review of the current studies on using linked data for data exchange and exploitation for gaining insights into the data required for energy performance improvement. Finally, Section 2.6 presents a summary of the open research problems found in the study of the state of the art.

2.2 ENERGY CHALLENGES FOR SUSTAINABLE CITIES

The main energy challenges for sustainable cities include the eradication of energy poverty and the improvement of energy efficiency [45], and better energy efficiency is critical to alleviating the energy poverty. The deployment of new intelligent technologies is seen as a key factor in decreasing greenhouse gas emissions and improving the energy efficiency of cities [46]. The use of ICTs as an enabling technology provides the opportunities to reduce energy use in cities, which has great potential for supporting the transition to more sustainable cities regarding the management of urban systems and the support for more sustainable lifestyles [47]. As a result, smart cities and communities using ICTs have been implemented [48]. Furthermore, in order to improve energy efficiency and promote energy innovation in EU countries, main energy and climate policies have been formulated based on the Europe 2020 strategy and the ratified Paris agreement [49].

2.2.1 Energy Poverty and Rapid Urbanization

Nowadays, there are increasing issues in energy consumption growth and fossil energy shortage. According to the International Energy Agency (IEA), the world's primary energy consumption has doubled from 1973 to 2013, as seen in Figure 5; the increase especially reflects in developing countries such as China and India [1]. Furthermore, the energy growth trend is predicted to continue in the following 30 years; the three main sectors of

energy consumption include industry, transport and building, among which the building sector will account for a greater proportion in the future [10].

Figure 5: World's total primary energy consumption from 1971 to 2013 by region (source: IEA).

Contemporary cities largely depend on intensive use of energy from fossil fuels; three quarters of the global energy demand are estimated from urban populations, notably over 80% in western Europe [50]. As a result, the current rapid urbanization increases the severity of energy resources shortage. According to the United Nations, the world's population has been increasing consistently since last 1950s, by now almost triple than 50 years ago [3]. However, people do not settle in a homogeneous way; urban growth has been manifested particularly since the second half of the 1970s [51]. Among the total population, the urban population reached for the first time in history more than 50% in 2008; by 2040, the urban population is estimated to be greater than 75% in developed countries, and be approximately 50%-75% in most of the developing countries [52]. Figure 6 shows the urban population forecast in different countries by 2040. In Spain, the urban population is estimated to reach to a share of 84%.

Due to the large urban population, cities are confronting increasing challenges to meet the growing energy demand and resolve urban environment concerns. Therefore, it is critical to consider cities as part of the solution to promote sustainable development [53]. The shortage of energy supply, which rises the energy prices, aggravates the energy (fuel) poverty in cities. Energy poverty is a situation where a household lacks a socially and materially necessitated level of energy services, due to the rising energy prices, inefficient buildings and appliances and specific households energy needs [54]. Energy poverty is an increasing issue encountered by the EU Member States [55].

Improving energy efficiency is a crucial solution to alleviate energy poverty. In Europe, ninety percent of social housing consists of buildings which need to be refurbished; these buildings usually have high energy consumption and low energy efficiency [45]. The modernisation of such housing space is a necessary condition for guaranteeing neighbourhoods and cities with long-term sustainability [45]. In addition, multiple buildings also lack effective collective management. Therefore, to improve the energy efficiency of buildings, the urban community as a whole should be considered, not just the buildings per se [53].

Figure 6: Urban population in different countries by 2040 (source: UNICEF).

The energy efficiency of demand side and supply side is of equal importance. The current condition of the energy infrastructures in many cities has not been adequate to provide satisfied services to the rapidly growing population [56]. Since environmental issues produced by fossil energy consumption are exacerbating in cities [57], the supply-side measures such as the use of renewable energy sources and the renewal of the energy supply network are supposed to be effective solutions to mitigate energy poverty. In recent years, the energy use in the EU has gradually shifted from fossil fuels to renewable energy sources, such as solar energy, wind power and biofuels [58]. The EU has launched a number of demand-side and supply-side initiatives, such as the promotion of co-generation, the energy performance of buildings and the energy labelling for domestic appliances, in order to increase energy efficiency and reduce energy demand [58].

2.2.2 Smart Cities and Communities Initiatives

The initiatives of smart cities and communities are important measures adopted to attain sustainability in cities. A smart city is a collection of smart infrastructures and services that uses ICTs for wise management and control of natural and social resources, accessible for citizens to participate in the management, in order to provide better quality of life for its

citizens [59]. Smart city essentially means efficiency, which is based on the intelligent management, integrated ICTs and active citizen participation [60]. The concept of smart city has been used for the last 20 years; it has been introduced as a strategic device to encompass modern urban production factors in a common framework and, in particular, to highlight the importance of ICTs [61]. Kramers et al. [47] explored the opportunities of using ICT as an enabling technology to reduce energy use in cities. In the EU, one of the main aims of smart cities is to support environmental sustainability by reducing greenhouse gas emissions in urban areas, due to the growing needs to solve the challenges related to urbanization [46].

As the next stage of urbanization, smart cities and communities have been gaining increasing importance in the agendas of policy makers [62]. Smart cities and communities are one of the key areas of European Horizon 2020 [63]. Research activities in this area cover low energy district, integrated infrastructures and sustainable urban mobility. With this vision of smart city in mind, the European Union is investing a great amount in ICT research and developing policies to make cities more sustainable in view of Europe's 20-20-20 target⁶. To speed up the deployment of smart cities, the European Commission has launched the European Innovation Partnership on Smart Cities and Communities in order to bring together European cities, industry leaders, and representatives of the civil society to smarten up Europe's urban areas [64].

There are plenty of flagship cases of smart cities, including PlanITValley in Portugal, SmartCity Malta, SmartCity Málaga, etc. [6]. The European project R2CITIES⁷, together with EU-GUGLE⁸ and ZenN⁹, are involving 15 municipalities for greater leverage in sharing and promoting energy efficient renovation solutions for cities and communities, under the label of “My Smart City District”. ICTs and energy are two main research areas of R2CITIES; both together have created a multidisciplinary group focused on the application of ICTs in the field of energy, including energy efficiency, energy saving, integration of renewable energy systems, electricity market, demand response, smart grid,

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⁶ Europe's 20-20-20 target is a goal to improve energy efficiency by 20%, increase renewable energy use by 20% and reduce CO₂ emissions by 20% in 2020, compared to the level in 1990.

⁷ The project R2CITIES aims to develop and demonstrate replicable strategies for designing, constructing and managing large scale district renovation projects for achieving nearly zero energy cities. For more information see: <http://r2cities.eu/>.

⁸ The project EU-GUGLE aims to demonstrate the feasibility of nearly-zero energy building renovation models in view of triggering large-scale, Europe-wide replication in smart cities and communities by 2020. The project is part of the Smart Cities and Communities Initiative of the European Commission. Eight pilot cities are involved, including Vienna (AT), Aachen (DE), Milan (IT), Sestao (ES), Tampere (FI), Bratislava (SK), Gothenburg (SE) and Gaziantep (TR). For more information see: <http://eu-gugle.eu/>.

⁹ The research project ZenN aims to reduce energy use in existing buildings and neighbourhoods. It focuses on the zero-energy building renovation process through the implementation and study of five demonstrations near Zero Energy Renovation projects at neighbourhood scale. For more information see: <http://zenn-fp7.eu/>.

etc. In addition, one of the objectives of R2CITES is the optimization of energy management systems to control demand, renewable energy sources, energy distribution systems and storage devices.

A smart city includes a range of pertinent application domains. According to the study of Neirotti et al. [62], these domains can be generally classified as “hard” or “soft”, regarding the importance of the ICTs as key enabling technologies. Hard domains refer to buildings, energy grids, natural resources, energy and water management, environment and so on, in which an improvement in sustainability relies on the deployment of ICTs for processing and integrating real-time information. While, soft domains include education, culture, policies, innovation, social inclusion and e-government, in which ICT has a more limited role and real-time information may not be necessary.

Buildings, energy grids and energy management are three main domains in smart city regarding energy use and supply [62]. The new technologies in smart cities and communities provide new potentials in energy management at different scales [6]. For this reason, smart energy city is proposed, in which sustainable and integrated application of new technologies, collaboration of multiple stakeholders, and integration of multiple urban energy domains are essential [65].

Morvaj et al. [66] provided an overview of the features and paradigms of a smart energy city in regard to smart buildings and smart grid. They proposed that in a smart energy city it is very important to increase energy efficiency, decrease total energy consumption and maintain an open and fair internal energy market. The smart grid concept and technologies must be implemented into the energy infrastructure, especially when a cluster of distributed generation is installed [7]. Smart grid is an essential component to integrate the renewable energy and/or distributed energy resources (DER). A smart grid is a two-way transmission grid for energy supply; it uses ICTs to gather and act on information in an automated way to improve efficiency, reliability, economics and sustainability of the production and distribution of energy [67]. In doing this, a smart grid enables the control and optimization of renewable energy resources and demand side management by delivering real-time information to control nodes, facilitating near-instantaneous balance of supply and demand at the level of individual consumers, such as buildings and even appliances [66]. Likewise, a smart grid that connects the distributed generation and end-users in a small scale can be considered as a microgrid, which could be islanded or networked [68].

Buildings play a major role in mitigating climate change in the short- to medium-term, which are one of the main energy end-users [69]. Therefore, when considering energy infrastructure in cities, it is essential to take into account buildings. Traditional buildings are usually energy consumers without communicating with the outside world. With the use of integrated renewable energy generation such as solar panels, buildings have the means to be self-sufficient smart prosumers [70]. Furthermore, they tend to be integrated into

smart grids and play a more active role in the grid energy management based on the optimization of demand [71]. In doing so, buildings must be upgraded to smart buildings which can communicate with its surroundings (the grid or other buildings), and building prosumers should be able to view their energy production and consumption in real time and be an active member of the demand side management [66][71][72].

Smart buildings use integrated renewable energy generation, smart meters and ICTs for energy management. The core composition to integrate the application of smart grid and smart buildings are the smart metering networks. Smart meters enable two-way communication, which record consumption of energy in intervals of an hour or less and communicate such information at least daily back to the utility for monitoring and billing [73]. Smart meters act like gateways for the communication between buildings and their surroundings, which provide more interactivity among the buildings and the utilities.

To conclude, the initiative of smart cities and communities is a solution proposed to address the urbanization issues and attain sustainability in cities. Increasing attention has been paid to promote the development of smart cities and communities; numerous projects or cases thereby have been implemented. The domains including buildings, energy grids and energy management are three critical studying areas for developing smart energy city. They include the crucial measures for reducing energy consumption, improving energy efficiency and reducing CO₂ emissions in cities.

2.2.3 Policy Drivers

As increasing environmental challenges, energy issues have repeatedly entered the agendas of policy makers in the EU under a number of different frames [74]. Europe is on its way to achieve its targets for 2020¹⁰ in terms of renewable energy increase by 20%, GHG emissions reduction by 20% and energy efficiency improvement by 20%, based on the level of 1990. Meanwhile, significant efforts are needed to meet the increasingly ambitious energy and climate change targets for 2030 and 2050 [75]. The Europe 2020 strategy and recently ratified Paris agreement are the main documents in the EU involving energy and climate policy [49].

Under the Europe 2020 strategy, broad policies have been formulated to reduce GHG emissions, improve energy efficiency and support renewable technologies. The emissions trading system (ETS)¹¹ is the EU's key tool for cutting greenhouse gas emissions from

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¹⁰ It is the target of the 2020 climate & energy package. The 2020 package is a set of binding legislation to ensure the EU meets its climate and energy targets for the year 2020. For more information see: https://ec.europa.eu/clima/policies/strategies/2020_en.

¹¹ The EU emissions trading system (ETS) is a cornerstone of the EU's policy to combat climate change and its key tool for reducing greenhouse gas emissions cost-effectively. It is the world's first major carbon market and remains the biggest one. For more information see: https://ec.europa.eu/clima/policies/ets_en.

large-scale facilities. In addition, national emission reduction targets under the "Effort-sharing decision"¹² aim to cut emissions in sectors that are not included in the ETS, such as building, agriculture, waste and transport. Member States have set binding national targets for increasing the share of renewables in energy consumption under the Renewable Energy Directive¹³. The EU supports the development of low carbon technologies through two main programmes: NER300 programme¹⁴ and Horizon 2020 programme¹⁵. Furthermore, measures and policies for increasing energy efficiency have been set out. For example, energy efficiency certificates are mandatory for the sale and rental of buildings; energy efficiency labelling is essential for the energy products such as household appliances, lighting and boilers; EU Member States should prepare National Energy Efficiency Action Plans every three years; and large companies should conduct energy audits at least every four years. In addition, the Energy Efficiency Directive¹⁶ establishes a set of binding measures to use energy more efficiently at all stages of the energy chain, from production to final consumption. Some examples of the specific measures and policies include that: energy distributors have to achieve 1.5% energy savings per year through the implementation of energy efficiency measures; the public sector should purchase energy efficient buildings, products and services; energy consumers should be empowered to better manage consumption; and efficiency levels in new energy generation capacities should be monitored.

In December 2015, the COP21 (21st Conference of the Parties) Sustainable Innovation Forum (SIF15)¹⁷ was held in Paris. Governments from different countries were determined

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¹² The Effort Sharing Decision establishes binding annual greenhouse gas emission targets for Member States for the period 2013–2020. For more information see: https://ec.europa.eu/clima/policies/effort_en.

¹³ The Renewable Energy Directive establishes an overall policy for the production and promotion of energy from renewable sources in the EU. The Directive also specifies national renewable energy targets for each country, taking into account its starting point and overall potential for renewables. For more information see: <http://ec.europa.eu/energy/en/topics/renewable-energy/renewable-energy-directive>.

¹⁴ NER 300 is one of the world's largest funding programmes for innovative low-carbon energy demonstration projects. The programme is conceived as a catalyst for the demonstration of environmentally safe carbon capture and storage (CCS) and innovative renewable energy (RES) technologies on a commercial scale. For more information see: https://ec.europa.eu/clima/policies/lowcarbon/ner300_en.

¹⁵ Horizon 2020 is the biggest EU Research and Innovation programme ever with nearly €80 billion of funding available over 7 years (2014 to 2020) – in addition to the private investment that this money will attract. It promises more breakthroughs, discoveries and world-firsts by taking great ideas from the lab to the market. For more information see: <https://ec.europa.eu/programmes/horizon2020/>.

¹⁶ The 2012 Energy Efficiency Directive establishes a set of binding measures to help the EU reach its 20% energy efficiency target by 2020. On 30 November 2016 the Commission proposed an update to the Energy Efficiency Directive, including a new 30% energy efficiency target for 2030, and measures to update the Directive to make sure the new target is met. For more information see: <https://ec.europa.eu/energy/en/topics/energy-efficiency/energy-efficiency-directive>.

¹⁷ The Sustainable Innovation Forum (SIF15) was the largest business focused event held during the annual Conference of Parties (COP) last year on 7- 8 December at COP21 at Stade de France (Gate E) in Paris. Building on year-round work from Climate Action and the UN Environment Programme, the 2-day Forum

to act to the full extent to keep the increase of global average temperature to well below 2°C compared to pre-industrial levels. Nationally determined pledges give new impetus towards a lower-carbon and more efficient energy systems [18]. Later on, the Paris agreement was ratified in October 2016, the EU and its Member States agreed on a long-term goal of keeping the temperature increase below 2°C and binding targets to decrease GHG emissions [49].

The new pledges made by the EU sets out a new target 40-27-25 for 2030 in terms of climate and energy. They aim to reduce GHG emissions by 40%, increase renewable energy by 27% and improve energy efficiency by 25%, compared to the level of 1990. The target 40-27-25 is more ambitious than the previous target 20-20-20. The aim of the EU to cut GHG emissions by at least 40% by 2030 (compared to 1990 levels) will make it one of the world's least carbon-intensive energy economies.

Regarding the building sector, the main regulations and rules that have currently been implemented for improving building energy efficiency include the Energy Performance of Buildings Directive 2010/31/EU, the Energy Efficiency Directive 2012/27/EU and the Energy Performance Certification. In addition, policies related Nearly Zero Energy Buildings (NZEB) and Zero Carbon Footprint Buildings have also been implemented, due to the increasing need to use renewable energy. According to the Energy Performance of Buildings Directive, all new buildings should be nearly zero-energy by the end of 2020, and all new public buildings must be nearly zero-energy by 2018. Despite this, each EU country has developed their own policies, financial measures and other instruments to increase the number of nearly zero-energy buildings.

The NZEB policy is anticipated to have a big potential to contribute towards the achievement of smart cities in Europe [76]. According to the European Strategic Energy Technology Plan (SET-Plan)¹⁸, at least half of the existing buildings in 25 demonstration cities are required to be transformed into nearly zero energy buildings by 2020 [76]. The European Technology and Innovation Platforms (ETIPs) were created to support the implementation of the SET Plan. One of the most important plan includes the European Innovation Partnership on Smart Cities and Communities. This encourages significantly cities to progress towards a 40% reduction of GHG emissions through the sustainable use and production of energy [76].

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convened cross-sector participants from business, Government, finance, UN, NGO and civil society to create an unparalleled opportunity to bolster business innovation and bring scale to the emerging green economy.

¹⁸ The European Strategic Energy Technology Plan (SET-Plan) aims to accelerate the development and deployment of low-carbon technologies. It seeks to improve new technologies and bring down costs by coordinating national research efforts and helping to finance projects. For more information see: <http://ec.europa.eu/energy/en/topics/technology-and-innovation/strategic-energy-technology-plan>.

2.3 ENERGY MANAGEMENT IN DISTRICTS AND BUILDINGS

Energy management is an important measure adopted to improve energy efficiency [19]. Better management of the energy generation, distribution and consumption is a key component to making cities smarter and more sustainable.

Table 1: Definition of energy management in previous literature [78]

Source	Definition
O'Callaghan and Probert [79]	Energy management applies to the supply, conversion and utilization of energy, which involves monitoring, measuring, recording, analysing, examining, controlling and redirecting energy and material flows through systems so that least power is expended to achieve worthwhile aims.
Kannan and Boie [80]	Energy management is the judicious and effective use of energy to maximize profits and to enhance competitive positions through organizational measures and optimization of energy efficiency in the process.
Association of German Engineers [77]	Energy management is the proactive, organized and systematic coordination of procurement, conversion, distribution and use of energy to meet requirements, taking into account environmental and economic objectives.
Capehart et al. [81]	Energy management is the efficient and effective use of energy to maximize profits (minimize costs) and enhance competitive positions.
German Energy Agency [82]	Energy management is the proactive and systematic coordination of procurement, conversion, distribution and use of energy within a company, aiming on continuously reducing energy consumption and related energy costs.
Abdelaziz et al. [83]	Energy management is the strategy of meeting energy demand when and where it is needed. This can be achieved by optimizing energy using systems and procedures so as to reduce energy requirements per unit of output while holding constant or reducing total costs of producing the output from these systems.
German Federal Environment Agency [84]	Energy management comprises the total of planned and executed actions in order to ensure a minimum of energy input for a predefined performance.
Ates and Durakbasa [85]	Energy management (EM) is a combination of energy efficiency activities, techniques and management of related processes which result in lower energy cost and CO ₂ emissions.

There are different definitions of energy management, as listed in Table 1. However, a common point of these definitions is that they all address the objectives of energy management in reducing energy use, improving energy efficiency and saving energy cost. According to the Association of German Engineers [77], energy management can be defined as the proactive, organized and systematic coordination of procurement, conversion, distribution and use of energy to meet requirements, taking into account environmental and economic objectives. This definition comprehensively comprises the important factors of a nowadays' energy management process. For example, an appropriate energy procurement can reduce energy cost in buildings; a better interaction between energy supply and demand

can help to achieve energy balance in districts; and an optimized energy use will help energy saving at both levels.

To implement energy management, an energy management system (EMS) is a supportive tool. According to ISO 50001 [86], an EMS should establish energy policies and energy objectives in an organization, in addition to the processes and procedures to achieve such energy objectives. An EMS usually encompasses both the organizational and informational structures and the technical tools needed to implement energy management [77]. In a narrower scope, a building energy management system (BEMS) is an integrated automation and energy management system for buildings, utilizing IT or ICT, intelligent and interoperable digital communication technologies promoting a holistic approach to controls and providing adaptive operational optimization in buildings [87].

Table 2: Aggregated dimensions in an energy management framework [78]

Dimensions	Themes	Concepts
Strategy/planning	Energy strategy and policy; Operational energy planning; Strategic energy risk management.	Strategic orientation; strategic perspective; objectives and targets; project planning; energy exposure.
Implementation /operation	Energy audit; Energy efficiency measures and activities; Investment decisions.	Energy efficiency technologies; capital budgeting; business case; payback period; non-energy benefits; energy consultants; optimization of energy procurement.
Controlling	Energy accounting; Performance measurement; Benchmarking.	Energy information system/ICT tools; key performance indicators (KPIs); monitoring; evaluation; benchmarking; decision support; metering; documentation.
Organization	Energy manager; Integration; Standardization.	Responsibilities/tasks; joint management; process descriptions/procedures.
Culture	Educating/training; Staff motivation; Internal communication.	Manpower requirement; human resources; top management involvement/support; incentives; rewards; awareness; information tools.

Schulze et al. [78] performed an excellent, systematic review of previous studies in energy management in industry and developed a comprehensive conceptual framework of energy management. Five aggregated dimensions are included in this EM framework, including strategy/planning, implementation/operation, controlling, organization and culture. Table 2 lists the five dimensions and their related themes and concepts. To establish and operate an effective energy management, each of these dimensions is indispensable. The authors

summarized that energy management should include the minimal requirements such as development of a strategic plan and objectives, development of relevant policies and procedures, implementation of energy efficiency measures, identification of key performance indicators (KPIs), monitoring and controlling of energy use, and involvement of the employees. Although the different dimensions are of equal importance, a major proportion of the current studies focus on aspects related to the implementation/operation and controlling of energy management; while, a considerable lower proportion of studies address aspects with regard to the strategy/planning, culture and organization.

2.3.1 Timeline of Energy Management

Energy management has been extensively studied for almost 40 years [20]. Figure 7 shows the number of publications in relation to energy management from 1980 to 2016. The development of energy management begins from the end of 1970s, because the first oil crisis happened in 1973, and the second global oil crisis occurred in 1979. The oil crisis marks a turning point regarding the global awareness of energy demand and thereby sets a starting point for energy management [78]. Furthermore, the publications with regard to energy management have been increasing exponentially since 2000. This is due to a full outbreak of the global energy crisis¹⁹.

Figure 7: Number of publications in relation to energy management²⁰.

In order to study the development of building energy management in different periods, a literature review of journal publications from 1980 to present has been conducted. Four main periods have been investigated, namely 1980s, 1990s, 2000s and 2010s. In each of the periods, the publications with keyword “Building Energy Management” have been searched and summarized. As a result, Table 3 lists the found research mainstream in each period and the example references.

¹⁹ For more information about energy crisis see: https://en.wikipedia.org/wiki/Energy_crisis.

²⁰ Data source from the database “ScienceDirect” through requiring the key word “Energy Management”.

Table 3: Building energy management in different periods from 1980s to 2010s

Period	Research mainstream	Related references
1980s	Improve energy efficiency of equipment and use new equipment	[88], [89], [90], [91], [92], [93]
	Computer-aided control system	[94], [95], [96], [97], [98]
1990s	Artificial intelligence; building automation; intelligent building	[99], [100], [101], [102], [103], [104]
2000s	Benchmarking; assessment; decision support model; optimization techniques	[105], [106], [107], [108], [109], [110], [111], [112]
2010s	Information model; knowledge-based energy management; advanced data analytics; smart building; district-scale energy management	[15], [32], [113], [114], [115], [116], [117], [118], [119], [120], [121], [122], [123], [124], [125], [126]

Building energy management in 1980s emphasized on improving energy efficiency of equipment and developing new equipment with higher efficiency. For example, Reay [88] considered energy management in buildings in terms of heat recovery system selection. Dubin and Arch [89] studied energy management in relation to energy conscious design and solar energy. Ramamurthy and Dutt [90] proposed that energy saving and management is essential for the new developments towards alternative energy sources such as solar energy. In addition, a limited number of studies address computer-aided control system in building energy management [94][95][96].

In 1990s, the most of studies evolved into the application of new technologies, such as artificial intelligence for building control, building automation systems and intelligent buildings. Clark and Mehta [99] and Dounis et al. [103] used artificial intelligence and networking for building management and control systems. Bushby [100] applied BACnet^{TM} – a data communication protocol for building automation and control networks. Loveday et al. [101] and Smith [102] studied energy management in intelligent buildings. In these works, the “intelligence” implies facilities management via building automation systems (BAS).

In 2000s, building energy management gradually put more focus on management issues such as benchmarking, assessment, decision-making support and optimization techniques for improving energy performance. In this period, a great deal of effort was made to find methods to optimize the energy performance in buildings. In Europe, such efforts were mainly made through the provision of the Energy Performance of Building Directive (EPBD), aiming for energy saving and CO₂ emission reduction [108]. For example, Radhi [108] proposed a systematic methodology for optimising the energy performance of buildings. Diakaki et al. [109] investigated the feasibility of multi-objective optimization

techniques in improving the energy efficiency in buildings. Djuric et al. [111] studied the optimization of energy consumption in buildings, which influences the energy and investment cost as well as the thermal comfort.

In 2010s, information system and knowledge-based management has been widely discussed in energy management. The main drivers are the rapid development of ICTs and the increasing implementation of smart building and smart grid. As a result, building energy management evolves into a smarter way and, furthermore, has the transition to be fulfilled at a larger scale such as districts and cities. Knowledge management is one of the big trends. A considerable number of publications are related to this topic. For instance, GhaffarianHoseini et al. [113] applied nD BIM Integrated Knowledge-based Building Management System (BIM-IKBMS) for inspecting post-construction energy efficiency, Fan et al. [116] used temporal knowledge discovery in big BAS data for building energy management. Data science for building energy management has been paid increasing attention. Molina-Solana et al. [32] reviewed this topic and indicated that the technology of data science is capable of analysing and exploiting building energy data in meaningful ways and increasing energy efficiency of buildings. It is a valuable tool which is capable of extracting and exploiting the knowledge and information inherent in user data.

The development of building energy management has passed through these four main eras. A summary of the development timeline is illustrated in Figure 8. The first era began to realize the importance of energy conservation in buildings; its research focus is on replacing or improving the inefficient equipment. The second era emphasized on effective use of technologies such as sensing, monitoring, control and automation. The third era began to focus on the management aspects, including the use of optimization techniques and decision support tools to improve building energy performance and the implementation of performance benchmarking and assessment. The fourth era has the trend to improve energy at the district scale; energy management has ushered into its information era. Increased data and information awareness has led to the development of new energy management methods.

Figure 8: Timeline of building energy management [127].

A new concept of Internet of Energy (IoE) was proposed in order to manage energy at a large scale [128]. IoE is a system that integrates and interfaces the power grid to the data network represented by the Internet, embracing energy generation, delivery, distribution control, metering and billing, diagnostics and energy information systems (EIS) to work seamlessly and consistently. Another field called energy informatics has also been proposed by Watson and Chen [129], in which the core idea is to collect and analyse energy data to support optimization of energy demand and supply. The role of information system in reducing energy consumption and CO₂ emissions is widely recognized. As a result, energy intelligence has also been proposed as a new concept that uses information management, cross-domain data integration and real-time processing of data streams and events to help organizations manage energy consumption more effectively [130].

2.3.2 Energy Management at the District and Building levels

Integrated energy management at the district and building scales should consider both the buildings and the district energy systems and both the energy demand and supply sides. Table 4 reviews approximately 70 works related to the main research topics in relation to building and district energy management. Generally, current energy management is implemented on three scales: (1) the individual buildings/homes; (2) the district energy systems; and (3) the district as a whole (integrated buildings and district energy systems).

Table 4: Summary of works regarding energy management at the building and district levels

Scale	Topic	Source
Individual buildings/homes	(Smart) Home energy management	[23], [131], [132], [133]
	(Smart) building energy and thermal comfort management	[19], [87], [134], [135], [136], [137], [138], [139], [140], [141]
	Building energy management based on smart grid, demand response in buildings	[142], [143], [144], [145]
	Data science for building energy management; knowledge-based energy management	[32], [146], [147], [148], [149], [150], [151]
	BIM (Building Information Modelling) for energy management	[113], [121]
District energy systems	Management for district energy systems or distributed energy resources	[152], [153], [154], [155], [156]
	Smart grid/Microgrid energy management	[31], [157], [158], [159], [160]
	Prosumer based energy management and sharing in smart grid or cooperative management for prosumers	[22], [161], [162]
	Power demand and supply management	[163], [164]
	Demand-side management in smart grids	[27], [165], [166]
	Big data and data mining in smart energy management	[167], [168]
District as a whole (integrated buildings and district energy systems)	Energy management from buildings to districts for integrated buildings and district energy systems	[8], [15], [24], [25], [123], [125], [169], [170], [171]
	Demand-side management and demand response in districts	[172], [173], [174], [175]
	District monitoring and management	[176], [177], [178], [179], [180], [181], [182], [183]
	District/city information modelling for energy management	[184], [185]

2.3.2.1 Energy management for individual homes/buildings

With the arrival of the smart grid era and the advent of advanced ICTs, smart home energy management systems (SHEMS) have been developed, usually combined with the application of demand response strategies. Liu et al. [23], Zhou et al. [132], Beaudin and Zareipour [133] and Vega et al. [131] have conducted reviews of SHEMS, highlighting their major components, functionality modules, renewable energy sources and various technological approaches. The importance of SHEMS on the intelligent use of electricity and demand response is emphasized. In the near future, the extensive use of SHEMS will

thoroughly change the way of electricity usage and renewable energy utilization in the residential houses [132].

The residential sector plays an important role in energy use, even it is always composed of small consumers. Energy management systems in most cases are equipped in larger complex buildings. A building energy management system (BEMS) should connect effectively building, systems and people, ensuring efficient operation of systems and comfort of occupants [87]. For example, Sun et al. [134] proposed an integrated management of active and passive HVAC and lighting systems for effectively reducing energy costs and improving human comfort. Hurtado et al. [136] presented an analysis framework for BEMS aiming to exploit the built environment flexibility while ensuring the minimum comfort levels required by occupants. The authors conducted a state of the art literature review of the typical energy systems in buildings (Figure 9), which are composed of five important parts: energy generation, storage systems, comfort systems, building load and measuring unit.

Figure 9: Building's energy sub-systems diagram [136].

In a smart grid context, buildings are expected to be active participants and autonomous response consumers or prosumers [70]. Park et al. [142] developed a SG-BEMS (Smart Grid Building Energy Management System) solution to reduce energy usage, costs and

carbon emissions in buildings. SG-BEMS is a combination of building energy management systems and advanced software that controls the facility in a more energy efficient way to provide demand response controls when situations within the power grid demand it. This solution has been demonstrated in a smart grid test bed, which found that a significant amount of energy cost was reduced through the management of peak load and load shift.

With the use of smart technologies, modern BEMSs offer promising flexibility for demand side management (DSM) and demand response (DR) [144]. Demand side management is the planning, implementation and monitoring of utility activities that are designed to influence customer use of electricity; while, demand response is a specific tariff or program to motivate end-use customers to respond to changes in price or availability of electricity over time by changing their normal patterns of electricity use [165]. DR programs can be roughly classified into incentive-based, price-based and demand reduction bids [186]. According to Palensky and Dietrich [187], DSM includes everything that is done on the demand side of an energy system, ranging from replacing an inefficient ventilation system with a better one up to installing a sophisticated dynamic load management or demand response control system. Demand response and demand side management offer solutions to utility operations, meanwhile, promoting more robust and intelligent building energy management. The study of Arteconi et al. [145] shows that energy costs in buildings can decrease largely using demand side management when electricity tariffs presents a considerable difference between on-peak and off-peak rates. Furthermore, DSM can be implemented in different scales, from an individual building to a cluster of buildings. However, current DSM is always “utility driven”; it might move a bit towards a “customer driven” activity in the near future [187].

Demand response (DR) is implemented in buildings that connects the building energy system with the utility grid. DR is a means by which a building can participate actively in the grid energy system and make a profit through optimizing its energy consumption, meanwhile achieving the overall targets of energy efficiency and emission reduction [188]. Previous studies indicate that DR can help achieving 20-50% peak clipping and 10-15% reduction of overall consumption [189].

ICT is a key enabling technology for building energy management. With the use of ICTs, a huge amount of data involved in building processes can be accurately monitored, collected and stored. In order to analyse and exploit such data in meaningful ways for decision making and energy performance improvement, there is a new trend to use data science and knowledge discovery for building energy management. Molina-Solana et al. [32] reviewed the application of data science techniques in the field of building energy management. Data science techniques have been currently used to address the following problems: (1) predicting the energy demand and consumption of a building; (2) optimizing building operation; (3) enabling building retrofitting; (3) verifying the operational status and failures of building equipment and networks; (4) analysing the economic and

commercial impact of energy consumption; and (5) detecting and preventing energy fraud. However, challenges are encountered to develop solutions for the management of huge amounts of heterogeneous data in real time and the ways to deal with their associated uncertainty.

In order to improve building energy data management, Cavalheiro and Carreira [146] developed a high-quality reusable multidimensional data model that can be applied to create or improve the data model designs of building energy management systems. Ahmed et al. [151] proposed a multi-dimensional building performance data management for continuous commissioning. Tomašević et al. [149] developed an ontology-based facility data model for energy management under the contemporary Semantic Web paradigm.

Data mining techniques for knowledge discovery is another field with increasing attention and interests, Wijayasekara et al. [147] proposed a Fuzzy Anomaly Detection and Linguistic Descriptions (Fuzzy-ADLD)-based method for mining building energy management system data, in order to identify the suboptimal behaviours for the performance of BEMS. Gao et al. [148] used data mining techniques to predict comfort levels in buildings and to optimize the energy performance of building energy systems. In addition, Wicaksono et al. [150] proposed a knowledge-based intelligent energy management system that can help occupants to monitor and control their energy consumption and to notice their energy saving potentials. The method of knowledge-driven energy analysis offers a more intelligent mechanism as an improvement of classical data-driven analysis.

GhaffarianHoseini et al. [113] reviewed 96 papers and suggested application of an nD BIM Integrated Knowledge-based Building Management System (BIM-IKBMS) for inspecting post construction energy efficiency in order to advance the successful implementation of sustainable building performances. Energy management in buildings should usually consider design specifications. The advent of BIM (Building Information Model) provides a systematic process of the management and dissemination of holistic information generated throughout the whole life cycle of buildings. The potential for using BIM as a tool to support the visualisation and management of a building's performance has been evaluated by Gerrish et al. [121].

2.3.2.2 Energy management for district energy systems

There is a profound revolution and transition of energy management from conventional centralized infrastructures towards distributed energy systems and autonomous responsive demand, due to the use of advanced metering infrastructure (AMI) and distributed energy technologies [132]. A system approach which views generation and associated loads as a subsystem or a “microgrid (MG)” is a better way to realize the emerging potential of distributed generation. A microgrid allows for local control of distributed generation

thereby reducing or eliminating the need for central dispatch [68]; it can be considered as a smart grid on small scale, which can be stand-alone or grid-connected [158].

A systematic review of microgrid energy management is conducted by Meng et al. [157]. Figure 10 shows the infrastructure of a microgrid, which includes RESs (Renewable Energy Sources), ESSs (Energy Storage Systems), conventional energy sources, distributed loads and a central EMS/MGCC (Microgrid Central Controllers). Centralized microgrid management usually requires data collection from both MG components and external grid; scheduling and optimization procedures are executed to achieve economic and efficient operation based on the gathered information. While, decentralized management usually uses decentralized control and information exchange to achieve more flexible operation and avoid single points of failure. Decentralized management systems such as multi-agent systems have indeed become a prominent research direction. They can have the same hierarchy and functions as centralized ones, but transferring the decision-making authority to local side. This is especially useful when the size of microgrid is large and/or the energy resources are owned by different entities who have their own operation goals.

Figure 10: Microgrid infrastructure [157].

Microgrid energy management is an active field of research. It is complicated due to the inherent system uncertainty in energy demand, renewable generation and energy prices. Such energy management urgently requires the implementation of predictive control and demand response measures to match fluctuating demand with fluctuating supply from renewable energy sources [15]. Parisio et al. [190] proposed a novel MPC (model predictive control)-based EMS for residential microgrids to optimally manage and coordinate energy supply and demand in multiple houses, taking user preferences and user comfort into account. Pascual et al. [191] developed an energy management strategy for a renewable-based residential microgrid with generation and demand forecasting.

A principle task of power demand and supply management in microgrids is to maintain a balance between power generation and consumption at the minimum cost. In order to tackle the management challenges triggered by the high fluctuation of renewable energies, Wang et al. [163] proposed a power demand and supply management scheme, which includes an uncertainty model to capture the randomness of renewable energy generation and a two-stage optimization approach to determine the optimal power consumption and generation scheduling for minimizing the fuel cost. Yu and Hong [164] used a Stackelberg game approach and proposed a price-based demand-response model for electricity trading between one utility company and multiple users, aiming at balancing supply and demand and smoothing the aggregated load in the system.

Demand side management (DSM) is an important solution adopted by utility operators to improve the performance of supply side. The main objective of demand side management is to encourage users to consume less power during peak times or to shift energy use to off-peak hours so as to flatten the demand curve. Gelazanskas and Gamage [165] have conducted an excellent review of demand side management in smart grid, focused on the drivers and benefits, shiftable load scheduling methods and peak shaving techniques. Figure 11 shows the basic load shaping techniques of demand side management, including peak clipping²¹, valley filling²², load shifting²³, strategic conservation²⁴, strategic load growth²⁵ and flexible load shape²⁶. In order to facilitate energy users to change their power consumption to benefit the whole system, the authors also proposed a novel electricity demand control technique using real-time pricing to balance demand side with supply side more effectively, reduce peak demand and make the whole system more efficient.

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²¹ Peak clipping includes the reduction of system's peak load by using time-based rate options or incentive-based strategies. It can help to reduce the peaking capacity and reduce operating cost.

²² Valley filling encompasses building off-peak loads, especially when the long-run incremental cost is less than the average price of energy.

²³ Load shifting involves shifting load from on-peak to off-peak periods, using measures such as storage and customer load shifts.

²⁴ Strategic conservation, which comprises the reduction in consumption as well as a change in the pattern of use by using energy conservation measures and efficiency improvement measures.

²⁵ Strategic load growth, which refers to a general increase in sales beyond the valley filling mentioned previously, using emerging technologies such as electric vehicles (EV).

²⁶ Flexible load shape, which involves a variety of interruptible or curtailable load, integrated energy management systems, or individual customer load control.

Figure 11: Basic load shaping techniques of demand side management [165][192].

Prosumers are important elements of smart grid or microgrid. They play a vital role in peak demand management and are important stakeholders of smart grids [161]. A prosumer produces and consumes energy and can share surplus energy with grid and other energy end users. As a result, cooperative management for prosumers within a smart grid is an important aspect to integrate and balance electric supply and demand. Zafar et al. [161] conducted a comprehensive review of the prosumer based energy management and sharing (PEMS) in smart grid environment. The process of energy sharing among prosumers involves two key elements: ICTs and optimization techniques. The authors surveyed the PEMS schemes in previous studies, such as the energy sharing model among prosumer communities developed by Ciuciu et al. [193] and the extended DSM strategies using IoT principles introduced by Monnier [194]. Rathnayaka et al. [22] analysed the prosumer management schemes used by existing approaches. The authors identified several open research issues related to PEMS, such as the lack of approaches to share energy between prosumers and consumers and the lack of methods to group prosumers.

Using energy management systems with the continuous application of sensors, wireless transmission, network communication and cloud computing technologies, large amount data are expected to be generated and accumulated. In order to fulfil the potential of energy big data and obtain insights to achieve smart energy management, Zhou et al. [167] presented a comprehensive study and proposed a process model of big data driven smart energy management. Four major aspects are discussed, namely power generation side management, microgrid and renewable energy management, asset management and collaborative operation, as well as demand side management. Several challenges encountered in implementing big data driven smart energy management are summarized, including the update of IT infrastructure, the data collection and governance, the data integration and sharing, the data processing and analysis, the security and privacy, etc. The authors indicated that there are still many barriers on the integration and sharing of energy big data from various sources in order to enable big data driven smart energy management. One of the barriers is the data interoperability, since different energy companies or

organizations usually adopt different data definition, storage, and management standards and models. Another barrier is a lack of accessibility to the distributed data sources.

2.3.2.3 Energy management for integrated buildings and district energy systems

Due to the complexity and decentralisation of the energy infrastructure, as well as the growing penetration of renewable generation and proliferation of energy prosumers, the way in which energy consumption in buildings is managed must change [15]. Building energy management needs to be considered in a wider district-level energy landscape, in order to enable an integrated energy management of electric supply and demand in houses and buildings [8].

The districts or neighbourhoods in cities have the trend to be more autonomous and able to manage more efficiently and dynamically their energy by taking into consideration local resources, prosumption and needs of their stakeholders. Different energy actors should be able to interact with each other and take advantage of its optimal resource usage [27]. The diverse distributed energy resources in energy distribution networks requires energy management at a district scale for the purpose of integrating energy supply and usage [7].

The integrated energy management for building energy supply and demand at a district scale should consider various aspects, ranging from the microgrid and virtual power plant, via the aggregation of buildings to the individual buildings [23]. Figure 12 shows the scope of integrated energy management at the district scale. A virtual power plant (VPP) is usually composed of a number of DERs of various technologies with various operating patterns and availability [195].

Figure 12: Scope of district-scale energy management [23].

An energy district should consider a well-integrated structure of buildings and systems. The integrated energy management can facilitate the synergies between buildings and district energy systems for achieving higher energy performance at both district and building levels [7]. For example, the buildings can better monitor and manage their energy consumption, while the district utilities can gain more flexible mechanisms for power demand and supply management [24].

There are various studies about the energy management at a district scale, considering integrated buildings and the district energy systems. Reynolds et al. [15] reviewed a wide breadth of research papers on the topic of building energy management at both building and district level and proposed a Computational Urban Sustainability Platform (CUSP) framework which aims to implement advanced building and district energy management. This platform is enabled by cloud-based demand-response strategies through advanced data analytics and optimisation, underpinned by semantic data models. The authors argued that managing energy resources at a district level could provide greater flexibility, energy and cost savings to all users. Buildings of different uses could mutually benefit from each other, thus to be better managed in a ‘microgrid’ setting. Both single buildings and clusters of buildings could participate in grid demand response events.

Depending on the types of devices and facilities connected to the microgrid, Stluka et al. [24] proposed that energy management of microgrids should cover the following aspects:

- **Supply side optimization**, which aims to dispatch and optimize energy supplies in order to meet demand-side loads;
- **Integration of renewable generation sources**, which targets to balance different forms of energy sources, such as renewables, conventional sources and direct imports from the main grid;
- **Optimal use of energy storage**, which aims to improve the balance between energy generation and consumption by temporarily storing the surplus energy;
- **Demand side optimization**, which includes reducing or rescheduling the demand and optimizing the control of building energy systems such as HVAC; and
- **Optimal operation of the microgrid as a whole**, which can be achieved by optimizing both supply and demand sides simultaneously.

Full integration of supply side and demand side is a main direction; however, it also brings new challenges in terms of the complexity of the optimization of energy performance at different levels [24]. Many of the previous studies of energy management at district scale focus on the supply side. However, it is now the demand side that should receive increasing attention by research and industry [187]. Demand side management and demand response are important means by which to bring together supply side and demand side, facilitating the interaction between utilities and buildings with consumers/prosumers’ participation [27]. DSM, on the one hand, involves measures to reduce or reschedule energy demand by end-users; on the other hand, provides a stronger interaction between energy demand and supply to reduce peak load in response to real-time energy prices or financial incentives [7].

Palensky and Dietrich [187] categorized DSM into four types depending on the timing and the impact of the applied measures on the customer process. The four categories are the following:

- Energy efficiency. It refers to improve energy efficiency of buildings by using measures such as equipment replacement, system performance improvement and better envelop insulation, which result in permanent energy and emissions saving.
- Time of Use (TOU) price. It means that a change in a supply contract/tariff helps the customers (re)arrange their processes to minimize costs and emissions.
- Demand response (DR). Market DR involves real-time pricing, price signals and incentives; while, physical DR includes grid management and emergency signals which sends out binding requests for demand management if the grid is in a reduced performance.
- Spinning reserve. It means the primary (active power output depends on frequency) and secondary (restoring frequency and grid state with additional active power) control.

According to Gellings and Parmenter [192], the end-use sectors for demand side management include three main categories: residential, commercial and industrial, among which residential building is a major contributor to the energy balance. For the end-users, usually four actions can be taken [165]:

- Reducing load only during critical peak time and maintain normal load pattern during off-peak time;
- Offsetting electricity use from peak to off-peak time responding to high electricity prices or low availability;
- Using on site generation to reduce the demand seen by the utility;
- Reducing site energy use by improving energy efficiency of buildings and systems.

Energy management at the district scale is an ongoing societal priority for the realization of sustainable and smart cities. Calvillo et al. [178] conducted a review of energy management and planning in smart cities. Energy-related work on planning and operation models were studied by classifying their scope into five main intervention areas: generation, storage, infrastructure, facilities and transport. The authors also reviewed the complex urban energy models that integrate more than one intervention area and proposed a methodology for developing an improved energy model in the smart-city context. In addition, Malliotakis and Founti [176] presented the energy balance and primary energy consumption of a pertinent innovative energy management for districts with buildings coupled by thermal and electric microgrids. Mital et al. [179] proposed a cloud-based smart community management and control system, which is a flexible platform to manage and control the affairs of a condominium or society with thorough participation, visibility and transparency from a multiple stakeholder perspective.

Using district information modelling and city information modelling for energy management is a current new trend. Ronzino et al. [184] used integrated modelling for

energy efficiency management at urban scale, focusing on interoperability between Building Information Models (BIM), GIS (Geographic Information System) models and Energy Analysis Models (EAM) for designing Renewable Energy Strategies (RES) among the demonstrator. A District Information Model (DIM) is created in order to make a whole series of data concerning the energy efficiency at district level usable for various stakeholders. Furthermore, Schiefelbein et al. [185] developed a city information model (CIM) with focus on buildings and energy systems. The model includes different building and energy system types plus geometry, building physics and occupant information. Its structure has been implemented on a PostgreSQL database, which has been linked to a geographic information system (GIS) to enable graphical data analysis and modification.

Large-scale data management and analysis remains a key challenge for integrated energy management [196]. In order to manage and control the complex, integrated homes/buildings and district energy systems, semantic representation of the district energy landscape which aims to link information and characteristics from various heterogeneous and multi-domain data sources is one of the research directions [15]. Semantic web technology provides the tool to enable the exchange of data between different data models and systems. Semantic-based modelling could provide the link among the building information, the real-time operational data collected by sensors and the physical components and characteristics of buildings and energy systems.

2.3.3 Stakeholders' Engagement in Energy Management

Integrated energy management is a process that requires the interaction between both smart grid stakeholders and building stakeholders [27]. The engagement of stakeholders is key to the successful implementation of demand side management and demand response [27]. In addition, the stakeholders such as utility companies, technology vendors, consumers and producers (or prosumers) must all engage in order to support the implementation of any energy sharing programs [161]. The distributed energy and information sources usually belong to different actors in districts and buildings. In order to enable the exchange of energy and information sources, stakeholders' engagement is of the utmost importance, which is a prerequisite to promoting integrated energy management at the district and building levels.

To develop an engagement strategy for district energy, normally five major steps are involved [29], as shown in Figure 13. Stakeholder engagement is not a one size fits all exercise; thus, the first step is to understand the context in which engagement is being undertaken. Afterwards, the second step is to identify stakeholders and analyse the nature of stakeholders' interests, goals and motivations, potential concerns and level of importance. The determination of the key messages or information that should be exchanged among the stakeholders is the third step. There are a range of engagement methods; while, the selection of specific engagement channels depends on the aims to inform, consult, involve,

collaborate and/or empower stakeholders. Finally, an integrated implementation plan should be created for stakeholder engagement.

Figure 13: Major steps for developing an engagement strategy for district energy [29].

In order to develop an effective engagement mechanism among stakeholders in integrated energy management, the identification and analysis of stakeholders is a great challenge. Due to the complexity of energy management, hundreds to thousands of different stakeholders may be involved. Furthermore, different practical cases always have different potential stakeholders, due to their specific energy performance concerns. In order to manage this complexity, a holistic method by which to analyse the stakeholders and identify the key stakeholders in the energy management context is critical.

The concept of the stakeholder was initially introduced into the management discipline in 1984 [197]. Stakeholders can be defined as persons or groups who are directly or indirectly affected by a project, as well as those who may have interests in a project and/or the ability to influence its outcome, positively or negatively [198]. The role of stakeholders in collaborative decision-making is gaining increasing attention. It is necessary to balance the interests of various stakeholders in order to create value sustainably and ethically [28]. However, although the importance of stakeholders for the success implementation of a project is indisputable, there have been very few studies conducted in regard to the identification of stakeholders in energy management. The most common means by which to identify stakeholders in the energy field is through the study of similar projects. In most cases, stakeholders are chosen without carrying out a detailed analysis [29][199].

A literature review in relation to current practices for stakeholder identification and analysis has been conducted. It has been found that the current studies about stakeholder identification and analysis usually focus on disciplines such as business management, political science, development studies, project management and environment and natural resource management (ENRM).

Table 5 summarizes the work about stakeholder identification and analysis in different disciplines.

Table 5: Literature about stakeholder identification and analysis in different disciplines

Discipline	Literatures	Topic

Business management	Mitchell et al. [200]	A theory of three relationship attributes (i.e., power, legitimacy and urgency) for stakeholder identification and salience
Requirements engineering	Sharp et al. [201]	An approach to identify the stakeholders involved in requirements engineering processes
Computer system	MacCaulay [202]	Four categories of stakeholders in relation to computer systems
Environmental and natural resources management (ENRM)	Colvin et al. [203]; Billgren and Holmen [204]; Reed et al. [205]	A survey or review of the methods for stakeholder identification in ENRM
Operational Research	Gooyert et al. [28]; Ranängen [206]	A review of the role of stakeholders in operational research; stakeholder management in operational strategies and interactions
Construction project	Yan Mok et al. [207]; Oppong et al. [208]	Stakeholder management in construction projects
Energy infrastructure project	Cuppen et al. [209]	Stakeholder engagement in large-scale energy infrastructure projects
Energy planning	Gustafsson et al. [210]; Ouhajjou et al. [211]	Stakeholder participation in local strategic energy planning; stakeholder-oriented energy planning support in cities
Energy prosumer as a stakeholder	Olkkonen et al. [212]	The role of the energy prosumer as a new type of stakeholder
Energy supply chain management	Gold [213]; Chien and Shih [214]	Stakeholder identification in energy supply chain management
District and building energy retrofitting	Barbano [199]; Shao et al. [215]; Torrens et al. [216]; Mosgaard et al. [217]	Identification and list of stakeholders involved in the retrofitting processes
District energy system	Natural Resources Canada [29]	Development of local stakeholder engagement strategies when considering district energy systems
Districts' energy hub systems	Sepponen and Heimonen [218]	Analysis of stakeholders with varying business ideas for optimal energy services

Business management is the research field where stakeholder theory initially emerged. Mitchell et al. [200] proposed a well-known theory of three relationship attributes (i.e., power to influence the organisation, legitimacy of the relationship towards the organisation and urgency of the claim) for stakeholder identification and salience in the business context. However, there are also other studies addressing different methods in different fields. For example, Sharp et al. [201] developed an approach to identify the stakeholders involved in requirements engineering processes. MacCaulay [202] identified four categories of stakeholders in relation to computer systems, including 1) those who design and develop the system, 2) those who have a financial interest, 3) those who introduce and maintain the system and 4) those who are interested in using the system. In addition, operational research

is also a field with growing attention in stakeholders, since it is in nature a collaborative discipline that deals with the application of advanced analytical methods to help make better decisions [28]. Furthermore, Colvin et al. [203] and Reed et al. [205] conducted a review of the current approaches to stakeholder identification in ENRM (Table 6).

Table 6: Common approaches to stakeholder identification and analysis in ENRM [203][205]

Approaches	Description
Geographical footprint	Through constructing a footprint of project impact, all individuals within that footprint are considered to be stakeholders.
Interests	Based on the interests triggered by a given issue (e.g., financial, lifestyle, sense of place, moral).
Influence	Involves analysis or brainstorming of all who may be able to influence the issue or project.
Intuition	Includes the use of tacit skills and understanding of the social dimension of the issues.
Key informants and snowballing	Individuals from initial stakeholder categories are interviewed, identifying new stakeholder categories and contacts.
Past experiences	It identifies stakeholders using reflection by the participants on their past experiences.
Stakeholder self-selection	Stakeholders can self-select for engagement in projects or issues of concern.
Focus group	A small group brainstorms stakeholders, their interests, influence and other attributes.
Semi-structured interviews	Uses interviews with a cross-section of stakeholders to check/supplement focus group data.
Social network analysis (SNA)	Uses structured interview/questionnaire to identify the network of stakeholders.
Knowledge mapping	Identifies stakeholders who are particularly knowledgeable about a specific issue and determines how their knowledge is being used and by whom.
Q methodology	Stakeholders sort statements drawn from a concourse according to how much they agree with them.

Although there are different methods developed for stakeholder analysis in different disciplines, there is little information regarding how, when and why these methods are effective [205][219]. For example, the approaches of interests or influence usually involve a wide range of stakeholders, especially when applied to a project at a large scale. This undoubtedly increases the difficulty for stakeholder analysis and engagement, particularly when aiming to achieve a win-win situation. In addition, the methods of intuition and past experiences are predominantly subjective and depend greatly on practitioners' knowledge levels and partial opinions. Furthermore, commonly used techniques such as brainstorming,

mind-mapping, generic stakeholder lists and studies of similar projects usually contain stochastic processes for stakeholder identification [220]. Given that some stakeholders are likely to be ignored, the list of identified stakeholders cannot be considered complete. Likewise, the methods mentioned above are all qualitative; a quantitative method by which to analyse and prioritize the stakeholders has not been addressed.

There is also an increasing number of studies related to stakeholders' involvement in energy fields such as energy supply chain, energy retrofitting and energy planning. However, a common ground of the current studies in such fields is that they only present generic lists of stakeholders without addressing the method used to identify and analyse the stakeholders [218][216][217][212].

The importance of stakeholders has been attracting growing interests and attention in the energy field. Stakeholder analysis and engagement are crucial to energy management as the complexity of energy operations at the district and building scales involves numerous actors. The implementation processes of energy management should take different types of stakeholders' views and needs into consideration [30]. However, the present focus of energy managers is usually technical in nature and includes specification of monitoring and control systems along with energy optimization techniques [30]. Although stakeholders are crucially important for successful implementations of energy management, it has been found that studies on stakeholder analysis in energy management are very limited. Specifically, there is a lack of structured, well-functioning methods that can identify and prioritize stakeholders in the energy management context.

2.3.4 Information-driven Process in Integrated Energy Management

The use and sharing of distributed local information is a prerequisite to implement energy management at the district and building levels for integrated buildings and district energy systems. The ability of different stakeholders to share the information enables coordination among different energy performance needs and goals. Furthermore, through the exchange of relevant information, the operation of buildings and energy systems can be dynamically influenced to improve energy efficiency.

Related information in relation to energy performance at different levels usually comes from different domains, while its integration is key to facilitate joint energy management at district and building levels, and from supply side to demand side [31]. Different islands of information should be accessible and integrated to improve the information flow throughout the organization.

Therefore, a literature review has been conducted to find out the various information and data domains in relation to integrated energy management at district and building levels. Table 7 summarizes the various information domains involved in current work, including their frequency. As can be seen, there are in total 14 domains identified which include

information that is crucial for energy performance at the district and building levels. Such domains include: weather, location, device status, energy customer, energy pricing, energy billing/cost, building, energy, resource, sensor/meter, occupancy, comfort, user behaviour and scheduling. Among them, the domains with more attention are weather, building, energy and sensor/meter.

Table 7: Information domains pertaining to integrated energy management

Information domain	Frequency	Sources
Weather	10	[221], [222], [223], [190], [216], [224], [37], [167], [225], [36]
Location	5	[31], [151], [185], [167], [225],
Device status	4	[32], [37], [167], [36]
Energy customer	2	[221], [226]
Energy pricing	3	[227], [167], [226]
Energy billing/cost	6	[222], [151], [225], [36], [228], [226]
Building (geometrics and physics)	13	[144], [221], [222], [223], [216], [151], [224], [185], [37], [225], [229], [36], [228]
Energy (generation, storage, distribution, consumption, etc.)	13	[144], [227], [129], [31], [223], [216], [224], [32], [37], [167], [225], [147], [226]
Resource	4	[223], [224], [167], [228]
Sensor/meter	12	[221], [129], [31], [216], [151], [224], [167], [229], [36], [228], [147], [226]
Occupancy	6	[144], [222], [223], [216], [36], [119]
Comfort	6	[144], [223], [151], [224], [32], [37]
User behaviour	6	[230], [222], [223], [224], [32], [167]
Scheduling	7	[221], [227], [222], [223], [216], [36], [228]

It is widely-known that weather conditions affect energy production and building energy use [222]. Weather data usually includes historical, current and forecast information about different environmental parameters such as temperature, humidity, precipitation, solar radiation, cloud cover and wind speed [221]. Among which temperature and humidity affect significantly the use of heating, ventilation and air conditioning; while, solar radiation, cloud cover and wind speed influence directly power generation by solar and wind renewables. The weather data can be correlated with consumption and/or generation data, thus helping visualize weather-sensitive electricity or fossil fuel consumption and generation [36]. For district energy systems, the weather data is also important in enhancing system reliability and stability [167]. In addition, weather forecast data supports optimal decision on energy dispatch, storage schedule and demand response policies [190].

Location is decisive for the weather conditions, which also helps to position the buildings and/or systems, as well as the operation problems, so as to improve energy performance. Location data is also known as geospatial data. Sometimes GIS (Geographic Information System) are used to capture, store, manipulate, analyse, manage and present the geographic data. GIS can not only describe the geographic features of a certain region but also include spatial and attribute data. Schiefelbein et al. [185] linked GIS to relational databases in order to combine entity location and further object data. Through using the GIS, electrical networks and geographical locations can be correlated to provide important decision support for energy systems [231]. Furthermore, GIS enables the analysis not only at a building scale but also at a higher district level [225]. As a result, location data can work as an infrastructure platform of energy saving services and applications in order to support smart energy management [167].

Device status data and outage data are crucial for the operation of buildings and energy systems. Device status data is a common type of operational data collected in building energy management systems or distribution management systems, which helps the fault detection in equipment [37].

Energy customer information usually comes from Customer Information Systems (CIS) of the energy utility, which describe the customers in an utility's service area and their address, billing records and service requests [221]. Since energy customers in a smart grid context are transferred into active users of electricity (also related information), the integration of energy customer information will help implement demand response programs. The response of customers to variable pricing schemas (dynamic pricing or time-of-use tariff) plays an important role in demand side management. Dynamic pricing, also known as variable pricing or real-time pricing, can guide the user's energy consumption behaviours and improve the reliability of power systems [167]. Variable pricing schemes in combination with building energy management systems incentivize customers to reschedule their energy consumption to reduce it during peak times and to increase it in periods with low demand [227]. Energy users can manage their consumption wisely based on variable pricing and increase energy efficiency [226].

Energy billing or energy cost are directly influenced by energy pricing. Through checking energy billing information, energy customers or consumers can obtain an overview of their energy consumption and understand the basic energy performance [36]. Furthermore, if energy consumers can compare the energy billing information with their neighbours or national average, they can find their energy performance problems more easily so as to take measures to improve it and reduce the energy cost [226]. Energy cost data includes the running cost and the investment cost, which respectively refer to the cost of the consumed energy and energy-related operation and maintenance and the cost of new construction or refurbishment interventions on the existing building stock, linked to both the building envelope and to the technical building systems [225].

Building static data is also especially important for understanding the energy performance of a building and operating efficiently the building. It contains information about architecture and building physics [223]. A building holds a multitude of parameters. Elementary building parameters include building type (e.g., residential, public and commercial), year of construction, number of floors, floor height and net floor area; building geometric parameters comprise dimensions of building elements such as walls, windows, roofs and floors; and building physical parameters include the building material properties such as specific heat capacity, density, heat transition coefficient and U-value [185]. In a district, there are a plurality of heterogeneous buildings. Therefore, the collection of building data not only in a single building but also at a district level can help energy performance analysis at both individual building and district scales [185]. The current trend to use BIM (Building Information Model) provides a solution to effectively capture and maintain building information. Significant benefits can accrue in projects through using BIM to enable the interoperability among processes such as design, construction and maintenance. Operational BIM that connects the static repository of information to performance and environment information could lead to greater benefits for energy managers [228].

Energy and resource information is a main type of information collected in energy management systems which enables energy operation and optimization. Energy information refers to energy quantities of generation, storage, distribution and consumption, as well as energy forecast [225]; while, resource information involves the available data of energy facilities and their characteristics [223]. A high-level granularity of energy data will enable to develop information systems for improving energy performance and reducing energy consumption [129]. Resource information is associated with energy information. The energy resources are those appliances which either consume, produce, store or deliver energy.

Sensor and meter data include all of the observed information collected from electric meters and sensors, including also the type of sensor and/or meter used, their location, data frequency, observed customer or equipment and observation time period. The meter data is usually collected by AMI (Advanced Metering Infrastructure) in a smart grid and stored by the Meter Data Management (MDM) systems of the utility [221]. Meanwhile, sensor data is normally collected by a sensor network with wired or wireless technologies, which provides information for the optimization and management of the energy flow [129]. In a single building, the number and placement of sensors and meters are also crucial for building performance monitoring and analysis. Sensors can measure parameters such as temperature, pressure, flow rate and power [36]. The metered and sensed data support discovering previously unknown building performance characteristics, relationships, dependencies or trends [151]. However, sensor or meter data standalone are mostly mere numerical values; the related contextual information should be added and integrated in

order to discover meaningful knowledge from the large amount of data. Contextual information means situational data of each sensor including the place and relationship with the object on which the sensor or meter is installed [229].

In addition, the occupancy level is also one of the decisive factors of energy requirements in a building [144]. A range of occupancy factors can result in various impacts on energy use. Typical occupant data includes occupants' number, density, gender, age, income level, activity level and so on. Such factors also influence occupant behaviour. The occupants are primarily interested in their own comfort at their location (room/zone) [151]. Thus, occupant satisfaction in a building depends largely on the comfort levels. To gather data on comfort issues such as temperature, humidity, air quality, acoustics and lighting, occupant surveys or sensors can be used [36]. Thermal comfort and air quality in a building are related to the use of heating, ventilation and air conditioning (HVAC) systems. A significant percentage of building energy use is driven by occupant behaviours due to their needs in thermal comfort, air quality and lighting comfort [222]. Hong and Turner [230] proposed a framework to describe occupant behaviours in order to achieve low energy buildings. A better understanding of the potential impacts of occupant behaviour can not only help buildings perform better [222], but also improve utility operations [167].

Scheduling data can apply to both people and facilities [221]. An appropriate occupant schedule helps reducing peak demand and saving energy cost. In a smart energy management system, an optimal operational scheduling for energy components such as customer demand, local generation, storage devices and grid connection can contribute to grid balancing and guarantee high energy efficiency of local energy systems [227]. Furthermore, a maintenance schedule can track equipment and system changes over time and indicate when routine maintenance or equipment replacements are necessary to maintain optimal performance [36].

To conclude, Figure 14 shows the main information domains involved in integrated energy management at district and building levels. The data from the various information domains are usually not standalone. They are closely related to the energy operation of buildings and district energy systems and usually have a direct/indirect relationship with or influence on each other [37]. It is essential to integrate and share the cross-domain data in order to facilitate the data exploitation and knowledge discovery. Energy managers should identify and use the implicit or explicit associations (i.e., connections or relationships) and correlations between the multi-domain data in order to benefit the data and develop energy efficient measures for both buildings and energy systems [37].

Figure 14: Main information domains regarding integrated energy management at district and building levels.

However, with the multiple domains involved and the upward trends to use advanced ICTs, an incredible amount of energy-related data could be generated. The growth of data tends to be exponential due to the high velocity, volume and variety of data generation. Although discovery and exploitation of the information hidden within the collected data is extremely useful because of the economic and environmental benefits, energy managers find themselves drowning in a big data ocean [32]. Both opportunities and challenges exist in order to make sense of such big amount of cross-domain data [33].

2.3.4.1 Opportunities in cross-domain data

The big amount of cross-domain data provides new analysis possibilities for energy performance at different levels, which support data driven decision-making for energy efficient measures. Data driven analysis can be conducted based on the collected data by performing query, calculation or visualization. New knowledge can be drawn from reuse and analysis of the historical and/or real-time data. Through exploiting the data, energy managers are gaining insights for potential energy performance improvement to identify energy saving opportunities, energy efficiency problems and enable better energy operation [232].

Given that extensive benefits could be provided by analysing and exploiting the big amount of cross-domain data, various practical experiments were conducted in previous studies using data driven solutions for energy management. For example, Fan et al. [116] presented temporal knowledge discovery in big BAS (Building Automation System) data for building energy management, which helps identifying dynamics, patterns and anomalies in building operations, derive temporal association rules within and between subsystems, assess building system performance and spot opportunities in energy conservation. Capozzoli et

al. [119] used data analytics for occupancy pattern learning to reduce the energy consumption of HVAC systems in office buildings. Kontokosta and Tull [124] proposed a data-driven predictive model of city-scale energy use in buildings. Wijayasekara et al. [147] used data mining for building energy management systems (BEMS) in order to improve the state-awareness for suboptimal behaviours in the BEMS. Gao et al. [148] adopted data mining in optimisation of building energy consumption and thermal comfort management. Moreover, Molina-Solana et al. [32] and Zhou et al. [167] respectively reviewed data science for building energy management and big data driven solutions for smart energy management.

The practical benefits through analysing and exploiting the big amount of cross-domain data at the district and building levels include mainly the following:

- effective and efficient decision support for stakeholders;
- energy efficiency improvement and new business opportunities (energy cost saving);
- discovery of new energy trends and patterns;
- improvement of accuracy and efficiency in renewable generation forecasting based on the massive weather data;
- improvement of accuracy in energy demand prediction;
- optimal site selection of renewable generation;
- efficiency improvement for asset management and collaborative operation by integrating and sharing production, operation, marketing and management data;
- optimal allocation of resources and its utilization;
- discovery of valuable knowledge from the massive electricity consumption data for supporting demand side decision-making;
- enhancement of energy awareness and understanding of energy behaviours;
- enabling building retrofitting through examining the relations between energy loads, real consumption and different building components (e.g., walls, windows, doors, lighting, heating, cooling, and ventilation);
- verification of operational status and failures of building equipment and networks;
- analysis of economic and commercial impact of user energy consumption;
- energy fraud detection and prevention.

2.3.4.2 Challenges in cross-domain data

Although the expansion of data presents multitude opportunities for improving energy performance in energy management, there are still great challenges in how to make sense of it. The massive amount of energy-related data is meaningless unless valuable knowledge that supports effective and efficient decision-making throughout the energy management process can be discovered [167]. However, the complexity of energy management systems

in districts and buildings, the huge amount of data generated and the multiple interrelationships between cross-domain data all increase the difficulties in data exploitation and knowledge discovery [147].

According to the study of Zhou et al. [167], some of the primary challenges in using energy big data, as well as other energy-related data from different domains, are concluded the following: (1) how to effectively collect, store and manage the data; (2) how to efficiently analyse and mine the data; (3) how to use the data to support more effective and efficient decision-making; (4) how to get insights and obtain values from the data; (5) how to effectively prevent risks and protect privacy while utilizing the data; and (6) how to efficiently integrate and exchange the data with other domains.

The collection, storage and management of data is influenced by the information technology infrastructure. Although technologies are available for collecting, storing and managing a big amount of data, the value covered by such data is usually sparse. It is essential to extract the valuable data and select the relevant information in order to support more effective and efficient decision-making. The insights and values obtained from the big amount of data should underpin the actual performance concerns of stakeholders. Furthermore, there are also many barriers on the integration and sharing of cross-domain data from various sources, since the data from different platforms and applications usually have different data structure and format, which are usually heterogeneous, independent and mutually islanded [167]. In addition, a shift is needed in the perception of who owns the various data sources and who benefits from them in order to facilitate the exchange [32].

According to Chinese Society for Electrical Engineering Information Committee [233], the big data in the electric power industry has a unique “3E” (energy, exchange and empathy) features. “Energy” (data-as-an-energy) means that the value of big data can provide guidance for energy saving and loss reduction. “Exchange” (data-as-an-exchange) means that the interaction between energy data and other cross-domain data can bring even greater value. “Empathy” (data-as-an-empathy) refers to that users’ needs can be better satisfied based on the value of big data.

The “3E” features not only fit for the energy big data, but are also applicable for the other cross-domain energy-related data when seeking to utilize them for enhanced energy management. Considering the “3E” features, three main challenges are encountered, as shown in Figure 15.

Figure 15: Main challenges in using big amounts of data for enhanced energy management.

In order to use the data for energy performance analysis, it is essential to know what energy performance aspects are on the concern of stakeholders and how to extract the data that contain valuable information or knowledge for improving performance. This will avoid analysing the big amount of data aimlessly. For this purpose, it is necessary to define a method by which to find the valuable information (eliminate irrelevant information) and extract the core data. However, the data usually come from different sources; in most cases distributed data sources should be gathered from different stakeholders and they are often heterogenous. The issue of how to enable the data exchange among various stakeholders should be addressed in order to obtain access to cross-domain data. An effective approach should be developed in order to exchange heterogenous data. If the exploitation of such data is able to help improving stakeholders' satisfaction in energy performance, this will further promote stakeholders' involvement in data sharing. While, the problem is how we can use the data to support stakeholders to achieve their performance goals.

To conclude, the main challenges encountered when seeking to analyse and exploit the big amount of cross-domain data for enhanced energy management include the following:

- The extraction of core data that contain valuable information for improving energy performance on the concern of stakeholders;
- The development of an effective approach to resolve the interoperability problem of cross-domain heterogenous data;
- The improvement of stakeholders' satisfaction and achievement of their energy performance goals.

2.4 PERFORMANCE INDICATORS FOR ENERGY MANAGEMENT

Performance Indicators (PI) are a good way of measuring the progress towards achieving the stakeholders' performance goals and to summarize pieces of performance information from a big amount of data.

The regulation ISO 50001 specifies the requirements for establishing, implementing, maintaining and improving an energy management system [234]. The standard requires that an organization creates energy objectives before implementing an energy management plan and that it identifies appropriate energy PIs to track energy performance for the purpose of ensuring continuous improvement. Generally, the energy objectives should comply with relevant regulatory requirements yet should represent stakeholders' goals. ISO 50001 provides guidance on the identification of energy PIs but presents no instructions regarding whether the indicators underpin stakeholders' goals or not. The PI can represent a piece of performance information but may not be concerned with the stakeholders. Therefore, the definition of a method to identify the indicators that support stakeholders' performance goals is necessary.

Energy performance indicators are a way to measure an organization's energy performance; normally they are represented by the energy intensity which is calculated by dividing the total energy consumption by a related metric (e.g., floor area and occupant rate), thus gauging effectiveness of the energy management efforts. However, since various factors influence energy production, delivery and consumption of the energy systems in buildings and districts, such as weather conditions, types of activities taken place in buildings, building envelope, HVAC system and occupancy, the measurement of a building and/or multiple buildings' energy performance is not an easy task [235]. Furthermore, performance indicators in different aspects such as environmental and economic ones should be taken into account in order to implement successfully an energy management plan. Since PIs can vary significantly depending on a building's location, climate, legislation, usage and so on, selecting the most appropriate indicators is a big challenge [236]. Furthermore, due to the numerous PIs involved, especially for district-scale energy management, weighting the importance of each indicator according to the stakeholders' involvement is essential when aiming to identify the key performance indicators (KPIs) that underpin the stakeholders' performance goals.

In order to facilitate the selection of KPIs for energy management at the district and building levels, the following Section 2.4.1 illustrates the main characteristics of KPIs; Section 2.4.2 overviews the existing KPIs in the fields related to energy management in buildings and districts; and Section 2.4.3 reviews the current methods used to identify and prioritize KPIs.

2.4.1 Main Characteristics of Key Performance Indicators

According to CEN/TC348²⁷, an indicator is a measured or calculated characteristic (or set of characteristics) of a product according to a given formula, which assesses the status or level of performance at defined time; while, a key performance indicator (KPI) is an indicator that provides essential information about performance of the client organization. KPIs allow gathering knowledge and exploring the best way to achieve organization goals [237]. They are quantifiable performance measurements used to define success factors and measure progress toward the goals; it is paramount for organizations to define and implement a consistent set of KPIs that reflect a true statistical picture of their operations and to capture and analyse key performance information [238].

KPIs, if selected and implemented appropriately, can help energy managers to improve operational performance and save energy cost. Badawy et al. [237] summarized the main characteristics of KPIs. In total, 12 characteristics are illustrated, which are the following:

- Sparse: The fewer KPIs the better. If an organization includes too many KPIs, this can weaken the focus on aims;
- Drillable: Users can drill from KPIs into detail;
- Simple: Users can understand the KPIs clearly;
- Actionable: KPIs help users understand the performance measures that lead to a failure and users know how to affect outcomes of KPIs;
- Owned: KPIs have associated owners;
- Referenced: Users can view origins and context of KPIs;
- Correlated: KPIs drive desired outcomes and have clear connections to business objectives;
- Balanced: KPIs consist of both financial and non-financial metrics;
- Aligned: KPIs do not undermine each other;
- Validated: Workers cannot circumvent the KPIs;
- Regulated: KPIs are measured frequently (e.g., 24/7, daily, or weekly);
- Distributed: KPIs are measures that tie responsibility of different actors.

In addition, Archibus [238] also defined a principle with the acronym SMART to determine what are valuable and actionable KPIs. The “SMART” principle includes:

- Specific: a KPI should have a widely accepted and easy understanding definition;
- Measurable: a KPI provides a valid measure that accurately defines a standard, budget or norm;
- Achievable: a KPI has to be clear and detailed enough to be actionable;

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²⁷ The scope of the CEN/TC is the preparation of European standards for Facility Management (FM) covering operational, tactical and strategic levels to support primary processes.

- Relevant: a KPI must measure some practical and critical aspect of the organization's objective and directly contribute to achieving it;
- Time-Phased: a KPI should express a relationship between the performance measure and the time frame in order to establish a temporal baseline for future KPI comparisons.

Both studies emphasize that KPIs should be easily understandable, actionable, relevant to organization's objective and time-phased. KPIs are especially useful to deal with complex contexts, such as a district and its buildings. Modern energy management systems rely heavily on information technology to set goals, track performance and communicate results; KPIs represent the critical pieces of actionable information in the ocean of information and help to evaluate and track the key critical performance of an organization [35]. KPIs are designed to measure the success of key elements in an energy management plan and to provide energy managers with timely pieces of information needed to achieve energy performance goals [35].

2.4.2 Existing Key Performance Indicators

KPIs are widely implemented in different disciplines, such as construction and facility management. There are a range of previous studies addressing the identification of KPIs. Cao and Pietilainen [224] proposed that the commonly used building performance indicators include: a) indicators related to occupancy costs, space use, maintenance and energy costs; b) energy and water consumption; and c) customer satisfaction metrics: indoor air quality, i.e., comfort and healthy, temperatures, cleanliness, lighting levels, etc. These indicators have a balance in different aspects including financial, environmental and social ones. In addition, Dejacó et al. [239] provided some KPIs for building condition assessment and making the best decisions when acquiring, operating, maintaining and repairing a building.

Furthermore, Lavy et al. [240][241] adopted a qualitative approach, based on the literature (research papers, assessment reports, surveys and presentations), to identify KPIs for a holistic facility performance assessment. A total of 35 major indicators are identified, which are classified into four major categories:

- Financial indicators, which involve costs and expenditures related to operation and maintenance, energy, building functions, real estate, plant, among others;
- Physical indicators, which are associated with the physical shape and conditions of the facility, buildings, systems, and components;
- Functional indicators, which relate to the way the buildings and facilities function and which express building appropriateness through space adequacy, parking, etc.;
- Survey-based indicators, which are based solely on respondents' opinion to surveys that are primarily qualitative in nature.

Using KPIs for building and district energy retrofitting has also attracted extensive interest. Barbano et al. [242] selected KPIs to assess different retrofitting solutions with regard to energy savings and sustainability for the EU-funded project FASUDIR (Friendly and Affordable Sustainable Urban Districts Retrofitting)²⁸. A repository including more than 600 sustainability indicators was built from current rating schemes, research projects and standards on building and neighbourhood in order to take advantage of already existing indicators. KPIs are selected from the repository by evaluating their suitability to assess district renovation projects. The main purpose of the KPIs is to help taking the best energy retrofit decision by providing quantitative or qualitative information about building and/or district performance. The indicators at both district and building levels assess the project along its environmental, social and economic performance, with focus on resource efficiency, low emissions, health, comfort and cost efficiency. The mentioned indicators in both studies are collected and listed in Appendix A.

The functionality of the KPIs has made it one of the most popular and valuable tools to measure the level of sustainability in construction projects. Kylili et al. [243] reviewed the previous studies that employed the KPIs approach in building renovation projects, in order to measure the sustainability of the built environment in terms of energy consumption reduction and indoor climate improvement. Eight types of KPIs are identified, including economic, environmental, social, technological, time-related, quality, site disputes and project administration. Some of the main KPIs are listed in Appendix A Table A.3. The economic KPIs are associated with the costs of the project and the economic performance of the building according to the perception of the involved stakeholders. The environmental KPIs measure the level of sustainability of building renovation projects, among which the energy-related KPIs regarding energy consumptions and savings, as well as the utilisation of renewable sources, are the most employed.

Apart from the KPIs defined for facility management and district/building retrofitting or renovation, there are also some other studies which provide KPIs exactly for assessing building energy use and energy management. Harris and Higgins [244] introduced a set of KPIs for commercial building energy use based on the New Buildings Institute's (NBI) investigation. It indicates that the developed KPIs can provide an orderly way to better define superior or inferior performance of certain aspects of design, operations or occupant behaviours. Additionally, Siemens [245] proposed two types of KPIs for energy management, they are strategic KPIs and site controls-specific KPIs. The former is intended to serve as guideposts for dialogue energy efficiency and sustainability, and the latter includes variables that have over time proven critical to the success of energy management systems. The proposed KPIs in these studies are respectively listed in Appendix A Table A.4 and Table A.5.

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²⁸ For more information about the project FASUDIR see: <http://fasudir.eu/>.

Furthermore, Hussain et al. [246] identified KPIs related to intelligent buildings in order to access the overall energy efficiency of the buildings. Four types of KPIs are identified: (1) economical KPIs, which evaluate the operational and maintenance costs of a building; (2) environmental KPIs, which measure energy and water conservation, greenhouse gas (GHG) emission, materials, durability, waste, safety and environmental risk factors; (3) reliability KPIs, which involve condition based maintenance indicators, remaining useful life predictors and equipment power factors; and (4) quality KPIs, which include CO₂ concentration, humidity and individual dissatisfaction index of an energy zone. In addition, Alwaer and Clements-Croome [247] also selected KPIs from four groups of indicators for assessing sustainable intelligent buildings. The four groups of indicators include environmental, social-cultural, economic and technological, which are listed in Appendix A Table A.6.

The Energy efficiency index (EEI) is the most commonly used index as a KPI to track and compare performance of energy consumption in buildings, which is also sometimes called building performance index (BPI). Abu Bakar et al. [235] reviewed the EEI as an indicator for measuring building energy performance. Generally, EEI can be viewed as the ratio of energy input to the factor related to the energy using component. Additionally, some worldwide building performance assessment methods and tools such as BREEAM, HK-BEAM, LEED and CASBEE can also provide a useful set of tools to identify KPIs, if they are properly applied [236].

The specific KPIs related to energy management in smart grid or microgrid have also been studied. Personal et al. [248] reviewed the existing metrics and proposes a set of KPIs for assessing smart grid goals and making the most appropriate decisions. The authors developed a hierarchical structure of KPIs, whose layers from top to bottom are macro-objective, objective, indicator and measurement. Four macro-objectives are defined, including improvement of energy efficiency, increase of renewable energy use, reduction of emissions and secondary objectives. Appendix A Table A.7 lists the KPIs and their associated objectives and macro-objectives.

There are also some standards and studies which provide indicators for sustainability assessment at city or district level. For example, BS ISO 37120:2014²⁹ establishes a set of indicators in different themes, such as economy, education, **energy**, **environment** and finance, in order to provide standardized definitions on what to measure in a city. The standardized indicators help cities make informed decisions through data analysis, evaluate the overall performance and build smart and sustainable cities. The energy-related indicators include:

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²⁹ BS ISO 37120:2014: Sustainable development of communities: Indicators for city services and quality of life. For more information see: <https://www.iso.org/obp/ui/#iso:std:iso:37120:ed-1:v1:en>

- Total residential electrical energy use per capita;
- Percentage of city population with authorized electrical service;
- Energy consumption of public buildings per year;
- The percentage of total energy derived from renewable sources, as a share of the city's total energy consumption;
- Total electrical energy use per capita;
- Average number of electrical interruptions per customer per year;
- Average length of electrical interruptions (in hours).

The EU-funded project CITYkeys³⁰ developed and validated KPIs and data collection procedures for the common and transparent monitoring as well as the comparability of smart city solutions across European cities. Energy and mitigation indicators are included, which considers energy consumption reduction, waste energy use and renewable energy production.

The Inter-American Development Bank (IDB) proposed an ESC (Emerging and Sustainable Cities)'s methodology³¹, which provided indicators for sustainable cities in different topics such as waste management, energy and air quality. The energy topic includes three subtopics: energy coverage, energy efficiency and alternative and renewable energy. In total, eight indicators are defined, such as total annual electrical consumption per residential household and energy intensity of the economy.

The ITU-T (International Telecommunication Union – Telecommunication Standard Sector) Focus Group defines KPIs definitions for smart sustainable cities³². The index systems of cities from different organizations (e.g., ISO, UN-Habitat, IBM and Siemens)³³ are concluded, including different topics. For example, the European green city index developed by Siemens is classified into eight categories: CO₂ emissions, energy, buildings, transport, water, waste and land use, air quality and environmental governance. Appendix A Table A.8 lists some proposed indicators in terms of CO₂ emissions, energy and buildings, which are considered to be associated with district and building energy management.

The indicators related to energy management include three main aspects, namely environmental (energy, material, environmental impact and others), economic (cost, economic performance and so on) and social (user comfort, functionality and others).

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³⁰ The project CityKey defines the needs, analyses existing results and develops recommendations for the use of performance indicators for smart city project evaluation. For more information see: <http://www.citykeys-project.eu/>

³¹ For more information see: <http://www.iadb.org/en/topics/emerging-and-sustainable-cities/implementing-the-emerging-and-sustainable-cities-program-approach,7641.html>

³² For more information see: <http://www.itu.int/en/ITU-T/ssc/Pages/KPIs-on-SSC.aspx>

³³ For more information see: https://www.itu.int/en/ITU-T/focusgroups/ssc/Documents/website/web-fg-ssc-0270-r3-KPIs_definitions.docx

However, due to the numerous existing performance indicators in different topics, it is a challenging issue to select appropriate indicators for energy management in a local context, especially for a specific case that should underpin its own stakeholders' performance goals. Therefore, it is essential to find a method that helps identifying the most appropriate KPIs for an energy management plan. The following Section 2.4.3 reviews the current methods used to identify KPIs.

2.4.3 Current Practices to Identify Key Performance Indicators

Most of the current studies for KPI identification focus on formulating an ad-hoc list of KPIs, rather than developing a holistic method to identify KPIs. For example, the study of Personal et al. [248] formulates a list of KPIs for assessing smart grid goals, Cabeza et al. [249] collected, organised and classified KPIs used for thermal energy storage, Weissmann et al. [250] proposed a peak load ratio (PLR) index for representing the percentage reduction of peak load of a district system from a simple sum of individual peak loads of buildings, or Dejaco et al. [239] provided a set of KPIs for building condition assessment.

Despite this, studies addressing different methods for KPI identification in different fields have also been performed. For example, May et al. [251] proposed a 7-step methodology to develop firm-tailored energy-related KPIs (e-KPIs) for energy management in production and aim to measure energy efficiency performance of equipment, processes and factories. The method provides a practical guide for manufacturing companies to identify their most important e-KPIs. It supports companies in their operative decision-making process and the identification of weaknesses and areas for energy efficiency improvements.

Xu et al. [252] identified a list of KPIs for sustainability assessment of building energy efficiency retrofit in hotel buildings using a three-step method. Such steps include: (1) a literature review and in-depth interviews with industry experts and academic researchers, which filters the performance indicators for assessing sustainability; (2) a questionnaire survey to collect data from various groups of experts to analyse the significance of the selected performance indicators; and (3) a model based on fuzzy set theory designed to identify the KPIs for the sustainability of building energy efficiency retrofit. Eight KPIs were identified based on fuzzy set theory. Since the data for studying KPIs are collected from the previous questionnaire survey, experts' opinions are subjective and involve fuzziness. Therefore, fuzzy set theory [253] is applied to assist in identifying the KPIs.

In addition, González-Gil et al. [254] selected KPIs for optimal energy management of urban rail systems through a scientific approach validated by different stakeholders. The list of KPIs is developed following a consensus oriented process that involved all relevant stakeholders. Firstly, an extensive review of the literature on railway energy consumption is undertaken, including academic papers and former/running state-of-the-art projects, thus to develop a preliminary set of indicators. Subsequently, the KPIs are revised and updated

through constructive discussions among representative partners from industry, operators and public transport authorities. Finally, a complete set of KPIs were agreed amongst all stakeholders and validated through their use in the assessment of different energy saving measures.

Hussain et al. [246] used existing mathematical formulation of KPIs from past research and formulates some new KPIs for evaluation of energy conservation in buildings. Teixeira et al. [255] selected a set of performance indicators adapted from international guidelines and existing literature for energy management in municipal water services through consensus between experts and stakeholders. Lavy et al. [240][241][256] established KPIs for facility performance measurement using a qualitative approach, based on the literature. This approach relies on an extensive literature search of extant research papers, assessment reports, surveys and presentations to identify and categorize KPIs.

Rodrigues et al. [257] provided a set of process-oriented indicators to support and enhance eco-design implementation and management. The performance indicators are selected taking the following steps: (1) cross-analyse performance indicators from literature against eco-design practices at the process level; (2) propose, evaluate and consolidate new indicators; and (3) the indicators are evaluated by 8 experts in eco-design. As a result, a repository of 27 indicators from literature and 114 newly proposed indicators are presented for companies to customize, adapt, mix and derive according to their needs, strategic drivers and overall context.

KPIs allow gathering knowledge and exploring the best way to achieve organization goals. Many researchers have provided different ideas for determining KPI's either manually, and semi-automatic, or automatic which is applied in different fields. Badawy et al. [237] conducted a survey of different approaches for exploring and predicting KPIs, including manual approaches, semi-automatic approaches and predict approaches.

The manual approaches including literature reviews, interviews with industry experts and academic researchers and questionnaire-based surveys are the most commonly used methods for KPI identification [258][240][241][256][246]. However, these approaches to identify KPIs depend largely on the personal experiences of the members in the selection of KPIs. The experts' opinions are usually subjective [252]. Fuzzy set theory can to some extent address this issue. In any case, involving all of the relevant stakeholders is essential for the identification of the appropriate KPIs that represent the business objectives for a specific case. Therefore, stakeholders' consensus with further validation is also frequently used for KPI identification. The study of González-Gil et al. [254] follows a consensus-oriented process to develop KPIs for energy management of urban rail systems. Teixeira et al. [255] used the consensus between experts and stakeholders to select indicators for energy management in water services. The stakeholders' consensus and validation are qualitative means by which to select KPIs. A previous study by Chen et al. [259] proposes

an energy-time consumption index (ETI) to select KPIs for intelligent building lifespan assessment; this involves a quantitative approach but fails to consider stakeholders' involvement.

In addition, the studies of using semi-automatic approaches to identify KPIs include that of Peral et al. [260]. The authors presented an approach based on data mining techniques to obtain specific KPIs for business objectives in a semi-automated manner. The main benefit of the approach is that organizations do not need to rely on existing KPI lists or test KPIs over a cycle as they can analyse their behaviour using existing data. However, in case that the existing data sources are unavailable or there is a need to select KPIs before collecting the data sources, this approach will not be applicable.

Selecting KPIs is a multiple criteria decision-making problem, involving a number of factors and related interdependencies. In order to weight the indicators for identifying KPIs and determining their importance, the Analytic Hierarchy Process (AHP) or the Analytic Network Process (ANP) are often used. AHP and ANP are multi-criteria decision-making methods in which factors are arranged in a hierarchic structure [261]. Carlucci [262] proposed an ANP-based model for driving managers in the selection of KPIs. The model draws upon the consideration that KPIs can be evaluated and selected on the basis of a set of criteria theoretically founded and the feedback dependencies between the criteria and performance indicators. Based on a review of management literature, the paper identifies a set of criteria for selecting KPIs. Such criteria form the building blocks of the proposed ANP model.

Shah et al. [236] and Alwaer and Clements-Croome [247] also used the AHP method to evaluate the importance of KPIs for sustainable intelligent buildings. Alwaer and Clements-Croome [247] adopted a consensus-based model, which is analysed using the AHP for multi-criteria decision-making and for the selection and priority setting of KPIs. This study introduced the use of a multi-attribute model for priority setting in the sustainability assessment of intelligent buildings. It is based upon a survey perception held by selected stakeholders and the value they attribute to selected KPIs. The method gives a detailed insight into the selection of sustainable building indicators, as well as their degree of importance. However, the priority levels for the selected criteria of decision making is largely dependent on the integrated design team, which includes the client, architects, engineers and facility managers. Furthermore, Khalil et al. [263] used the AHP to rank indicators of building performance and the users' risk. Kucukaltan et al. [264] proposed a decision support model based on the ANP for identification and prioritization of KPIs in the logistics industry.

The pillars of AHP for selecting and ranking KPIs are the selected criteria for decision-making. However, according to the previous studies, such criteria are usually identified based on a literature review or the judgement of the experts. Therefore, the priority levels

for a selected criterion largely depend on the experience and knowledge of the experts. Furthermore, even though the decision-makers are all experts, results can sometimes be very subjective. To avoid this, an effort must be made during the process of selecting KPIs to be more objective whilst including all relevant stakeholders.

A key finding of the current practices for KPI identification and selection is the lack of a quantitative and more objective means by which to weight, select and validate the KPIs that underpin stakeholders' performance goals in energy management. Moreover, there is a need to define a systematic, structured process to implement KPIs, in order to integrate and comprehensively consider the energy management context, stakeholders' needs and concerns, key performance information and key data for a multi-level energy performance measurement and analysis. The Center for Construction Innovation (CCI) initially developed a KPI system process [265]. This process defines procedures such as the definition of system requirements, the identification of stakeholders, the selection of KPIs and the management of KPI data. However, the system process is aimed for construction projects and the detailed method to implement each procedure has not been defined to date.

2.5 LINKED DATA APPLICATION IN ENERGY MANAGEMENT

Data are the most important and basic elements for energy performance evaluation, analysis and improvement. As studied in Chapter 2.3.3, energy management at the district and building levels needs data from different domains in order to create valuable information and knowledge. The exploitation of cross-domain data requires data integration and sharing, rather than silos of data. However, multi-domain energy-related data are often heterogeneous and stored in different information islands. Interoperability of heterogeneous data is one of the main barriers for data exchange and sharing. To resolve the data interoperability problem, the semantic web provides a possible solution and linked data harnesses the ethos and infrastructure of the Web to enable data sharing and reuse on a massive scale [39].

The semantic web aims to represent information more meaningfully for humans and computers alike [266]. To achieve the Web of Data, it is important to have a huge amount of data on the Web available in a standard format, reachable and manageable. Meanwhile, it is essential to describe the relationships among data to create interrelated datasets as opposed to a sheer collection of datasets. The interrelated datasets on the Web can be referred to as Linked Data [267]. Linked Data can be used for large scale integration of, and reasoning on, data on the Web. To achieve and create Linked Data, technologies should be available for a common format RDF (Resource Description Framework)³⁴, to make

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³⁴ RDF is an international standard for data interchange on the Web produced by the W3C. RDF is based on the idea of identifying things using web identifiers or HTTP URIs, and describing resources in terms of simple properties and property values. For more information see: <https://www.w3.org/RDF/>.

either conversion or on-the-fly access to existing databases (relational, XML, HTML, etc). It is also important to be able to setup query endpoints using technologies such as SPARQL³⁵ to access such data more conveniently [267].

The representation of linked data is based on ontologies. An ontology is a formal, explicit description of a domain of interest [268]. It facilitates knowledge sharing over distributed systems and plays a major role in solving the interoperability problem between applications across different organizations, by providing a shared understanding of common domains [43]. Therefore, the main purpose of an ontology is to achieve a common and shared knowledge that can be interchanged between people and between application systems. Ontology engineering in the Semantic Web is primarily supported by languages such as RDF, RDFS³⁶ and OWL³⁷ [42].

Using linked data, it is possible to exchange and share the energy-related heterogeneous data from different domains and among different stakeholders. The main purpose of data interchange in integrated energy management is to enable data exploitation and data-driven decision-making for energy performance improvement at both the district and building levels. However, in order to assess the energy performance about whether the improvement measures are needed or not, it is essential to obtain the key performance information. The key performance information can be underpinned by KPIs, which represent the main issues of concern and are usable as communication tools among stakeholders [242]. The exchange and sharing of KPI information and its related data can further improve the energy performance analysis and decision-making. Therefore, using linked data to support the interchange of both cross-domain data and key performance information represented by the KPIs will be optimal for enhanced energy management.

In order to leverage linked data to achieve this goal, the following Chapter 2.5.1 studies the state of the art of the application of linked data for energy and buildings; and Chapter 2.5.2 reviews the existing ontologies that have been developed for information exchange in energy management.

2.5.1 Current Linked Data Application for Energy and Buildings

In recent years, linked data has been the subject of growing interest and applications in the energy and building fields. An appropriate application of linked data could potentially

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³⁵ SPARQL (SPARQL Protocol and RDF Query Language) defines a query language for RDF data, analogous to the Structured Query Language (SQL) for relational databases. For more information see: <https://www.w3.org/TR/rdf-sparql-query/>.

³⁶ RDF Schema (RDFS) provides a data-modelling vocabulary for RDF data. It is an extension of the basic RDF vocabulary. For more information see: <https://www.w3.org/TR/rdf-schema/>.

³⁷ OWL (Web Ontology Language) is a knowledge representation and vocabulary description language for authoring ontologies, based on RDF and standardized by the W3C. For more information see: <https://www.w3.org/TR/owl-features/>.

provide the means to facilitate data retrieval, interoperability and decision support in the built environment. A review of the linked data application for energy and buildings has been conducted. A summary of the works and their topics is depicted in Table 8.

Table 8: Literature about linked data application in the energy and building fields

Source	Topic
Pauwels et al. [269]	Using semantic web as an alternative of building information modelling (BIM) to reach interoperability in the design and construction industry
Pauwels and Deursen [270]	The transformation of IFC models to RDF graphs in the semantic web
Pauwels et al. [271]	Linked data in architecture and construction
Madrazo and Costa [272]	Interlinking data generated around different BIM domains using linked data, focusing on product modelling
Abanda et al. [273]	The relationships between linked open data and building information modelling
Curry et al. [274]	Using scenario modelling and linked data for building management and operation, helping customise and improve data-driven decision support for building managers during building operation
Curry et al. [130]	Using a linked dataspace in enterprise energy management for energy intelligence
Corry et al. [275]	The role of linked data and the semantic web in building operation, presenting a data driven approach for building performance assessment to support decision making for key building stakeholders
O'Donnell et al. [276]	Building performance optimisation using cross-domain scenario modelling linked data and complex event processing
Curry et al. [38]	Integrating cross-domain building data in the cloud using linked data
Corry et al. [40]	Using semantic web technologies to access soft AEC data
Lee et al. [277]	A linked data system framework for sharing construction defect information using ontologies and BIM environments
Radulovic et al. [278]	Guidelines for linked data generation and publication
König et al. [279]	Architecture of an open knowledge base for sustainable buildings based on linked data technologies
Wagner et al. [280]	Using linked data and complex event processing for the smart energy grid
Lopez et al. [281]	QuerioCity: a linked data platform for urban information management
Janssen et al. [282]	Big and Open Linked Data (BOLD) to create smart cities and citizens insights from smart energy and mobility cases

Pauwels et al. [269] proposed the use of semantic web technologies for interoperability in the design and construction industry. The authors compared the semantic web technologies with building information modelling (BIM), argued that the interoperability in the domain of AEC is not fully reached by BIM, thus proposed the semantic web as an alternative approach to reach the targeted interoperability. Pauwels and Deursen [270] indicated that

IFC (Industry Foundation Classes)³⁸ models can be made available as RDF graphs in the semantic web and can be linked to other additional information. Madrazo and Costa [272] interlinked data generated around different BIM domains using ontologies and semantic web technologies following the Linked Open Data initiative, specifically for product modelling. Lee et al. [277] developed a linked data system framework for sharing construction defect information between heterogeneous data sources using ontologies and BIM environments; this approach provides a data feedback mechanism for defect data that contains knowledge about specific work conditions in order to prevent reoccurrence of defects and improve current defect management practices.

Two community groups have been formed based on the efforts of the LDAC (Linked Data for Architecture and Construction) workshop series in order to promote the application of linked data in the AEC domain. The two groups are the W3C Community Group on Linked Building Data³⁹ and the BuildingSMART Linked Data Working Group⁴⁰ [271]. The W3C Community Group on Linked Building Data aims to define existing and future use cases and requirements for linked-data-based applications across the life cycle of buildings. It will benefit the organizations which use data from building information modelling and other cross-domain data to achieve their business processes. The buildingSMART Linked Data Working Group focuses on building and maintaining a recommended version of an ifcOWL ontology for building information modelling.

There are also a range of studies about the application of linked data for building management and operation. Curry et al. [274] used scenario modelling and linked data for more effective building management and operation. Since the holistic management of facilities is a multi-domain problem encompassing financial accounting, building maintenance, human resources, asset management and code compliance, affecting different stakeholders in different ways, the use of scenario modelling and linked data helps to customise and improve data-driven decision support for building managers during building operation. Curry et al. [130] proposed the use of linked data in enterprise energy management for energy intelligence; energy Intelligence platforms can help organizations manage power consumption more efficiently and facilitate the energy consumption to be understood, changed and reinvented. The authors used linked data and complex event processing to overcome the current challenges in energy intelligence platforms, including

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³⁸ Industry Foundation Classes (IFC) is data model intended to describe building and construction industry data. It is developed by buildingSMART to facilitate interoperability in the architecture, engineering and construction (AEC) industry, and is a commonly used collaboration format in Building information modelling (BIM) based projects. For more information see: <http://buildingsmart.org/ifc/>.

³⁹ W3C Linked Building Data Community Group, <https://www.w3.org/community/lbd/>.

⁴⁰ BuildingSMART Linked Data Working Group, <http://www.buildingsmart.org/standards/standards-organization/groups/linked-data-working-group/>.

information management, cross-domain data integration, leveraging real-time data and assisting users to interpret the information to optimize energy usage.

In addition, Corry et al. [275] analysed the role of linked data and the semantic web in building operation. In order to integrate the different building data silos to deliver a complete view of building performance, the authors presented a data-driven approach to the structured performance assessment of buildings, utilising semantic web and performance metrics. The conventional performance analysis usually focuses on only the data measured in a Building Management Systems (BMS); while this considers the integration of many other data related to building performance, such as weather, occupant feedback, mobile sensors and feedback systems, schedule, and equipment usage. This integration provides a wider decision support framework for key building stakeholders. An improvement study of Corry et al. [40] uses semantic web technologies to access soft AEC data, which refers to those which are usually not accessible to the existing BMS and difficult to aggregate and infer information from due to their qualitative nature. Such data typically include social media, occupant communication, mobile communication devices, occupancy patterns, human resource allocations, and financial information. The authors illustrated how ‘soft-data’ sources from outside the building operation domain can be used to supplement existing structured performance measurement frameworks and indicated that the integration of untapped silos of information can lead to greater awareness of stakeholder concerns and building performance.

Information integration related to building sustainability is also studied by König et al. [279] who analysed the requirements for information sharing among AEC stakeholders. The authors presented an information integration model for sustainable buildings in order share the information among stakeholders. Finally, a prototype of an open knowledge-base system based on linked data technologies was designed and created; such prototype made it possible to capture, analyse and share information on building sustainability among the stakeholders.

Furthermore, Curry et al. [38] studied the integration of cross-domain building data in the cloud using linked data. The objective of linking building data in the cloud is to create an integrated well-connected graph of relevant information for managing a building. Linked data facilitates the interaction between the islands of information in traditional BMS and the broader domains of building data, such as utility information, occupancy patterns, weather data, etc. The ever-increasing volume of information can become overwhelming without an appropriate information management. Moving the data to the cloud combined with the use of linked data technologies offers a viable means for the sharing and reuse of big amounts of data across silos. Furthermore, the cloud-based building data services can offer different views of information for different stakeholders, although navigating through a mass of data in a coherent manner to derive information and tailor outputs to specific end users is still a challenge.

The studies mentioned above all focus on the application of linked data in individual buildings. There are also precedents which use linked data in a larger scale, such as smart grid and smart cities. For example, Wagner et al. [280] used linked data and complex event processing for smart energy grids. The smart grid is usually integrated with many other smart systems (e.g., smart buildings and smart cities), thus a multitude of stakeholders will be involved and a large amount of data should be exchanged. In order to achieve ad-hoc data exchange among heterogeneous systems, the authors outlined an envisioned smart grid architecture based on semantic web technologies, using linked data principles to enable decentralised publishing and resource discovery, ultimately to foster data integration.

In addition, Lopez et al. [281] developed a linked data platform, named QuerioCity, for urban information management. The platform enables to catalogue, index and query highly heterogeneous information coming from complex systems, such as cities. An approach for incremental and continuous integration of static and streaming data, based on semantic web technologies, was proposed. Additionally, Janssen et al. [282] used Big and Open Linked Data (BOLD) to better understand existing resources in cities and to suggest improvements for the urban environment. Through two cases concerning different aspects of smart cities, energy and mobility, the authors found that BOLD can help linking and combining data, employing data or predictive analytics for better use of resources. However, a major challenge is to deal with widely distributed data and align the data with the citizens' needs.

Radulovic et al. [278] presented a set of guidelines for linked data generation and publication in the context of energy consumption in buildings based on the EU-funded project READY4SmartCities. These guidelines offer a comprehensive description of the tasks needed for linked data generation, as shown in Figure 16. In total, eight tasks are included. The first task is to select the data sources that need be transformed into linked data. After obtaining access to the data sources, their licenses should be analysed in order to determine the terms of use. Afterwards, the data sources are analysed in detail in order to get insight into the data and know the structure of the data. A resource naming strategy should be specified in order to define the URIs of the generated resources. Subsequently, an ontology for describing the data must be developed and the data should be transformed into the RDF format in order to map to the ontology. Finally, the generated data can be linked to other datasets.

Figure 16: Linked data generation process [278].

To conclude, linked data as a new field of application for energy and buildings has obtained an increasing interest in recent decades. Linked data facilitates the exchange of cross-domain AEC data among different stakeholders and improve data-driven decision making for energy optimization and building operations. Linked data are not only applied for individual buildings, but also for smart energy grids and cities. Furthermore, guidelines for generating linked data in a smart city context are available. However, despite the wide range of benefits in linked data application, there are still challenges to integrate big amounts of distributed data and to draw information that exactly meets the needs of specific stakeholders.

2.5.2 Review of Existing Ontologies in Energy Management

Ontologies are the foundation of linked data. It is essential to develop ontologies that aim to describe specific domains in order to generate linked data. Over the years, ontologies have become a popular research topic in a range of disciplines with the aim of increasing understanding of, and building a consensus in, a given area of knowledge [43]. Ontologies allow the formation of a machine readable, multi-domain knowledge base [15] and are scalable, since they can be reused and extended. Zhou et al. [283] demonstrated that different ontologies can be defined separately for various domains in relation to the built environment and then be linked together by an upper level ontology resulting in a holistic urban knowledge model.

In Europe, there are a range of projects which use ontology-based approaches to energy analysis, building and district retrofitting and energy management. For instance, the European FP7-funded project SEMANCO uses ontological modelling to access widely

dispersed energy-related data pertaining to cities for the purpose of improved energy analysis [225]. Undergoing projects such as NewTrend⁴¹ and OptEEmAL⁴² create ontology-based district information models for building and district retrofitting. In addition, the project RESILIENT⁴³ developed a district information model based on ontologies, representing the electricity grid, district heating network, distributed energy resources and buildings, in order to support district energy management and decentralized decision making at various levels. Furthermore, the project READY4SmartCities collected and summarized a range of ontologies pertaining to smart cities, energy and other related fields [44].

Generally, the application of ontologies in EM includes two types, one is for knowledge engineering, artificial intelligence and system control, the other one is related to knowledge management, information integration and retrieval. The application of ontologies in linked data for data reuse and exploitation belongs to the latter.

Table 9: Review of ontologies applied in energy management on different scales

Ontology application	Building/home (demand-side)	Smart Grid/ microgrid (supply-side)	District (integration)
Ontology for system control and operations in EM	[284], [223], [150], [285], [286]	[287], [288], [289], [290]	[291], [292], [293], [294]
Ontology for knowledge management and information integration in EM	[275], [38], [295]	[283], [221], [296], [297]	[298]
Ontology for performance assessment	[299], [300], [301]		[302]

A review of the existing ontologies in the field of energy management on district and building scales has been conducted. Table 9 lists some relevant works concerning the use of ontologies at different levels. Currently, the application of ontologies in energy

⁴¹ The project NewTrend (New integrated methodology and Tools for Retrofitting design towards next generation of ENergy efficient and sustainable buildings and Districts). For more information see: <http://newtrend-project.eu/>.

⁴² The project OptEEmAl (Optimised Energy Efficient design platform for refurbishment At district Level). For more information see: <https://www.opteemal-project.eu/>.

⁴³ The project RESILIENT (coupling REnewable, Storage and ICTs, for Low carbon Intelligent Energy maNagementT at district level). For more information see: www.resilient-project.eu/.

management is aimed at system control more than at the purpose of generating linked data. While most of the research is focused on using ontologies for smart buildings/homes or smart grids, only a limited number of studies have been carried out to integrate both buildings/homes and grids to enable integrated, multi-level energy management.

2.5.2.1 Ontologies for System Control and Operations

Previous studies have been conducted to use ontologies for system control and operations in building energy management. For example, Grassi et al. [284] proposed an ontology framework for intelligent smart home management and energy saving, constructing a device ontology for devices description and an energy ontology for power generation/consumption representation in smart home. Kofler et al. [223] defined a semantic representation of energy-related information in smart homes; a Smart Home Ontology was developed to make knowledge easily available to smart home systems and to support the control processes. This ontology has a wider scope including the domains of building, user information, process, exterior conditions, and energy and resource information. Additionally, Wicaksono et al. [150] and Han et al. [285] used ontology-driven approaches for intelligent building energy management. Caffarel et al. [286] developed an ontology-based energy management platform Bat-MP for an open energy management system control and monitoring. However, all these studies are aimed for system control and limited on the scale of a building or home.

To extend the energy management on a district scale, energy utility is an important aspect. There are previous studies about using ontologies to optimize energy management in smart grids or microgrids. For example, Rohjans et al. [287] proposed an ICT-architecture for both transmission and distribution grids, using semantic web services to realize information exchange between Energy Management Systems (EMS), Distribution Management Systems (DMS) and Enterprise Resource Planning (ERP) systems. Neumann et al. [288] used the CIM (Common Information Model) ontology for system integration in power systems. In addition, Salameh et al. [289] proposed a full-fledged microgrid ontology (OntoMG) for better management of microgrids. Macek et al. [290] proposed an ontology driven design of a service-oriented energy monitoring and control system for smart energy grids and microgrids.

There are also some studies about the integration of buildings/homes and microgrid energy management. Anvari-Moghaddam et al. [291] used an ontology-driven multi-agent control system to optimize the real-time dispatch of an integrated building and microgrid system. The EU-funded research project ENERSip proposed the ENERSip ontology to model Smart Grid neighbourhoods, including domains like building, neighbourhood, information system and user [292]. Another European FP7-funded project DIMMER created a virtual District Information Model (DIM) for systems interoperability and energy management in smart cities, which correlates information about BIM (Building

Information Model) for each building, SIM (System Information Model) of energy distribution networks, GIS (Geographic Information System) for georeferenced information of different entities, and sensor network data [293]. Additionally, there are also studies about ontological approaches to energy management for buildings and districts using artificial intelligence [294].

2.5.2.2 Ontologies for Knowledge Management and Information Integration

All the studies described above aim for system interoperability and control in EM. However, the use of ontologies to generate linked data for data reuse and exploitation is another topic. Corry et al. [275] addressed the role of linked data and the semantic web in building operation, and presented a data-driven approach to the structured performance assessment of buildings utilizing semantic web technologies and performance metrics. Similar studies also include the research of Curry et al. [38], who proposed to integrate cross-domain building data using linked data and to create an integrated well-connected graph of relevant information for managing a building. In addition, Shah et al. [295] proposed an ontology for home energy management, aiming to study general classifications of home electrical appliances provided by various home appliance vendors and manufacturers.

Regarding the application of linked data in power grids, Zhou et al. [283] developed a semantic information model, composed by electrical equipment, organization, infrastructure, weather, spatial and temporal ontologies. Yogesh et al. [221] proposed an integrated smart grid ontology for semantic information integration in smart grids, which supports load optimization in utilities and advanced analytics. In addition, Gillani et al. [296] proposed a generic ontology for prosumer-oriented smart grids, integrating heterogeneous sensor data, current and historical information, infrastructure type, electrical appliances, electrical generation systems, power storage systems, weather reports, events, service contracts, etc. Gomes et al. [297] also developed a new ontology to represent time series of multiple observations in microgrids, and made real-time consumption data available on the web as linked data, in order to enable consumption reporting and to facilitate other researchers accessing the data.

As described above, there are precedents to generate linked data for either buildings or microgrids. However, only a small number of studies aims to integrate the related data sources in both the building and the microgrid to enhance multi-level energy management. Up to date the related studies that integrate buildings and utilities include a 3D city modelling method using CityGML, which integrates building information models and power systems to support urban energy management [298].

2.5.2.3 Ontologies for Performance Assessment

To draw the knowledge and insights in linked data for energy performance improvement, it is essential to define a way to evaluate performance. An ontology that integrates

performance information and its related data sources can facilitate both the evaluation and the performance problems identification. There are several ontologies about performance assessment in buildings, such as the Performance Information Model (PIM) ontology [44] and the performance framework (PF) ontology [300]. These two ontologies provide a framework to evaluate building performance, but without detailed description of the needed data sources from different domains. Díaz et al. [301] also proposed an Energy Efficiency Ontology (EEOnt) for a unified representation of energy efficiency in buildings, which contains the information related to building structure, systems and devices, EEI_B (Energy Efficiency Index) and EEL_B (Energy Efficiency Landscape). This ontology aims to supply useful information for the diagnosis and the correction of inefficiencies in buildings. However, all these performance ontologies described above are designed for representing performance information only in buildings. The ontologies that describe energy performance in a microgrid or in a district have not yet been identified, except in the case of a Global City Indicator Environment Ontology [302] which assesses the environment in a city, but does not describe the aspects of energy management.

To conclude, a key finding from the existing ontology review is the absence of an ontology to integrate both the key performance information and the related cross-domain data at district and building scales. A noticeable opportunity emerges when both the multi-level evaluation and the performance problem identification are considered together. It is quite important that a new ontology can represent the key performance information of stakeholders' concerns and build upon the variety of information available from district and building energy management. The related data sources from the buildings, utility/microgrid, district and external environment are all essential for exploring the insights for multi-level performance improvement. The access to the accurate and reliable key performance information and its related data sources, in addition to the information exchange in a structured, systematic and contextual manner, can promote stakeholders' engagement and interaction in energy management and enhance the multi-level energy management through an improved energy performance analysis at the district and building levels.

2.6 SUMMARY

The state of the art focuses on the topic of energy management, studying in detail: the current situation and trends of energy management in buildings and districts; the problems encountered in stakeholder engagement and information-driven processes when implementing energy management; and the possible solution to use KPIs and linked data to improve decision-making and enhance multi-level energy management.

A summary of the state of the art and the open research problems (P1 – P4) that aim to be addressed in this thesis is illustrated in Figure 17.

Figure 17: Summary of the study of the state of the art.

At first, the increasing energy challenges for cities in terms of rapid urbanization and energy supply shortage have been studied. The initiatives of smart cities and communities are implemented as a solution to the attainment of sustainable cities. As a result, new energy management trends to manage building energy towards a district scale have emerged.

Through a comprehensive literature review of the current situation and trends of energy management in buildings and districts, it has been found that district-scale energy management should consider both the buildings and the district energy systems. However, such integrated energy management is a multi-stakeholder information-driven process that requires stakeholder interaction through exchange and analysis of energy-related information from different domains. Due to the numerous potential of stakeholders involved in energy management, it is essential to identify and analyse the stakeholders and their needs. However, a review of the current studies found that there is a lack of well-functioning methods for identifying and analysing stakeholders in the energy management context from building to district level.

Furthermore, to enable integration and exchange, there are two main challenges: one is the extraction of core data that contain valuable information of stakeholders' concerns; the other one is the interoperability problem of cross-domain heterogeneous data.

KPIs are a useful way to represent key performance information and to underpin stakeholders' performance goals. A study of the characteristics of KPIs has been conducted and a review of the current KPIs used in energy-related fields has been carried out. It has

been found that there are a plenty of existing indicators. However, to identify the appropriate indicators in a specific context is still a challenge. The current methods to identify KPIs in previous literature have been reviewed. A key finding is the lack of a quantitative and more objective methods to weight, select and validate the KPIs through stakeholders' involvement.

Meanwhile, linked data is a solution to resolve the data interoperability problem; but it needs the development of related ontologies that describe the specific domains in order to facilitate data integration and interchange. A review of the current studies that use ontologies for energy management at different scales (building, microgrid and district) has been performed. The existing studies show the shortage of an ontology to integrate key performance information and core insightful data at both the district and building scales for multi-level energy management.

As can be seen, both KPIs and linked data support energy performance analysis and decision-making for performance improvement, but a structured approach is needed to ensure that the stakeholders' performance goals at different levels are addressed by the data driven performance analysis and decision-making.

Emanating from the study of the state of the art, the four main open research problems that aims to be addressed in this thesis are stated as follows:

- **P1.** The absence of a structured, well-functioning method to identify and prioritize stakeholders in the energy management context;
- **P2.** The lack of a quantitative and objective method to weight, select and validate the KPIs that underpin stakeholders' performance goals and that represent multi-level key performance information;
- **P3.** The absence of an ontology to exchange key performance information and core insightful data among stakeholders at both the district and building levels for enhanced multi-level energy management;
- **P4.** The need of a structured approach to ensure that data driven performance analysis and decision-making address stakeholders' energy performance goals.

In a nutshell, it is essential to advance the state of the art in terms of stakeholder identification and extraction as well as exchange of key performance information and core insightful data, in order to improve multi-level energy performance, engage stakeholders and achieve their performance goals in integrated energy management scenarios.

3 THESIS METHODOLOGY

3.1 GENERAL RESEARCH PROCESS OF THE THESIS

The general research process of this thesis is presented in Figure 18. Literature review is the main research means adopted in this thesis, which studies the state of the art pertaining to energy management at district and building levels and linked data applications as illustrated in Chapter 2. Based on the comprehensive literature review, four open research problems (P1 – P4) have been identified.

Figure 18: General research process of the thesis.

The main research objective and sub-objectives of this thesis aim to advance the state of the art in the field of energy management for districts and buildings. Therefore, each of the objectives defined in Chapter 1.5 aims to resolve one of the open research problems identified in Chapter 2.6. The main objective aims to address P4 (the need of a structured approach to ensure that data driven performance analysis and decision-making address stakeholders' energy performance goals). Sub-objectives 1, 2 and 3 aim to address, respectively, P1, P2 and P3.

All the prepared work targets for the focus of this study, namely the development of a systematic KPI-based, linked data methodology for enhanced multi-level energy management. This methodology aims to identify stakeholders for enabling an effective stakeholder engagement mechanism, to extract the key performance information and core data of stakeholders' concerns, and to support data exchange and improved data-driven decision-making for multi-level energy performance improvement through linked data.

The demonstration of the proposed methodology has been carried out using a case study, which validates the feasibility and benefits of the methodology. The case study supports

verifying the hypothesis and getting the conclusions. Such conclusions summarize the key findings from the research results with regard to each research problem and objective.

3.2 A SYSTEMATIC METHODOLOGY OF KPI AND LINKED DATA

The general framework of the KPI-based linked data methodology developed in order to enable multi-level energy performance analysis and enhance multi-level energy management comprises 12 tasks, as illustrated systematically in Figure 19. Firstly, stakeholders are identified and prioritized in order to find their energy performance goals. Secondly, the stakeholders' performance goals are underpinned by key performance indicators through their involvement in KPIs selection. Thirdly, the selected KPIs are used to identify master data that provide the core valuable information. Fourthly, linked data are generated to integrate and exchange key performance information and master data among different stakeholders. Finally, linked data analysis is conducted to ascertain the performance problems and the key areas for improvement, so as to address stakeholders' performance goals.

Tasks 1 to 3 identify stakeholders and their respective priorities. In doing so, these tasks determine the relevant stakeholders and rank them in terms of their importance for the task at hand. The concept of intervention points [303] is introduced for identifying the stakeholders. The purpose of these is to specify processes and the role of each stakeholder within each process. In doing so, the processes that have a greater impact on multi-level energy performance emerge. As a result, stakeholders become involved in energy management through these intervention points. In order to identify a complete list of stakeholders, roles are identified, instead of highlighting the specific actors in Task 2. Relevant stakeholders are therefore related to each role and are classified into internal and external stakeholders [304]. Not all stakeholders are equally important. Therefore, the performance goals of some stakeholders take precedence over others. For this reason, a prioritization analysis identifies the key stakeholders.

Tasks 4 to 6 involve the identification of PIs and the selection of KPIs. By doing so, KPIs transform the stakeholders' performance goals in such a way that they can be measured and tracked to represent key performance information. KPIs, in practice, are a subset of an overarching set of PIs. The definitive set of PIs is identified through district and building energy reviews, including features such as energy structure, energy systems and energy flow analysis [234][305]. These PIs reflect the basic performance concerns in the specific energy management context. KPIs are selected from this list of PIs, and they include those that represent the critical performance.

Figure 19: General framework of the KPI-based, linked data methodology for enhancing multi-scale energy management.

Tasks 7 focuses on the identification and collection of master data. The ever-increasing volume of monitored data relating to energy management is attributed to the accelerated adoption of ICTs. As a result, the concept of master data is introduced to represent the insightful core data that provide key valuable information [306]. Precedents exist for the identification of key data using indicators and metrics [35][307], and such approaches are also applicable to master data collection. The master data are identified with KPIs to ensure that they underpin the stakeholders' goals and avoid the unnecessary data. Master data include KPI calculations and the key data for performance analysis. It is sometimes necessary to review the existing data sources and to carry out further data collection.

Task 8 generates the linked data to integrate and exchange master data and KPIs among different stakeholders. Ontologies are the foundation of linked data. Thus, in Subtask 8.1, an EM-KPI ontology has been developed. The target EM-KPI ontology should describe two parts, namely, the EM master data part and the KPI part. The KPI part represents the key performance information and provides the basis for KPI calculation and energy performance tracking. The EM master data part integrates the master data domains and helps exploiting the knowledge and insights in the data for performance improvement. To generate linked data, the data sources need to be mapped to the ontology, thus

instantiating the ontology. The data sources may have different formats and should be converted to the standard RDF (Resource Description Framework) format in Subtask 8.2.

Task 9 comprises the calculation and evaluation of the selected KPIs. KPIs are calculated using the master data. In this context, benchmarking against performance targets is especially important. If the performance targets are achieved, the final step would be to carry out an experiential study. Otherwise, Tasks 10 and 11 need to be conducted in order to ascertain the performance problems and take measures to improve these. The identification of performance problems in Task 10 is realized by the linked data analysis. Energy managers can query any piece of master data and use reasoning to find a more implicit relationship between different data sources and to identify performance problems and key areas for improvement.

The systematic methodology proposed involves a process of continuous improvement until the final energy performance targets are achieved. The development of each task will be elaborated in the following chapters. Stakeholder identification and prioritization, as well as the PI identification and KPI selection, will be illustrated in Chapter 4; the identification of KPI-related master data will be depicted in Chapter 5; the development of the EM-KPI ontology and principles for linked data generation will be, respectively, studied in Chapter 6 and Chapter 7; the other tasks for KPI assessment and multi-level energy performance improvement analysis will be demonstrated based on the case study in Chapter 8.

4 IDENTIFICATION OF STAKEHOLDERS AND KEY PERFORMANCE INDICATORS

4.1 INTRODUCTION

Stakeholders' engagement is critical to the successful implementation of integrated energy management at the district and building levels. Integrated energy management can potentially improve multi-level energy efficiency, but requires the exchange and analysis of energy performance information gathered from different stakeholders. However, with the complexities of energy management, there are numerous potential stakeholders and a considerable amount of information to consider. Therefore, a primary challenge is the development of a method that identifies key stakeholders and extracts key information.

This chapter proposes structured approaches to identify key stakeholders and KPIs for the purpose of drawing key performance information that underpins stakeholders' performance goals. Firstly, a three-task method for the identification and prioritization of stakeholders is suggested in Section 4.2. The method corresponds to tasks 1 to 3 of the proposed methodology as illustrated in Figure 19. It defines the detailed process to identify stakeholders and to conduct a prioritization analysis in order to find the key stakeholders that take precedence over others in decision making. Afterwards, the method used for identifying a pre-list of energy PIs that represent the basic energy performance concerns in the energy management context is depicted in Section 4.3. Finally, a bi-index method to select the KPIs through stakeholders' involvement is defined in Section 4.4. KPIs are selected from the pre-list of energy PIs, and they are represented in a hierarchy of three dimensions in order to represent the multi-level energy performance information.

4.2 STAKEHOLDERS IN DISTRICT AND BUILDING ENERGY MANAGEMENT

Stakeholders play important roles in energy management. Better energy management through better information exchange among the stakeholders is a key to success. A good practice of energy management should take the needs of stakeholders into account. To understand the stakeholders' energy performance goals, the first and the most important step is to identify and analyse the stakeholders and, subsequently, to identify the priority of each for the purpose of prioritizing their performance concerns. In this section, the method used to identify stakeholders and determine their priorities for energy management is defined.

As described in previous Section 2.3.3, a stakeholder can be defined as an internal or external organization and/or individual that has a vested interest in, and/or ability to influence, a project, being directly or indirectly impacted by the project [198]. Although

the importance of stakeholders for the success of a project is clear, there have been very few studies conducted with regard to the identification of stakeholders in the energy management field.

Stakeholder identification and analysis is not an easy task, especially for district-scale energy management. There is a diversity of potential stakeholders involved due to the complexity of energy systems and operations in districts and buildings. The definition of stakeholders can be helpful for stakeholders identification to some extent, but far from sufficient [198]. A detailed method is needed to deal with the practical problem to identify the stakeholders in a specific project.

The most common approaches to stakeholder identification include those adopted by a study of previous similar projects, brainstorming, mind-mapping and the generation of lists of generic stakeholders [220]. In addition, the most commonly used means by which to identify stakeholders in the energy field is through the study of similar previous projects. Using such methods, it is very possible that some stakeholders are omitted, since the processes associated with such methods are usually quite stochastic. Given that some stakeholders will most likely be left out, the list of identified stakeholders cannot be considered complete; therefore, the performance goals of some stakeholders may be unfulfilled. Moreover, in most cases, the stakeholders are chosen without carrying out a detailed analysis, for instance, the stakeholders provided by CanmetENERGY for district energy system [29] or the stakeholders identified for district and building energy retrofitting in the FASUDIR project [199].

There have also been studies carried out in different disciplines that address different methods adopted to identify stakeholders. For instance, Mitchell et al. [200] proposed a theory of three relationship attributes (i.e., power, legitimacy and urgency) to identify both the stakeholders and their importance. Sharp et al. [201] developed an approach to identify the stakeholders involved in requirements engineering processes. Meanwhile, MacCaulay [202] identified four categories of stakeholders in relation to computer systems (i.e., those who design and develop the system, those who have a financial interest, those who introduce and maintain the system and those who are interested in using the system).

Inspired by these studies, especially by the four categories of stakeholders proposed by Macaulay [202], we realized that the stakeholders involved in energy management also come from different stages of the project's life cycle, since their impact on energy performance exists at various stages, such as the plan and design stage, the construction and commissioning stage, the operation and maintenance stage and the end use stage. Furthermore, the information related to energy performance can also be gathered from the various stakeholders at the different stages. Therefore, life cycle is considered as the time dimension for identification of stakeholders. However, integrated energy

management is complicated due to the diversity of the energy operations at the district and building levels; it involves numerous district systems, building blocks, building systems and equipment, all of which should be aligned spatially. Thus, the stakeholders, along with both the space and the time dimensions, should be identified.

The allocation of stakeholders in both the space and the time dimensions results in a detailed three-task method designed for stakeholders' identification and prioritization analysis, as illustrated in Figure 20. Firstly, energy performance intervention points at the different spatial levels are identified as the entry points of stakeholders. Afterwards, stakeholders' roles at the different life cycle stages are identified in accordance with the intervention points. Lastly, a prioritization analysis for identification of key stakeholders is carried out by analysing the stakeholders' importance levels at different intervention points. The following Section 4.2.1 to 4.2.3 present and introduce in detail each of the tasks.

Figure 20: Three-task method for stakeholder identification and prioritization analysis.

4.2.1 Identify Intervention Points to Energy Performance

The identification of energy performance intervention points at the different spatial levels is the first task in order to identify and analyse the stakeholders. The concept of intervention points was initially proposed by Bourdic and Salat [303] for modelling urban energy efficiency, emphasizing four points: urban morphology, building efficiency, system efficiency and individual behaviour. They were developed based on the four fundamental scales proposed by Ratti et al. [308], namely the urban context, the buildings, the systems and the occupants. Although each of the proposed points provides a different intervention mechanism for urban energy efficiency, they have limitations in terms of

describing all of the aspects of energy management. For example, the urban morphology includes energy demand and transportation, but omits other processes such as energy generation, the use of renewable energy and the search for synergy between the demand and the generation required to achieve district energy balance; besides, the building efficiency only accounts for passive designs such as building envelope, orientation and geometric parameters [309], neglecting other important aspects such as the function of the building or indoor comfort.

Therefore, energy managers are supposed to identify their own energy performance intervention points based on the concerns in their own energy management context. Normally, energy performance on the district scale can be described as a well-integrated structure of three levels, from top to bottom, namely the district level, the whole building and system level, and the zone and equipment level. At each level, different intervention points with different intervention mechanisms for energy performance can be identified. They influence different aspects of energy performance, such as the energy balance, the energy saving and the CO₂ emissions. As an example, Table 10 lists five typical intervention points at the three levels, and the aspects to which they relate.

Table 10: Five typical intervention points and their related aspects of energy performance [303]

Level	Intervention point	Related energy performance aspects
District	District energy profile	District energy balance, energy generation/use, renewable energy use, CO ₂ emissions
Building and system	Building performance	Building thermal load, energy use, building energy balance, building comfort (IAQ, thermal comfort, lighting comfort), building usage function, CO ₂ emissions, energy cost
	System efficiency	Energy efficiency, energy use, energy loss, energy cost
Zone and equipment	Equipment efficiency	Energy efficiency, energy use, energy loss, energy cost
	Occupant/Consumer behaviour	Energy demand, energy balance, energy peak curtailing and shifting, energy cost, building comfort

4.2.2 Identification of Stakeholders' Roles

Subsequently, stakeholders from the different life cycle stages get involved in energy management through the different intervention points and play different roles. For example, architects at the plan and design stages are involved because of their influence to building performance, whereas facility managers at the operation and maintenance stage get involved because of their impact to system efficiency.

The second task comprises the identification of the stakeholders' roles. Generally, stakeholders can be classified into two groups, internal and external [304]. Here, internal stakeholders are defined as those who participate directly in energy-related processes and intervene in various aspects of energy performance; while, external stakeholders are those who do not participate directly in the energy-related processes but have a specific interest in, and/or are impacted by, the outcome of the energy management.

The roles of internal stakeholders can be classified into five groups, according to the time dimension of the project's life cycle. Considering together the definition of a stakeholder [198], the five groups of stakeholders' roles are those related to:

- planning and design which have an impact on and/or an interest in various intervention points;
- construction and installation which have an impact on and/or an interest in the intervention points;
- operation and maintenance which have an impact on and/or an interest in different intervention points;
- energy end use;
- financial benefits which potentially involve a profit from energy management.

The roles of external stakeholders who act as regulators, in addition to local governments, are particularly important. Regulations and rules involve basic legal requirements that must be fulfilled. Efficient feedback provided to regulators regarding energy performance can improve further implementation of the related regulations.

The analysis of the stakeholders' role is aimed at formulating a complete list of stakeholders. Energy managers firstly determine the roles, and then identify individuals or groups of stakeholders who correspond to these roles. Table 11 lists some common stakeholder roles involved at different intervention points and life cycle stages. The stakeholders may play multiple roles simultaneously and, meanwhile, influence multiple intervention points. For example, facility managers usually also act as building energy managers, who influence the building performance, system efficiency and equipment efficiency; and energy consumers are often the occupants as well, who intervene to the occupant behaviours and the building performance.

Table 11: List of stakeholder roles involved in various intervention points [29][199]

	Intervention point Life cycle stage	District energy profile	Building performance and systems efficiency	Equipment efficiency and occupant/consumer behaviour
Internal	Plan and design	District planner, energy planner, energy engineer	Architect, electrical and mechanical engineer, energy engineer	Electrical and mechanical engineer, energy engineer
	Construction and installation		Construction company, equipment manufacturer, system installation company	Equipment manufacturer, equipment installation company
	Maintenance and operation	Distribution energy manager, asset manager, energy supplier	Building energy manager, facility manager, building solution provider, distribution energy manager, asset manager	Building energy manager, facility manager, asset manager
	Energy end use	Residential user, commercial user, office user, institutional user	Occupant, building energy consumers/ prosumer	Occupant, building energy consumers/ prosumer
	Financial benefits	Organization owner, energy supplier	Building owner/tenant, energy customer, organization owner	Building owner/tenant, energy customer, energy supplier
External		Central and local government, regulator, energy analyst, energy auditor		
		Environmental advocacy organization, local non-profit and community-based organization (environment/public health), neighbour		

4.2.3 Prioritization Analysis for Key Stakeholders Identification

Among the identified stakeholders, not all of them should be taken at the same level of importance. Therefore, it is necessary to identify the key stakeholders who take precedence in terms of decision making. In this task, a prioritization analysis of the stakeholders is conducted through analysing their importance levels at different intervention points.

To quantify the importance level, a 6-point Likert-type scale [310] is used. The rating scale varies from 0 to 5, where 0 represents the minimum importance, when the stakeholders have no relationship with the specific intervention point, and 5 represents the maximum importance. Referring to the definition of stakeholder, the stakeholders' importance levels at an intervention point can be analysed from three aspects, respectively

the level of their vested interests in the specific point, the level of the ability to influence the point and the level of the impact sustained by the point. Therefore, an impact/interest matrix [311] is introduced to analyse and present the rating value of stakeholders' importance levels relating to an intervention point, as illustrated in Figure 21. The horizontal axis represents the interest level, and the vertical axis indicates the impact level including both the ability to influence and the impact sustained by the point. Therefore, the stakeholders who have high interest and high impact are key players in the point and obtain a rating value of 5; the stakeholders who have high interest but low impact are those who should keep informed; and the stakeholders who have high impact but low interest are those who should keep satisfied and are assigned the rating value of 4 or 3 depending on their impact or interest level; and the stakeholders who have low interest and low impact with least importance have the rating value of 2 or 1. The other stakeholders who have no relation to the point are not included in the matrix and have the value 0.

Figure 21: Rating of the stakeholders' importance levels in an intervention point [311].

For each intervention point, a rating value for each stakeholder can be obtained. As an example, Figure 22 depicts a stakeholder's importance levels for the five typical intervention points, where L_{DEP} , L_{BP} , L_{SE} , L_{EE} and $L_{O/CB}$, respectively represent the importance level regarding district energy profile, building performance, system efficiency, equipment efficiency and occupancy/consumer behaviours. Evaluating the sum of all rating points as opposed to only using a single rating point therefore identifies the overall importance of a stakeholder.

Figure 22: Analysis of a stakeholders' importance level at the five typical intervention points.

A summated rating scale [312] can be constructed to represent the comprehensive importance level, the calculation of which is illustrated in **Equation 1**. The value of the rating scale is defined as the Stakeholder Prioritization Index (SPI), since it determines the stakeholder's prioritization. The result of the SPI varies from 0 to 5. When the stakeholders have a value above the midpoint 2.5, they are identified as key stakeholders, taking precedence in achieving their performance goals.

Equation 1: $SPI = (L_{DEP} + L_{BP} + L_{SE} + L_{EE} + L_{O/CB})/5$

4.3 IDENTIFICATION OF THE PRE-LIST OF PERFORMANCE INDICATORS

After identifying the stakeholders, the next step is to transfer the stakeholders' performance goals into a way that can be measured and tracked. Performance indicators (PI) are an effective means for measuring progress towards stakeholders' performance goals, and also offer a typical summary of performance information. The purpose of the pre-list of PIs is to provide a total collection of indicators for facilitating KPI selection. The written list of PIs should completely represent the performance concerns in an energy management context.

The regulation ISO 50001 provides guidance to define the energy PIs for continual performance improvement [234]. It introduces the use of an energy review to find the related indicators. The energy review includes the analysis of the energy structure (e.g., electricity, gas), the energy systems (e.g., generation, storage, distribution and

consumption systems) and the energy flow (e.g., energy distribution and end use) [305]. Figure 23 illustrates the process adopted to identify the pre-list of PIs based on the regulation ISO 50001.

Figure 23: Process to identify the pre-list of performance indicators in energy management.

The procedures to identify the PIs can be depicted as follows:

- i. Firstly, energy managers should specify the functional and legal requirements for the energy management plan. The functional requirements should represent the key performance goals of stakeholders. The legal requirements should align to the respective regulations, such as the macro goals of the EU objective 40/27/25, which requires an increase of renewable energy use by 40%, a reduction of CO₂ emissions by 27% and an improvement of energy efficiency by 25%.
- ii. Secondly, the energy structure analysis involves the energy use features in the district, such as the type of energy resources generated or consumed. The energy structure analysis provides an overview of the energy types in the district.
- iii. Thirdly, a thorough understanding of different energy systems and equipment in the district and buildings is essential for identifying corresponding performance indicators. It is important to know what systems and equipment generate, store, deliver and consume energy. The systems and equipment could be listed in tables in order to make it clearer. The result of this process will also support implementing energy efficiency measures in further analyses [305].
- i. Subsequently, an analysis of energy flow from the energy generation, storage, distribution to the energy end use is conducted in order to understand the energy processes and to check if there are energy losses and which systems are the significant energy consumers. The energy flow in the district could be bidirectional with the use of smart grid or microgrid, which means energy can be supplied from the external grid and also fed into the grid.

- ii. Finally, a list of energy performance indicators can be devised according to the energy review. As a result, the generated list of PIs can represent the overall energy performance concerns in the energy management context.

Since a considerable amount of energy PIs already exists as reviewed in Section 2.4.2, energy managers can also reuse those previous indicators that are applicable in their specific energy management context. Some of the existing PIs can refer to current energy assessment systems for districts and buildings [313][303], such as LEED and LEED-ND, BREEAM and BREEAM Communities, CASBEE and CASBEE-UD. However, such assessment systems have two main deficiencies, namely the evaluation of energy and environmental efficiency at a hyper-aggregated level and a lack of attention to detailed system efficiency and individual behaviours [303]. Thus, we can also refer to the PIs proposed by other related studies or develop new PIs when necessary.

4.4 KPI SELECTION FOR DISTRICT AND BUILDING ENERGY MANAGEMENT

Since the KPIs are those key indicators that measure key performance goals, this implies that only the most representative PIs should be selected as KPIs. A good list of KPIs should be inclusive and holistic in order to provide key energy performance information at different levels (i.e., district, building, system, equipment) and to capture the interdependences between the various KPIs. Additionally, the list of KPIs should be wide-ranging to cover different energy related aspects, clearly defined for different stakeholders to interpret easily, scientifically valid for decision making support, and flexible for further improvement [254].

According to the principles of facility management [314], the hierarchy of KPIs can be presented as strategic, tactical and operational; each of these refers to different decision levels. Similarly, the KPIs related to energy management can also follow these levels. In addition, different decision levels can relate to different aggregation levels and scales [315]. Therefore, the KPIs are illustrated in a well-integrated structure on three levels as shown in Figure 24. This KPI hierarchy supports tracking multi-level energy performance. The strategic KPI is aggregated and designed for the district level. The tactical KPI can be disaggregated from the strategic equivalent and associated with the building and system levels. The operational KPIs represent the operational performance of basic energy units such as equipment and zones. This hierarchy has the advantage of distributing the different KPIs at different levels, yet in an interrelated form and maintaining their interdependences. Energy performance information and assessment align to this multi-level structure, which are the foundation for improvement analysis.

Figure 24: Three dimensions of strategic, tactical and operational KPIs [314][315].

To identify the KPIs, the most common methods used currently include literature reviews, stakeholder validation, or discussion with industry players and experts [252][254]. However, these methods are predominantly qualitative. The method of stakeholder validation takes into account stakeholders' involvement once the KPIs have been identified, and stakeholders only need to validate these KPIs. These validated KPIs can support stakeholders' performance goals to some extent. Nevertheless, a more favourable outcome should be attainable if stakeholders are able to select their specific KPIs at the beginning of the process. Furthermore, a quantitative method to weight and validate the indicators is still needed.

A previous study by Chen et al. [259] proposed an energy-time consumption index (ETI) to select KPIs for intelligent building lifespan assessment. It is a quantitative approach to the selection of the KPIs. However, it does not consider the stakeholders' involvement. Other methods, such as the balanced scorecard (BSc), are usually applied in enterprise contexts [316].

In this section, a bi-index method is proposed in order to select the KPIs that underpin the stakeholders' performance goals from the written pre-list of energy PIs. The two indexes are the stakeholder prioritization index (SPI), as proposed in Section 4.2.3, and a stakeholder vote index (SVI).

The SVI index is determined by stakeholders' interviews. The stakeholders grade the PI from 0 to 5 based on a 6-point Likert-type scale [310], where 0 means that the PI is not related to the stakeholder's performance goals, while 5 means that the PI is of the most importance to them. Each stakeholder gives an SVI to every specific PI. The issue of whether each PI is considered a KPI or not depends on the summated rating scale decided by the votes from all the stakeholders. Thus, a comprehensive index (CI) is defined to represent the value of such rating scale. The calculation of the CI follows **Equation 2**, where SVI_{Si} represents the vote of stakeholder i , and w_i represents the weighting factor of the vote. The vote of stakeholders guarantees that the selected KPIs support their goals, and the purpose of the weighting factor is to prevent the stakeholders from maximizing

their own benefits at the expense of others. The sum of w_i is designed to be 1, which ensures that the rating value varies also from 0 to 5.

Equation 2: $CI_{PI} = \sum_{i=1}^n (w_i * SVI_{Si})$, where $\sum_{i=1}^n w_i = 1$

Since stakeholders have different priority levels, it is reasonable that the weighting factor of their vote is based on their significance. Therefore, the SPI is used to calculate w_i . In doing so, the selected KPIs can also balance the benefits of various stakeholders. The calculation of the weighting factor follows **Equation 3**, where SPI_{Si} represents the prioritization of stakeholder i .

Equation 3: $w_i = SPI_{Si} / \sum_{i=1}^n SPI_{Si}$

Considering both the stakeholders' votes and prioritization, the value of CI can be calculated for each PI. The CI determines whether the PI will be chosen as a KPI or not. If it is higher than the average rating value 2.5, the PI will be considered a key performance indicator. The final list of KPIs should be validated again by the stakeholders [254].

4.5 SUMMARY

This section elaborates the development of a three-task method to identify key stakeholders and a bi-index method to select KPIs, in order to enable stakeholder engagement and extract multi-level key performance information that underpin the stakeholders' goals.

Since integrated energy management is a multi-stakeholder issue, there are numerous potential stakeholders, in addition to a vast amount of information involved. Energy management should help achieving stakeholders' performance goals in order to motivate their engagement for information sharing and decision making.

Firstly, it is essential to know who are the stakeholders, and, furthermore, who are the key stakeholders taking precedence over others in decision making. The three-task method provides a structured method used to identify stakeholders and conduct their prioritization analysis. The method includes three tasks: (1) identifying energy performance intervention points at different spatial levels, (2) identifying stakeholders' roles from different life cycle stages and (3) analysing stakeholders' prioritization for identification of key stakeholders. The intervention points are introduced not only to identify the stakeholders, but also to analyse their importance and to calculate the stakeholder prioritization index (SPI).

The use of KPIs offers a means by which to represent a few critical pieces of actionable information and support stakeholders' goals. The bi-index method provides a quantitative

means by which to weight and select KPIs through stakeholders' involvement. KPIs are selected from a pre-list of energy PIs identified through the analysis of district energy structure, energy systems and energy flow, in addition to the literature review of previous indicators. The method proposed for KPI selection considers two indexes, namely the stakeholder vote index (SVI), obtained via stakeholders' interviews, and the stakeholder prioritization index (SPI), obtained from the prioritization analyses. The KPIs selected using these two indexes help supporting stakeholders' performance goals, yet balance their benefits. In order to represent the multi-level performance, KPIs are illustrated at three levels, respectively, strategic, tactic and operational.

5 IDENTIFICATION OF KPI-RELATED MASTER DATA

5.1 INTRODUCTION

The selection of KPIs aims for energy performance tracking and assessment; moreover, the purpose of the assessment is to provide improvement initiatives. However, energy managers can improve the performance only when the related data is available. Data plays a critical role in energy management. The related data sources are needed in order to support energy performance analysis and decision making in improvement measures. However, due to the accelerated use of ICTs, there is a massive amount of data involved in integrated energy management. The extraction of core insightful data is a major challenge.

In this section, the concept of master data is introduced to represent the core data that provides key valuable information. Firstly, Section 5.2 introduces the main data typologies involved in multi-level energy management. Afterwards, Section 5.3 proposes the method adopted to identify master data using the KPIs. The master data identified with the KPIs can ensure that it support stakeholders' performance concerns, so as to avoid unnecessary data collection and analysis.

The identification and collection of master data illustrated in this chapter is a detailed work of Task 7 in the proposed methodology as described in Chapter 3.

5.2 DATA TYPOLOGIES AT DIFFERENT LEVELS

The energy-related data involved in multi-level energy management are numerous, coming from different domains in buildings and districts, as reviewed in Section 2.3.4. The cross-domain data are also distributed at different spatial and time dimensions (Figure 25). The scales mainly include the district, building, system, equipment and zone; and the stages generally involve the plan and design, the construction and installation, the operation and maintenance and the energy end use. The two dimensions are consistent with those proposed in Section 4.2 for stakeholder identification, since the stakeholders are those who provide the cross-domain data. Figure 25 also shows some information examples generated from these stages, for instance the site details, 2D/3D drawings and material specification gathered from the design and construction stages; and the metering readings, sensor data and weather data provided by the operation and end use stages.

Figure 25: Energy-related information from different stages of the project's life cycle and different scales.

The energy-related data from different stages and scales can be further classified into several data typologies. According to the data frequency for their collection, they can be classified into three main categories, i.e., static data, dynamic data and streaming data [35][317].

- Static data are those that are not likely to be modified, such as the building area, building envelop, location, equipment ratings, the 3D building information model (BIM). Such data are typically collected during the initial design and construction stages.
- Dynamic data are those that are modified periodically, but there is no constant flow of information, updates may come at any time. The typical dynamic data in energy management include utility bills, the meter readings of energy generation and consumption during a period and so on. They are usually generated during the operation and maintenance stage and the end use stage.
- Streaming data are those that change continuously, which are different from dynamic data, since they have constant flow of information. The real-time or nearly real-time data from the smart meters or sensors are included in this type. They are also collected from the operation and maintenance and the end use stages.

Additionally, there are also some other studies in relation to more specific data classifications in buildings. For instance, in order to address the type and frequency of data collection in buildings, New Buildings Institute (NBI) designed four levels of data

with increasing levels of details. Level 0 represents the whole-building data such as monthly electric and gas bill data; level I represents the advanced metering interval data for electric use in a building; level II represents the sub-meter data of energy use in a building; and level III involves the sub-meter data of the systems [318].

The Internet Energy Agency Programme on Energy in Buildings and Communities (EBC) has also proposed three-level data typologies for residential and office buildings [319]. The proposed data typologies describe factors that influence energy use in buildings; it includes the simple, intermediate and complex database, which define the items for climate, indoor thermal environment, building characteristics, building envelope, building services and energy systems, and building operations with different levels of details.

Donnelly [36] also proposed three levels of building data in a similar way. The simple level building data focus on tracking monthly energy usage and cost data, which can help understand the basic building performance. The intermediate level building data comprise more detailed and more regular intervals of data for completing analyses on building systems' performance, such as the weekly utility data, electric power meter data and so on. The advanced level building data describe the real-time data collected by more advanced technologies, such as the data from sub-meters, smart meters, sensors and occupant survey. Such data help understand energy performance and make decisions to optimize energy use in real time.

These previous studies focus on the data typologies at an individual building level. The energy-related data for district-scale energy management in this study can be classified in a similar way. Four data typologies are proposed as shown in Figure 26. They are static data at simple level, yearly/monthly dynamic data at simple level, weekly/daily dynamic data at intermediate level and hourly/real-time streaming data at advance level. The static data at simply level comprises the district location, climate zone, building characteristics, building type, device information, etc; the yearly/monthly dynamic data at simple level includes the utility bills, energy bills, monthly energy meters and so on; the weekly/daily dynamic data at intermediate level involves the weekly energy bills, daily energy meters, occupant number, occupant activities and others; and the hourly/real-time data at advance level contains the data from smart meters, sub-meters, sensors, etc. The following Table 12 to Table 15 list some typical data according to their typologies.

Figure 26: Four data typologies in energy management at the district and building levels.

Table 12: Summary of typical static data at simple level

Static data	Data items
Climate	Climate zone
Location	District geographic coordinate, building address, zip code
District	Number of buildings, organizations, owners, energy usage type, fuel type
Whole building characteristics	Year-built, number of floors, thermal zones and rooms, conditioned and/or heated floor area, gross floor area, building use, building type (office, residential, commercial, manufacturing, etc.), building activity area, number of unit, building orientation
Building envelope	Floors, slabs, roofs, walls, windows and doors, material and thickness, u-value, shading, window-to-wall ratio, etc.
Building systems	The features including the type, fuel type, heat capacity and total power of heating system, cooling system, ventilation system, lighting system, domestic hot water system, appliances, power system and others
Building equipment	The product information and features of HVAC equipment, lighting equipment, appliances, power equipment, etc., such as energy rating
Building geometry	Geometry information from CAD plan or BIM model
District power system and equipment	The type, fuel type, capacity and total power of the distributed energy generation, power distribution and storage systems and equipment
Occupancy characteristics	Occupancy density, interest, family factors, energy-related attitude

Table 13: Summary of typical yearly/monthly dynamic data at intermediate level

Yearly/monthly dynamic data	Data items
Climate	HDD (heating degree day), CDD (cooling degree day)
Weather	Yearly and monthly average temperature, humidity, wind and solar radiation data in the location
Utility or energy bills	Yearly/monthly energy usage and cost data from utility bills
Energy price	Fixed energy price over a period
Building operation	Annual/monthly schedule of systems, such as number of days and weeks
Maintenance data	Maintenance schedules that track equipment and systems over a year or a month and indicate when maintenance or equipment replacements are necessary
Occupant	Number of occupants, Occupancy rates, thermal environmental satisfaction of occupants, occupancy schedule
Energy estimation data	Estimation of annual and monthly energy production and consumption by power rating and operating schedules

Table 14: Summary of typical weekly/daily dynamic data at intermediate level

Weekly/daily dynamic data	Data items
Weather	Weekly and daily weather conditions such as rainy, sunny and snowy in the location, weekly and daily temperature, humidity, wind and solar data in the location
Weekly utility data	Weekly energy usage, demand, costs and rates data collected directly from the utility
Electric power meters	High-resolution energy data capture from metering, when detailed energy consumption data is required but not available from the utility
Building management system (BMS), building automation system (BAS), or building energy management system (BEMS)	Data of the mechanical, electrical and plumbing systems in a building over certain periods of time.
Building operation	Weekly and daily schedule of systems, including number of days and operating hours, and range of running hours
Occupancy	Occupancy schedule, plug loads, plug schedule, number of occupant
Human resources (HR)	Number of employees, workspaces, hours of operation, and types of operations
Maintenance data	Weekly and daily maintenance schedules that track equipment and system over time
Energy estimation data	Short-term estimation of energy production and consumption based on the actual equipment and occupancy data and accurate weather forecast

Table 15: Summary of typical hourly/real-time streaming data at advanced level

Hourly/real-time streaming data	Data items
Local weather station	Real-time and nearly real-time data of environmental temperature, humidity, wind and solar in the location
Smart meters	Real-time and nearly real-time energy production, supply, usage and demand data of the buildings
Sub-meters	Real-time and nearly real-time consumption or performance data of specific sub-systems or pieces of equipment
Sensors of devices	Sensor data collected through BEMS or SCADA system; a variety of parameters of the devices can be monitored, such as temperatures, pressures, flow rates, power, etc.
Sensors of occupancy	Real-time or nearly real-time sensor data of room occupancy, occupant activity levels, and plug loads
Sensors of indoor comfort	Sensor data of indoor temperature, indoor humidity, ventilation rate, indoor air quality, indoor pollutant concentrations, acoustics, light intensities on work surfaces, indoor illumination
Energy market	Real-time energy price

5.3 USING KPIS TO IDENTIFY MASTER DATA

There is a massive amount of data involved in energy management. The energy information system has the trend to collect data as much as possible and as quickly as possible, thus it is critical to find the useful and insightful data in order to obtain economic and environment benefits from it [35]. However, although it is obvious that the exploitation of the generated data can play important roles in reducing energy use and costs, it is yet an issue that the energy managers can be overwhelmed by the big amount of data.

Master data is a way to represent the critical data that provide the most valuable information in an organization [306]. It has been used for enterprise data management since last decade, because of the large volumes of data generated in the business processes. The master data represents the key business objects that need to be shared across or beyond an enterprise, along with their associated metadata, attributes, definitions, connections and taxonomies [320]. Wang et al. [321] developed the steps and methodology to identify master data in business processes. Nowadays, a similar situation is facing in the energy field to use the big amount of data. An introduction of master data to the energy field can help to bring insightful energy-related data to value and improve the quality of decision making as well.

The master data in energy management should be tied to the energy processes and support the stakeholders' key goals. Using KPIS to identify the master data is a possible solution. There are also some similar practices to identify key data with KPIS or metrics [35][307]. KPIS can be taken as a representation of critical pieces of performance information

summarized from the master data, which can be used to track and measure performance. Using KPIs to identify the master data can avoid unnecessary data analysis and exclude irrelevant information.

The procedures developed to identify master data using KPIs are shown in Figure 27. The first two steps are associated to the understanding of energy management context and the selected KPIs. Using the KPIs, the related data can be identified from different master data domains. The domains contain master data objects. Afterwards, different master data elements pertaining to the objects can be identified.

Figure 27: Procedures to use KPIs to identify the master data.

The way to identify master data objects and elements is quite straightforward. Wolter and Haselden [322] has defined several criteria for deciding if a given entity should be treated as master data. The criteria include (1) the behaviour, which describes the way the data entity interacts with others; (2) the life cycle, which means the way the data is created, read, updated, deleted, searched; (3) the cardinality, which represents the number of elements in a set; (4) the lifetime, such as one year, one month, etc.; (5) the value, which means that if the data element is valuable to the organization, it will be considered a master data element; (5) the volatility, which refers that entities with attributes that do not change at all may not require a master-data solution; and (6) the reuse, which is one of the primary drivers of master data management, since the information has increasing needs to be shared across multiple applications.

The value and the reuse are chosen as the two main criteria for the identification of the master data objects and elements in this study. The master data objects should be related to the evaluated objects of KPIs. While, the master data elements comprise the data sources needed for the KPIs' calculation and performance analysis. Using the KPIs as a navigation, the master data with key value can be identified. Furthermore, it can ensure the maximal reuse of the master data for its exploitation and analysis.

After identifying the master data, the next step is to collect them in the related source systems. For example, energy consumption data in a building are usually gathered from the energy monitoring and control system; and energy distribution data in a district always come from the SCADA (Supervisory Control and Data Acquisition) system. In case that the existing data capture doesn't contain all of the needed master data sources, a further data collection plan should be made and fulfilled in order to gather the necessary data. For the collection of building data, the international standard ISO 12655:2013 [323] provides a guidance. The standard is applicable to the presentation of energy use of civil buildings for data collection, metering, statistics, audit and analysis.

Furthermore, the master data usually has its own data hierarchy. To manage and use the data, it is important to build the data model and maintain its hierarchy for further application. In the following Chapter 6, an ontology model will be developed to describe the interrelationship between the master data domains, objects and elements, as well as the interrelationship between the KPIs and master data.

5.4 SUMMARY

In order to categorize the data for an easier collection and analysis, this chapter firstly introduces the capture of energy-related information at different spatial scales and life cycle stages, in addition to the classification of data typologies according to their frequency and levels of detail. Some typical data in relation to each typology are listed. Subsequently, when seeking to access the large amount of energy-related data, the extraction of master data is introduced. The method using the KPIs for the identification of master data is proposed. Using the KPIs, the master data domains are identified first. Then, the related master data objects and elements in each domain are found out. The related master data are those which are necessary for the KPIs' calculation and performance analysis. The use of master data helps to focus on the data which is worth collecting and the analyses which are worth conducting.

6 DEVELOPMENT OF THE EM-KPI ONTOLOGY

6.1 INTRODUCTION

The key performance information represented by the KPIs and the cross-domain master data are usually stored in different information islands; there is little interaction between each other for effective data sharing and exchange [38]. One of the main barriers is due to the interoperability of heterogeneous data, since the data in EM usually includes multiple domains. However, the key performance information and the master data should be shared among different stakeholders in order to promote their collaborative engagement. If the stakeholders can gain easy access to both the performance information and the related master data, they can obtain a better understanding of performance and areas requiring improvement.

Therefore, an EM-KPI ontology is developed in this chapter to facilitate the interchange of key performance information and insightful master data at the district and building levels. The ontology aims to provide a more effective engagement mechanism between the stakeholders. It describes the relationship between the multi-level KPIs and the cross-domain master data. It integrates the KPIs, their calculation and the master data, in order to provide the basis for both performance tracking and exploration of insights for performance improvement. Stakeholders are involved in the data exchange in order to promote engagement and enhance multi-level energy management.

In Section 6.2, the methodology used for the development of the EM-KPI ontology is introduced. Following the procedures of the adopted methodology, Section 6.3 elaborates the ontology requirement definition, including its functional and non-functional requirement. Section 6.4 extracts the terms for developing the ontology. Section 6.5 illustrates the conceptual model of the target ontology. Section 6.6 searches and selects the existing ontology resources that could be reused by the target ontology. Section 6.7 implements the EM-KPI ontology. The evaluation of the proposed ontology is conducted in Section 6.8. Finally, the publication of the developed ontology is illustrated in Section 6.9.

This chapter develops in detail Subtask 8.1 of the proposed methodology as illustrated in Chapter 3. The ontology is aimed to facilitate the generation of linked data for the data exchange and exploitation. The implemented ontology is published on the web, which is available for open reuse and application.

6.2 METHODOLOGY FOR EM-KPI ONTOLOGY DEVELOPMENT

The development of the EM-KPI ontology follows the NeOn ontology engineering methodology [324]. This method builds ontology networks through reusing and re-engineering knowledge resources as opposed to building new ontologies from scratch. Since the energy management at the district and building scales is multi-domain and complex, the targeted EM-KPI ontology may be relatively complicated. If each term and domain need to be defined anew, there will be huge amounts of work. Fortunately, a range of reusable ontology resources already exists in different domains. Linking the existing knowledges in the existing ontologies to generate a new ontology network which has a specific aim of serving the new application can save time and work and, furthermore, facilitate the implementation of the ontology. The reusable ontological resources include the ontology patterns and vocabularies, which can be reused as a whole or partially. While, it is essential to justify the reason why the resources are chosen. In order to complete the ontology, new patterns and concepts also need to be defined for the purpose of representing the new creative content. The ontology network developed by re-engineering the existing resources and integrating the new defined ones could provide vigour to new applications.

Using the NeOn methodology, the process adopted to develop the EM-KPI ontology is illustrated in Figure 28. The first step involves the definition of ontology requirements. It contains six sub-steps, which are, respectively, (1) the identification of ontology purpose, scope and implementation language; (2) the determination of ontology intended end-users; (3) the design of the intended end use; (4) the identification of the non-functional and functional requirements of the ontology; (5) the grouping of the ontology requirements; and (6) the validation and prioritization of the ontology requirements.

Subsequently, the second step aims to extract the terms for building the ontology. Following this, the third step defines the conceptual model of the ontology based on the identified terms. In order to have a global view of the relationship between different domains, an initial model should be drafted first. Afterwards, the detailed model is developed to refine the model. The development of the ontology detailed model goes in parallel with the fourth step, ontology search and selection, in order to maximize the ontology reuse. The fifth step is to implement the ontology by integrating the reused ontologies and the new developed ontology patterns and concepts. If the ontology can represent all the data pointing to the applications or use-case experiments, it is completed, and is subsequently evaluated in the sixth step. Otherwise, additional work for the ontology completion should be performed.

Figure 28: Ontology development process with the NeOn methodology [324].

6.3 ONTOLOGY REQUIREMENTS DEFINITION

Ontology requirements definition is the first and the most important step for ontology development; the related activities are conducted to define why the EM-KPI ontology is being built, which is the implementation language, which are its intended uses, who are the end-users, and what requirements the ontology should fulfil.

6.3.1 Identifying Purpose, Scope and Implementation Language

The targeted EM-KPI ontology is aimed to exchange both the master data and key performance information between different stakeholders in district and buildings, in order to enhance energy management on both scales and to enable the exploitation of knowledge and insights in linked data for performance tracking and improvement.

The EM-KPI ontology is proposed to be represented by two components, namely the EM (energy management) master data and the KPI (key performance indicator) components, as shown in Figure 29. The purpose of the KPI component is to represent the key performance information. This includes KPI definitions, associated performance goals and stakeholders, evaluated objects, calculations and needed datum sources. This part provides the basis for energy performance tracking and assessment. Meanwhile, the purpose of the EM master data component is to integrate the master data in districts and buildings. It aims to describe the relationship between the master data domains, objects and elements. In doing so, this helps to exploit the knowledge and insights in the master

data sources for identifying energy performance problems and key areas for improvement, and to support energy managers in making informed decisions in regard to energy efficiency measures.

Figure 29: Proposed EM master data and KPI components of the EM-KPI ontology.

The link between the EM master data and the KPI components occurs through the data objects and elements, as the master data objects are associated with the KPI-evaluated objects, and the master data elements provide the datum sources for KPI calculation.

The KPIs that underpin the stakeholders' performance goals should represent different energy performance aspects at different levels. Generally, KPIs in energy management are classified into strategic, tactical and operational, as proposed in Section 4.4. The three-level KPIs, respectively, represent the energy performance information at the district level, the building and system level, and the zone and equipment level. Furthermore, the related master data domains in energy management include the energy, sensor and measurement, building, facility, utility, occupancy, weather, location, etc. [325].

The targeted ontology will be implemented in OWL (Web Ontology Language)⁴⁴.

6.3.2 Identifying the Intended End-users

Since the energy management is aimed to improve multi-level energy efficiency, the intended end-users of the ontology should be those who are responsible for the optimization of energy operations in district and buildings. In this case, energy managers are the main actors. The district energy managers and building energy managers interact through the ontology and use the shared data from different stakeholders to analyse and improve energy performance, so as to achieve the performance goals. In addition, the

⁴⁴Web Ontology Language (OWL) is a family of knowledge representation languages for authoring ontologies. An overview of OWL Web Ontology Language can refer to <https://www.w3.org/TR/owl-features/>.

stakeholders should become informed with regard to relevant energy performance by gaining access to related information, and thereby engage in decision-making. Therefore, the end-users of the ontology include as follows:

- User 1. District energy managers who perform district energy operations;
- User 2. Building energy managers who fulfil building energy optimization; and
- User 3. Stakeholders who are involved in the energy management.

6.3.3 Identifying the Intended Uses

The main intended uses of the ontology are, respectively,

- Use 1. To exchange the energy-related master data among different stakeholders;
- Use 2. To provide key performance information for different stakeholders; and
- Use 3. To support performance analysis through the linked data for identifying performance problems and key areas for improvement in district and buildings, thus to achieve stakeholders' performance goals.

6.3.4 Identifying the Non-functional and Functional Requirements

Regarding the non-functional requirements, the ontology should try to adopt the concepts and design patterns in reusable existing ontologies where possible, combining with the new developed ones when necessary. In addition, the ontology is developed in English language, in order to reach a wider range of audience.

The competency question (CQ) technique [326] is used for the identification of functional requirements that specify the knowledge which should be encapsulated within the ontology model. Considering the intended application and use-case experiments, the CQs are defined from the KPIs to the related master data domains using a top-down approach. In total 83 CQs are identified, which are presented in the Appendix B. Some examples of the CQs are as follows:

- Who are the stakeholders involved in energy management at district and building levels?
- What KPIs can be used to measure the performance goals of stakeholders?
- How can KPIs be calculated?
- What observation provides the datum sources for KPI calculation?
- Where is the district located?
- What type of buildings does the district contain?
- What kind of energy-generating units are installed in the district?
- When is the energy production monitored?
- What is the unit of measurement of the energy production?
- What energy aspects are influenced by the weather?

6.3.5 Grouping Functional Requirements

Subsequently, the CQs are categorized according to the domains to which their knowledge belongs. For example, CQ3 (what KPIs can be used to measure the performance goals of stakeholders) is classified into the KPI domain, since the answer to this question refers to the related KPIs; and CQ10 (what observation provides the datum sources for the calculation of KPIs) is grouped into the observation domain, because its answer involves the observation data. Each CQ is assigned to the respective domain, as shown in Appendix A. As a result, the 83 CQs are divided into ten groups, which are KPI, energy, utility, building, occupancy, location, weather, date and time, observation, and unit. Table 16 summarizes the CQs in accordance with their groups.

Table 16: Competency questions groups (CQGs) for the definition of ontology functional requirements.

Group	Domain	Competency Questions
CQG1	KPI	CQ1, CQ2, CQ3, CQ4, CQ5, CQ6, CQ7, CQ8
CQG2	Utility	CQ22, CQ24, CQ28, CQ29, CQ30, CQ31, CQ32
CQG3	Building	CQ33, CQ34, CQ35, CQ36, CQ38, CQ39, CQ40, CQ41, CQ45, CQ50
CQG4	Occupancy	CQ46, CQ47, CQ48, CQ49
CQG5	Location	CQ11, CQ12, CQ23, CQ37
CQG6	Weather	CQ13, CQ14, CQ15, CQ16, CQ17
CQG7	Date and time	CQ19, CQ26, CQ43, CQ53, CQ65, CQ68, CQ72, CQ75, CQ78
CQG8	Observation	CQ10, CQ18, CQ25, CQ42, CQ51, CQ64, CQ67, CQ70, CQ74, CQ77
CQG9	Unit	CQ9, CQ20, CQ27, CQ44, CQ52, CQ66, CQ69, CQ73, CQ76, CQ79
CQG10	Energy	CQ21, CQ54, CQ55, CQ56, CQ57, CQ58, CQ59, CQ60, CQ61, CQ62, CQ63, CQ71, CQ80, CQ81, CQ82, CQ83

Afterwards, the validation of the ontology requirements is performed by the energy managers, which outputs an Ontology Requirements Specification Document (ORS) as presented in Appendix B. The analysis to prioritize the ontology requirements is not conducted here, which means that the ontology must be able to represent all the functional and non-functional requirements defined above, and the knowledge contained in all of the CQs should be covered.

6.4 TERM EXTRACTION

Since the CQs contain the knowledge that should be covered by the ontology, most of the ontology terms can be extracted from the CQs and their answers related to the use-case experiments. Table 17 lists the terms that extracted from the CQs and their synonyms in brackets. Other terms can also be directly extracted from the data sources of use cases and/or the existing ontologies.

Table 17: Terminology from competency questions and their synonyms in brackets

Top terms
Key Performance Indicator (KPI), district, building, observation (measurement), location, KPI calculation, weather, interval and date time (temporal entity), unit, power system (utility), occupant
Other terms
Stakeholder, energy performance goal, KPI evaluated object, interval, KPI value, datum source, geographic coordinate point, weather condition, weather phenomenon, weather forecast, energy type, power equipment, generating unit, storage unit, power delivery unit, energy consumer, energy facility, building type, building dimension (area, volume, etc.), building element (wall, window, floor, roof, etc.), thermal property (U-value), building equipment, schedule, event, occupant behaviour, indoor comfort, energy parameter, energy production, energy storage, energy delivery (energy supply), energy consumption (energy demand), energy cost, energy tariff, energy forecast, equipment parameter

6.5 ONTOLOGY CONCEPTUALIZATION

With the identified knowledge domains and terms, the ontology conceptual model, represented by different ontology modules, is illustrated in this chapter.

An initial conceptualisation of the EM-KPI ontology was drafted in order to gain a global view of the main classes and relationships within the different domains. Figure 30 illustrates the conceptual model of the proposed ontology using the extracted terms. This model has been built taking into account both the ontology's purpose and scope as stated in Section 6.3.1, and the functional requirements identified in Section 6.3.4. It describes both the KPI and the master data components, which are shown respectively in the left and right parts. Some of the domains have been combined into one module, since they are closely interrelated. As a result, the target ontology is divided into seven ontology modules, namely KPI, infrastructure, weather, location, occupancy, observation and domain parameter. The module in red squares represents the KPI component; other modules are related to the EM master data component, including the master data domains, objects and elements.

Figure 30: Initial conceptual model of the EM-KPI ontology.

The KPI module represents the main classes and relationships related to the KPIs, including the KPI definition, its related strategic performance goals and stakeholders, the KPI calculation and so on. Since the KPI calculation requires the datum sources provided by observations, it is linked to the observation module. The observation module illustrates the various concepts for the description of observation results, observed property and its feature of interest. The time and unit domains are also included in the observation module, as they are essential for unambiguous descriptions of the observation data. It is of equal importance to represent the evaluation time and the unit of the KPIs also. In any case, each KPI and observation has an associated object, which can be either physical or virtual.

To represent the KPI-evaluated objects and the features of interest related to the observation, the infrastructure module and the occupant module have been developed. The infrastructure module describes the power system resources and the buildings in the district, including their subclasses, components and elements. Meanwhile, the occupant module represents the occupants in the buildings and occupants' behaviours that influence the energy usage. These two modules provide objects for the observation and the KPI evaluation. Additionally, the objects in these two modules offer different parameters for observations, such as the building parameters, the equipment parameters, the occupancy parameters and the energy parameters. Such parameters are represented in a separate domain parameter module; they can be treated as the subclasses of the observed property from the observation module. Furthermore, in order to identify the external environment of the objects, the location module and the weather module are indispensable.

among which the weather module provides the outdoor environment parameters for observation.

Each module in the initial conceptual model will be illustrated in detail in Section 6.7. The following ontology search and selection for implementing the detailed ontology uses this conceptual model as a guide. Following this, the detailed models will be developed.

6.6 ONTOLOGY SEARCH AND SELECTION

Some widely-known ontologies in the related domains contain the classes and/or properties that can be reused in the EM-KPI ontology. A literature review and online search of existing ontologies in regard to the related domains was carried out in order to find those that best fit the previously extracted terms. The online search was performed using the Google search engine, based on domain-specific keywords. In addition, the smart cities ontology catalogue developed in the READY4SmartCities project⁴⁵ was also used as a tool for searching reusable ontologies; this catalogue contains ontologies that describes the different domains in smart cities, including the building, facility and/or energy, among others. Furthermore, some widely-recognised ontologies were selected beforehand, since they are standard ones or are already well-known for describing certain classes and/or properties.

Table 18 lists the ontologies whose patterns and/or vocabulary have been reused for building the EM-KPI ontology, including their namespaces, prefixes and example terms. These ontologies are all available on the Web and the reason for their selection is offered below.

Table 18: Ontologies selected for the development of the EM-KPI ontology

Ontology	Namespace	Prefix	Term example
DUL ontology	http://www.ontologydesignpatterns.org/ont/dul/DUL.owl	dul	<i>PhysicalObject, hasLocation, isLocationOf</i>
Dublin Core ontology	http://purl.org/dc/terms/	dct	<i>identifier, title, description, type, Location</i>
WGS84 Geo Positioning Ontology	http://www.w3.org/2003/01/geo/wgs84_pos#	geo	<i>Point, lat, long, alt</i>
schema.org	http://schema.org/	schema	<i>Event, Postal Address</i>
gbBuilding Information Ontology (BIO)	https://www.auto.tuwien.ac.at/downloads/thinkhome/ontology/building/1_10/gbBuildingOntology.owl	bio	<i>Building, Building Element, Zone, containsArea, Area, containsVolume, Volume, BuildingStorey, Weather</i>

⁴⁵ <http://smartcity.linkeddata.es/>

Energy Resource Ontology (ERO)	https://www.auto.tuwien.ac.at/downloads/thinkhome/ontology/EnergyResourceOntology.owl	ero	<i>EnergyFacility, Equipment, Appliance, consumesEnergy, producesEnergy, EnergySupply, EnergyDemand, EnergyType</i>
Weather Ontology	https://www.auto.tuwien.ac.at/downloads/thinkhome/ontology/WeatherOntology.owl	wo	<i>WeatherCondition, WeatherPhenomenon, Humidity, SolarIrradiance</i>
User Behaviour and Building Process Information	https://www.auto.tuwien.ac.at/downloads/thinkhome/ontology/ProcessOntology.owl	po	<i>OccupancyParameter, hasInfluenceOn</i>
Semantic Sensor Network Ontology (SSN)	http://purl.oclc.org/NET/ssnx/ssn	ssn	<i>Observation, ObservationValue, observedProperty, Property, observationSamplingTime, observationResult</i>
Ontology of units of Measure (OM)	http://www.wurvoc.org/vocabularies/om-1.8/	om	<i>Unit_of_measure, Compound_unit, Singular_Unit, Unit_multiplication</i>
OWL-Time Ontology	http://www.w3.org/2006/time#	time	<i>Interval, hasEnd, hasBeginning, Instant</i>
Mathematical Modelling Ontology	http://identifiers.org/mamo/	mamo	<i>Mathematical_model, Variable, Independent_variable, Dependent_variable</i>

The purpose to reuse the DUL (DOLCE+DnS Ultralite) Ontology⁴⁶ is to provide some upper level concepts. An example of the concepts includes the *PhysicalObject*, which represents any object that has a space region. The object property *hasLocation* is also provided by the DUL ontology in order to describe the spatial location of any entities. The *identifier* property and the *title* property for distinguishing each entity is identified from the widely-known Dublin Core Ontology⁴⁷, which also provide another concept *Location*. The location contains a geographic coordinate point and/or a postal address. To describe the location, a geographic coordinate point and/or a postal address can be used, whose vocabularies are, respectively, provided by the well-known WGS84 Geo

⁴⁶ The DOLCE+DnS Ultralite (DUL) ontology a simplification and an improvement of some parts of DOLCE Lite-Plus library (cf. <http://dolce.semanticweb.org>), and Descriptions and Situations ontology (cf. <http://www.ontologydesignpatterns.org/wiki/Ontology:DnS>). It aims to provide a set of upper level concepts that can be the basis for easier interoperability among many middle and lower level ontologies.

⁴⁷ The Dublin Core Ontology is a translation of the Dublin Core element set into SHOE. The Dublin Core element set defines a set of metadata elements for cataloging library items and other electronic resources. The document of the ontology can be found in <http://dublincore.org/documents/dcmi-terms/>.

Positioning Ontology⁴⁸ and the website schema.org⁴⁹. The latter also contains a wide range of vocabularies for event description.

Several ontologies are found to describe the buildings, such as the IFC2X3 - University of Ghent Ontology⁵⁰ [327], the gbBuilding Information Ontology (BIO)⁵¹, the Architecture and Building Physics Information Ontology⁵² and the SimModel ontology [328]. Since the focus of this study is energy in buildings, a high level of detail in regard to building physics is not needed, but rather, only the main concepts related to aspect of energy are necessary. The SimModel ontology comprehensively describes the energy-related information in buildings, but, since it is not available, the BIO ontology is selected. The BIO provides a range of defined classes, axioms and datatypes for reuse, such as the class *Building*, *BuildingElement*, *BuildingParameter*, *EquipmentParameter*, *EnvironmentParameter*, and so on. In addition, the Energy and Resource Ontology (ERO)⁵³ is also selected to represent the energy information for buildings, since it provides the very useful concepts such as *EnergyParameter*, *EnergyFacility*, *EnergyType*, *EnergyDemand*, *EnergySupply*, *EnergyTariff*, and others.

Occupants and their behaviour are important impact factors in relation to energy use in buildings. The User Behaviour and Building Process Information Ontology (PO)⁵⁴ is an

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⁴⁸ The WGS84 Geo Positioning is an RDF vocabulary for representing latitude, longitude and altitude information in the WGS84 geodetic reference datum.

⁴⁹ Schema.org is a collaborative, community activity with a mission to create, maintain, and promote schemas for structured data on the Internet, on web pages, in email messages, and beyond. Schema.org vocabulary can be used with many different encodings, including RDFa, Microdata and JSON-LD. These vocabularies cover entities, relationships between entities and actions, and can easily be extended through a well-documented extension model. The link is <http://schema.org/>.

⁵⁰ IFC2X3 - University of Ghent Ontology is a OWL representation of the buildingSMART data model. The IFC data model is written in an EXPRESS schema (IFC2x3). This ontology is the result of an automated transformation of this EXPRESS schema into an OWL ontology. The ontology is available at <http://multimedialab.elis.ugent.be/organon/ontologies/IFC2X3#>.

⁵¹ gbBuilding Information Ontology contains basic classes, properties and customized datatypes that have been created through XSLT transformation from gbXML schema. The ontology is developed by TU Vienna.

⁵² Architecture and Building Physics Information is developed by Institute of Computer Aided Automation, Vienna University, Austria. It is an ontology representing building information (e.g., structure, material, architecture) for Smart Home Systems. Classes, axioms and customized datatypes have been retrieved from gbXML (www.gbxml.org). The ontology is available at:

<https://www.auto.tuwien.ac.at/downloads/thinkhome/ontology/BuildingOntologySharedVocabulary.owl>.

⁵³ Energy and Resource Information is an ontology representing energy information for Smart Home Systems, which is developed by TU Vienna. The ontology is available at:

<https://www.auto.tuwien.ac.at/downloads/thinkhome/ontology/EnergyResourceOntology.owl>.

⁵⁴ User Behaviour and Building Process Information is an ontology representing application, processes, profiles and patterns for smart home operation. It contains elementary operations that could describe basic human actions in the building during specified time periods. The ontology is available at:

<https://www.auto.tuwien.ac.at/downloads/thinkhome/ontology/ProcessOntology.owl>.

ontology used to represent the behaviours and processes involved in smart home systems. Since the processes of system operations are not in the scope of the EM-KPI ontology, only the class *OccupancyParameter* is selected from this ontology for the purpose of occupant description.

The weather influences energy use and production, so the patterns and terms in the Weather Ontology⁵⁵ are reused in order to describe the environmental parameters in detail. The Weather Ontology provides a set of concepts to describe the weather, including the *WeatherCondition*, *WeatherPhenomenon*, *Temperature*, *Humidity*, *Wind*, *SolarIrradiance*, and so on.

The widely-recognized W3C Semantic Sensor Network (SSN) Ontology⁵⁶ [329] is selected to describe the measurement of various parameters. It provides a set of terms like *Observation*, *ObservationValue*, *Property*, *FeatureOfInterest*, and others. The SSN ontology describes the observations and their related concepts, but without the other domains like time and unit; these domains are intended to be imported from other ontologies. Therefore, the well-known OWL-Time Ontology⁵⁷ and the Ontology of units of Measure (OM)⁵⁸ [330] are reused, respectively, to describe the observed time and the unit of measurement value. The OM is selected to describe the unit, because it contains all of the classes and instances needed to represent the unit in this case.

Most importantly, to represent the KPI calculation, the ontologies related to the mathematical modelling are searched. The Mathematical Modelling Ontology (MAMO)⁵⁹ is selected, because it provides the concepts like *Mathematical_model*, *Variable*, *Independent_variable*, and *Dependent_variable*. However, the MAMO is still

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⁵⁵ The Weather Ontology is an OWL ontology for weather information, containing data about both current conditions and weather forecasts. This ontology aims to enable smart home systems to make decisions based on current and future weather conditions.

⁵⁶ The W3C Semantic Sensor Network (SSN) Ontology is developed by W3C Semantic Sensor Network Incubator Group. It is an ontology aims to describe sensors and observations, and related concepts. However, it does not describe domain concepts, time, unit, locations, and others; these are intended to be included from other ontologies via OWL imports. The document of the ontology can be found at: https://www.w3.org/2005/Incubator/ssn/wiki/Report_Work_on_the_SSN_ontology.

⁵⁷ OWL-Time is an OWL-2 DL ontology of temporal concepts, for describing the temporal properties of resources in the world or described in Web pages. The ontology provides a vocabulary for expressing facts about topological (ordering) relations among instants and intervals, together with information about durations, and about temporal position including date-time information. (For further information see: <https://www.w3.org/TR/owl-time/>)

⁵⁸ The Ontology of units of Measure and related concepts (OM) model concepts and relations important to scientific research. It has a strong focus on units and quantities, measurements, and dimensions. The ontology is available at: <http://www.wurvoc.org/vocabularies/om-1.8/>.

⁵⁹ The Mathematical Modelling Ontology (MAMO) is a classification of the types of mathematical models used mostly in the life sciences, their variables, relationships and other relevant features. (For further information see: <https://biportal.bioontology.org/ontologies/MAMO>)

not able to completely describe the KPI calculation. Therefore, the patterns of the Model ontology in the OntoMODEL (Ontological Mathematical Modeling Knowledge Management) [331] is also reused. This ontology represents the different components for mathematical model, including the equation, assumption, variables and constants. However, since the ontology is not available in Web, some concepts extracted from the ontology will be represented with the namespace of EM-KPI ontology and the prefix *eko*.

Lastly, there are also some other ontologies, which is not available in web but part of their patterns has been used, such as the ontology to represent energy-related occupant behaviour in buildings proposed by Hong et al. [332][333], the CIM as an ontology proposed by Neumann et al. [288] and the CIM extension of microgrid energy management system proposed by Ding et al. [334].

6.7 ONTOLOGY IMPLEMENTATION

The detailed EM-KPI ontology model is developed through restructuring the selected ontology resources using the ontology network proposed in Figure 30, and integrating it with the newly defined patterns and vocabularies (with the prefix *eko* in the following description). The subsections below illustrate each of the ontology modules in detail. The domain parameters will be described together with the related objects in order to make their relationship clearer. We used black squares for classes and grey squares for instances, solid links for properties and dotted links for subclasses or instances. All of the elements are represented with the prefix before their names.

6.7.1 The KPI Module

The general pattern and most of the classes and properties in the detailed model of the KPI module are presented with the prefix *eko*, as they are new contributions from this thesis. Figure 31 describes the detailed model of the KPI module. A noticeable refinement of the initial model is that each KPI has an identifier and a definition for their distinction and interpretation. The class *KPI* is further divided into three subclasses, namely *StrategicKPI*, *TacticalKPI* and *OperationalKPI*, for representing the multi-level key performance information. The *StrategicKPI* is the hyper-aggregated KPI at the district level, which can be disaggregated to the *TacticalKPI* at the building and system level and then the *OperationalKPI* at the zone and equipment level. The class *PerformanceGoal* represents the strategic goal of the stakeholders, which has associated KPIs in order to measure the progress made towards achieving it. The model represents in detail the KPI calculation with the use of MAMO ontology and Model ontology [331]. The equation is linked to a string of MathML⁶⁰, which is an XML language for describing mathematical

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⁶⁰ MathML is a low-level specification for mathematical and scientific content on the Web and beyond. For more information see: <https://www.w3.org/Math/>.

expressions, and can be converted to Content MathML⁶¹ for calculation. The time step for a KPI calculation is represented as an *Interval*, which has a beginning instant and an end instant, according to the Time Ontology. The KPI-evaluated objects could be either districts, buildings, power system resources or their subclasses. The output of the KPI calculation is the *KPIValue*, and each value has a *Unit_of_measure*. Furthermore, the calculation of the KPIs requires the datum sources provided by the observation from the master data part, while the classes *DatumSource* and *Observation* are linked.

Figure 31: Detailed model of the KPI module.

6.7.2 The Observation Module

Subsequently, Figure 32 illustrates the detailed model of the observation module, including the observation time, units and domains. Mainly, the SSN Ontology [329], Time Ontology and OM ontology are reused to construct this model. Since the purpose of the EM-KPI ontology is to describe the master data rather than the sensors, only the observation aspects of the SSN Ontology are represented in the model, the reused terms include the *Property*, *FeatureOfInterest* and *ObservationValue*, etc. The feature of interest of the observation could be either districts, buildings, power system resources, occupants or their subclasses. Besides, each observation corresponds to an observed *Interval* or *Instant*, which are subclasses of the *TemporalEntity*. The units of observation values are classified based on the OM ontology. Most importantly, the observed

⁶¹ The intent of Content Markup is to provide an explicit encoding of the underlying mathematical meaning of an expression, rather than any particular rendering for the expression. Content MathML represents mathematical objects as expression trees. For more information see: <https://www.w3.org/TR/MathML3/chapter4.html>.

properties should include the different types of domain parameters needed for the KPI calculation and performance analysis. They can be primarily divided into five categories, namely the *BuildingParameter*, *OccupancyParameters*, *EquipmentParameter*, *EnergyParameters* and *EnvironmentParameters*, which are extracted respectively from the ERO, the PO, and the BIO ontologies.

Figure 32: Detailed model of the observation module.

6.7.3 The Location Module

Figure 33 presents the detailed model to describe the location of districts, buildings and power system resources. Districts contain buildings and power system resources, and each of these has an identifier and location. The location can be represented by a geographic coordinate with the use of WGS84 Geo Positioning Ontology which details the latitude, longitude and altitude, or a postal address with the use of the schema.org vocabularies which contains the country, region, postal code and street address.

Figure 33: Detailed model of the location module.

6.7.4 The Infrastructure Module

The power system resource in the infrastructure module can be classified into subclasses, as shown in Figure 34. The term *PowerSystemResource* is extracted from the Common Information Model (CIM) [335]. CIM is a series of standards developed by EPRI (Electric Power Research Institute) for the exchange of power system network and data between different organizations and applications, it describes the components of the power system at a distribution level [336]. *EquipmentContainer*, *PowerEquipment* and *EnergyFacility* are the three main subclasses of *PowerSystemResource*. The class *EquipmentContainer* is also extracted from the CIM [288]. An equipment container is a group of equipment, such as a substation or distributed energy resources, which is composed of different types of power equipment. The class *EnergyFacility* provided by the ERO ontology, which describes the facilities in buildings that produce, store or consume energy. The facilities represent the energy systems such as *PVSystem* and contain related equipment, it can be further classified into *EnergyConsumerFacility* and *EnergyProducerFacility*. An energy facility may contain different equipment. In order to distinguish the equipment in power grid and the equipment in buildings, *PowerEquipment* and *BuildingEquipment* are defined. Building equipment could be, but is not necessarily, power equipment, which will be described in Figure 35. The class *PowerEquipment* has subclasses including *GeneratingUnit*, *StoringUnit*, *PowerDeliveryUnit* and *EnergyConsumer* [334], which described the equipment ranging from energy production, storage and supply to consumption. The most commonly used generating unit is the *PhotovoltaicGeneratingUnit*. The class *PhotovoltaicType* is defined, because the generating efficiency depends on the type of PV unit. In any case, each type of power equipment has its own equipment parameters, such as capacity and input watts.

Figure 34: Detailed model of the power system resource in the infrastructure module.

Buildings are connected to the power system; the detailed model of the ontology related to the building is shown in Figure 35. Each building has a description of the building type, the year of construction and building parameters such as area and volume, because these factors all impact the level of energy use. The building contains energy facilities such as HVAC systems and lighting systems, and energy facilities contain building equipment. Each type of building equipment has its equipment type and some equipment parameters. The description of *EquipmentParameter* is extracted from BIO ontology, which describes different aspects, including capacity, efficiency, input watts and power. Building elements such as *BuildingStorey*, *Zone* and *Room* are also provided by BIO. Here, the zone refers to a building thermal zone. Since the thermal load of a zone is concerned with the building envelope, including its exterior wall, exterior window, exterior roof and floor, the classes *ExtWall*, *ExtWindow*, *Floor* and *Roof* are respectively defined. The thermal property of the envelope is represented as a *U-value*, which is a subclass of *BuildingParameter*, and it is also provided by the BIO ontology. Finally, occupants are those who use the zone; they are the attendees of the event taking place in the zone. Each event has a duration and schedule.

Figure 35: Detailed model of the building in the infrastructure module.

6.7.5 The Occupant Module

In order to describe the occupancy parameters and the factors which influence occupants' behaviour, Figure 36 describes the detailed model of the occupant module. The occupancy parameter concerned in this case only include the occupant number, regardless of their gender, age, and so on. Some patterns of this model are extracted from the ontology proposed Hong et al. [332]. The main drivers of occupants' behaviour include the event and the level of indoor comfort existing in the zone. Furthermore, the outdoor weather

influences the level of indoor comfort, so it indirectly impacts to occupants' behaviour. The occupants' behaviours have consequences for the energy consumer facilities, thus influencing the energy demand. The *IndoorComfort* and *Weather* are the subclasses of *EnvironmentalParameter*, among which *IndoorComfort* is further divided into *ThermalComfort*, *VisualComfort* and *IndoorAirQuality*.

Figure 36: Detailed model of the occupant module.

6.7.6 The Weather Module

The detailed model of the weather module is depicted in Figure 37. It reuses mainly the concepts and patterns of the Weather Ontology. The *Weather* class is defined here to describe different types of outdoor environment, which is divided into two subclasses, *WeatherCondition* and *WeatherPhenomenon*. The weather condition describes conditions such as rain, snow and sun, and the weather phenomenon includes outdoor temperature, humidity, wind and solar irradiance. The *SolarIrradiance* is classified into *GlobalHorizontalSolarIrradiance* and *GlobalInclined41SolarIrradiance*, because one of them represents the horizontal solar radiation intensity, while the other one represents the strongest solar radiation intensity at the location of application in Madrid, Spain. The weather has a direct influence on energy production, and the weather forecast influences the energy forecast in district and buildings, thus influencing energy supply.

Figure 37: Detailed model of the weather module.

6.7.7 The Energy Parameters Module

Finally, Figure 38 illustrates the detailed model related to the energy parameter in the domain parameter module. Some primary concepts and patterns of this model are selected from the ERO ontology. The model describes the energy type produced, stored, delivered and consumed. To describe the various aspects of energy parameters, the class *EnergyParameter* is divided into subclasses such as *EnergyProduction*, *EnergyStorage*, *EnergySupply*, *EnergyDemand*, *EnergyGain*, *EnergyCost*, *EnergyTariff*, and *EnergyForecast*. The class *EnergySupply* is further classified into three subclasses, namely *EnergySupplyFromStorage*, *EnergySupplyFromSiteProduction*, *EnergySupplyFromExternalGrid*, which respectively represent the energy suppliers of off-peak storage, the site renewable resources and the external grid. The *EnergyGain* describes the surplus energy that could be sold to the external grid. The *EnergyTariff* is divided into *EnergyCostTariff* and *FeedInTariff*, which respectively refer to the tariff for purchasing energy from, and for selling energy to, the external grid. Therefore, the energy cost depends on the energy tariff, energy gain, and energy supply from the external grid.

Figure 38: Detailed model of the energy parameter in the domain parameter module.

In summary, the figures above illustrate the different ontology modules of the initial conceptual model. Figure 31 describes the detailed model of the KPIs and their calculation, while Figure 32 describes the observations that offer datum sources for KPIs' calculation and analysis, Figure 33 to Figure 38 introduces in detail the KPI-evaluated objects and observed features of interest (e.g., districts, power system resources, buildings and occupants), in addition to the different observed parameters (i.e., building parameters, occupancy parameters, equipment parameters, energy parameters and environment parameters).

Through merging the reused concepts and patterns of the existing ontologies with the new developed terms and patterns for ontology completion, the detailed model of the EM-KPI ontology is implemented in OWL using the tool Protégé 5.1⁶². Appendix D shows an RDF/XML⁶³ segment of the implemented ontology. The ontology is able to reason, so as to find the implicit relationship between different classes. The inferred model will contain some hierarchy of the classes that are not described in the asserted model, which facilitates a deeper data exploration. In addition, the reasoning can help to check the logical consistency.

6.8 ONTOLOGY EVALUATION

The developed EM-KPI ontology has been evaluated using the OOPS! ontology pitfall scanner⁶⁴ to ensure that no modelling or reasoning problems exist in the ontology. The evaluation results of the ontology include several minor warnings. Such minor warnings are due to the unconnected ontology elements and missing annotations. They are, however, intentionally omitted, because two upper-level classes have no object properties and the reused classes and properties, as well as the inverse properties, have no need to be annotated. Similarly, the domain and/or range of the inverse properties have also been neglected, because the reasoner can infer them automatically and their absence will not influence the use of the ontology.

6.9 ONTOLOGY PUBLICATION

After evaluating and checking the ontology, the final version of the ontology is published online for open access, which is available at <http://energy.linkeddata.es/em-kpi/ontology>. Figure 39 shows the capture of the website where the developed ontology is published. In this website, the ontology in different formats, including N-triples, RDF/XML and TTL, can be downloaded. The introduction of the ontology and the description of different ontology modules are also presented. Each class, object property, data property and annotation property are introduced.

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⁶² Protégé is a free, open-source platform that provides a growing user community with a suite of tools to construct domain models and knowledge-based applications with ontologies. For more information see: <http://protege.stanford.edu/products.php>.

⁶³ RDF/XML is a syntax, defined by the W3C, to express (i.e., serialize) an RDF graph as an XML document. For more information see: <https://www.w3.org/TR/rdf-syntax-grammar/>.

⁶⁴ OOPS! (OntOlogy Pitfall Scanner!) is a web-based ontology evaluation tool developed by the Ontology Engineering Group of Universidad Politécnica de Madrid. The tool helps to detect some of the most common pitfalls appearing when developing ontologies. To access the tool, the website is <http://oops.linkeddata.es/>.

Figure 39: Screenshot of the website of the published EM-KPI ontology.

6.10 SUMMARY

The exchange and exploitation of multi-level energy performance information and data from different stakeholders help to improve energy performance and to achieve stakeholders' performance goals. However, the main barrier is the interoperability problem of the heterogeneous data and the vast amount of information involved. Therefore, an EM-KPI ontology is proposed in this chapter to facilitate the interchange of key performance information and insightful master data among different stakeholders. The ontology provides an effective engagement mechanism between the stakeholders for information sharing.

Firstly, the methodology and process used for the development of the EM-KPI ontology has been depicted. The process involves eight main steps, respectively, the ontology requirements definition, the terms extraction, the ontology conceptualization, the ontology search and selection, the ontology implementation and the ontology evaluation. In addition, the final version of the ontology has been published on the Web.

The resulting ontology is comprised of two components: the KPI and the EM master data components. The KPI component represents the multi-level key performance information, and provides the basis for KPI calculation and energy performance tracking. The EM

master data component integrates the master data domains; moreover, it has been divided into six modules, namely, the observation, infrastructure, occupancy, domain parameter, location and weather modules. The EM master data component helps to exploit the knowledge and insights in the cross-domain data for performance improvement. Therefore, the developed ontology can not only enable the exchange of key information and master data, but can also facilitate performance tracking and analysis for improved decision-making.

7 METHOD FOR LINKED DATA GENERATION

With the EM-KPI ontology developed in Chapter 6, the next step is to generate the linked data. The purpose of the linked data is to implement the exchange and exploitation of cross-domain data sources.

Berners-Lee [266] defined four principles of linked data. These principles are: 1) use URIs (Uniform Resource Identifiers) as names for things; 2) use HTTP URIs so that people can look up those names; 3) provide useful information to a URI using the standards (RDF, SPARQL); 4) include links to other URIs so that they can discover more things. In addition, Radulovic et al. [325] presented the requirements and guidelines for the generation of linked data in the energy field. These guidelines aim to help organizations from both public and private sectors in generating linked data from existing data sources. Eight tasks in the generation process are illustrated. They are as following:

1. Selecting the data sources that need to be transformed into linked data;
2. Obtaining the access to the data sources;
3. Analysing licensing of the data sources;
4. Analysing the data sources;
5. Defining resource naming strategy;
6. Developing ontology;
7. Transforming the data sources to RDF;
8. Linking with other datasets.

The requirements for the selection of data sources should be related to the intended use of the linked data and to the individuals or organizations that will use the linked data. The selected data sources may be internal or external. The internal data sources are owned by an organization which can be accessed without obstacles; while, the external data sources can be retrieved from a public domain or should be requested from other parties. Licenses declared for a dataset specify the legal terms under which a dataset can be used and exploited. The analysis of the data sources allows getting insight into the data and into the structured and organized forms of the data. Furthermore, URIs are used for resource identification, which has also been indicated by Berners-Lee [266]. The collected data sources should be mapped to the ontology, since ontologies represent the knowledge in a certain domain and they are the cornerstone of the linked data. The links between the datasets ensure that they are not just isolated data islands. After generating the linked data, additional steps may be performed to publish and exploit the data.

According to the guidelines proposed by Radulovic et al. [325], an adapted process for linked data generation in this thesis is proposed, considering the additional steps in

relation to KPIs. Figure 40 illustrates the steps for the linked data generation and exploitation using the EM-KPI ontology.

Figure 40: Steps for linked data generation and exploitation using the EM-KPI ontology [325].

The whole process for linked data generation and exploitation can be divided into six work packages, which are as follows:

- Work package 1: data preparation, which includes the selection of KPIs and their related master data sources, the access to the data sources and the analysis of the data sources. These steps with regard to selecting KPIs and their related master data sources have been studied previously in Chapter 4 and Chapter 5.
- Work package 2: ontology development, which comprises the definition of resource naming strategy and the development of the EM-KPI ontology. These steps have been conducted in Chapter 6.
- Work package 3: linked data generation, which involves the conversion of the collected data sources into RDF and the generation of the linked datasets. These steps will be carried out in Chapter 8 based on the real case.
- Work package 4: KPI calculation. Through retrieving the needed data sources in the linked datasets, the KPIs can be calculated. The results of the KPI calculation should be mapped again to the ontology.
- Work package 5: ontology and resources publication. These steps are optional. If the developers want more practitioners or researchers to use the ontology and benefit from the data, they can publish both of them. In this thesis, only the ontology is published, which has been mentioned in Section 6.9.
- Work package 6: linked data exploitation, which is the final step but also the most important step. The data exploitation aims for multi-level energy performance analysis that identifies energy performance problems and key areas for improvement, thus to achieve stakeholders' performance goals.

During the data preparation stage, the steps to select list of KPIs and master data sources are developed based on the intended use of the generated linked data. The linked data generated using the EM-KPI ontology aims to exchange and exploit the key performance information and data among various stakeholders. Therefore, only the data sources in relation to KPIs and the cross-domain master data concerned by the stakeholders should be collected. The access to the selected data sources is particularly critical. Such data sources are normally internal and gathered from the stakeholders. Since the involved stakeholders can benefit from the linked data for tracking and improving their performance, they are willing to share and exchange their data with the other stakeholders. Hence, the access to the associated data sources is expected to be easy to obtain. In any case, it is essential to know where, in what system and in which frequency the data sources are generated, and to which organizations or stakeholders should we request for the permission or data licences. The raw data collected from different systems and various stakeholders are potentially stored in different formats, such as databases, excel, csv, and others. Furthermore, redundant data, abnormal data and/or invalid data may exist. Therefore, it is necessary to analyse the data sources and clean the original data. In addition, the characteristics of the data, such as the data values and the data ranges, should be also analysed sometimes.

After preparing the data, the ontology is developed to represent all the data pointing to the application and use-case experiments. The development of the ontology can be conducted at same time as the data preparation. While before developing the ontology, it is necessary to define resource naming strategy. The resource naming strategy aims to assign one unique identifier for each entity involved in, and mapped to, the ontology. The URI (Uniform Resource Identifier) is used for resource naming. One URI must only identify one item, in order to distinguish them. The data sources that provide the instances for the ontology are also required to assign URIs.

With the prepared data sources and the developed ontology, the next stage is to generate the linked data by mapping the data sources to the ontology, instantiating the ontology classes with the data sources and assigning properties to each instance. The data sources must be transformed to RDF in order to map to the ontology. There are existing tools dedicated to this data transformation, such as RDF123, morph-RDB and OpenRefine. The transformed RDF files and the ontology files can be subsequently integrated in an RDF triple store, so as to generate the linked data. Through query language such as SPARQL, the data sources can be retrieved and exploited.

Since the master data represents the datum sources needed for the KPIs' calculation and performance analysis, the selected KPIs can be calculated using the data integrated in the linked dataset. Supportive tool may be needed in order to perform the calculation. The calculation results of KPIs should also be incorporated in the linked data for the purpose of performance tracking and analysis. Therefore, the analysis and cleaning of the

calculated data sources should also be conducted in order to map the results of KPI calculation into the ontology. Afterwards, the data sources should be transformed to RDF and integrated in the triple store, thus enabling the stakeholders to query their concerned key performance information.

The steps to publish the ontology and the resources are optional. The publishing of the ontology can make the ontology available to the other practitioners for the related application and also to the other researchers to make improvement of the developed ontology. The publishing of the resources can facilitate the results reporting and provide easy access to the performance information and master data for different stakeholders. In addition, it can also help the other researchers to gain insights from the project.

The exploitation of the generated linked datasets is an ultimate goal. The final purpose of leveraging the linked data is to improve multi-level energy performance and to achieve stakeholders' performance goals, thus to enhance the multi-level energy management. In doing this, energy performance analysis conducted using the available data sources is indispensable. The generated linked datasets enable the exploitation and analysis of multi-domain data.

Figure 41: Framework for linked data generation and application.

Figure 41 shows the different layers of the framework for linked data generation and application. The lowest layer is the original data sources, which are usually cross-domain and heterogenous stored in different format. The second layer is the data conversion. In such layer, the data sources are analysed, cleaned, mapped to the ontology and transformed to RDF. The third layer is the linked datasets. In this layer, the various RDF files are integrated in a triple store in order to generate the linked datasets. The highest

layer is the application in relation to data querying, data exploitation, performance tracking and performance analysis.

Table 19: Common tools for the support services of linked data generation and application

Support service	Tools
Data cleansing	OpenRefine (LODRefine) ⁶⁵ , Drake ⁶⁶ , DataWrangler ⁶⁷ , DataCleaner ⁶⁸ , Winpure Data Cleaning Tool, Datamartist ⁶⁹
Data transformation	morph-RDB, morph-streams, D2R Server, TopBraid Composer, RDF123, Excel2RDF, XLWrap, OpenRefine/LODRefine, XML2RDF
Linked dataset storage and querying	D2R Server ⁷⁰ , Pubby ⁷¹ , RDF4j, Virtuoso, 4Store, AllegroGraph, BigData, Jena TDB, Sesame, Stardog, OWLIM and uRiKa, Jena SDB, DB2, Sesame, Mulgara
KPI calculation	Excel, web-based calculators
Data visualization	Excel, The R Project for Statistical Computing ⁷² , Google Fusion Tables, Tableau Public, Many Eyes, VIDI, Plotly, DataHero, Chart.js, Raw, Dygraphs, ZingChart, InstantAtlas, Dashboard tools (ReportGarden, Agency Analytics, Klipfolio Dashboard, Google Dashboard, etc.)

In each of the layers, the related support services and tools are needed in order to implement the tasks. The tools include those for data source analysis, those for data transformation, those for linked dataset storage and querying, those for KPI calculation and those for data visualization. Table 19 lists some common tools for the support services of the linked data. The tool OpenRefine (formerly Google Refine) is one of the most commonly used tools for cleaning the data, transforming it from one format into another, and extending it with web services. Moreover, OpenRefine is also user-friendly and easy to use. In addition, the easiest tool for KPI calculation and data visualization is Excel. The

⁶⁵ OpenRefine is a simple and powerful tool for working with messy data, which is a web application for data cleansing. <http://openrefine.org/>.

⁶⁶ Drake is a simple-to-use, extensible, text-based data workflow tool that organizes command execution around data and its dependencies.

⁶⁷ Wrangler is an interactive tool for data cleaning and transformation.

⁶⁸ DataCleaner is a strong data profiling tool for discovering and analysing the data quality, finding the patterns, missing values, character sets and other characteristics of the data values.

⁶⁹ Datamartist is data cleansing tool that has an easy-to-use interface.

⁷⁰ D2R Server is a tool for publishing relational databases on the Semantic Web. It enables RDF and HTML browsers to navigate the content of the database, and allows querying the database using the SPARQL query language. <http://d2rq.org/d2r-server>.

⁷¹ Pubby can be used to add Linked Data interfaces to SPARQL endpoints.

⁷² The R Project for Statistical Computing is a general statistical analysis platform and environment.

queried data sources for KPI calculation in the generated linked data can be exported as excel files; and the formulas can be easily programmed in Excel.

To conclude, this chapter depicted the principles and process adopted to generate and exploit the linked data using the EM-KPI ontology. The process includes the main steps for data preparation, data transformation, data integration, KPI calculation and data exploitation. With the guidelines illustrated in this chapter, an example linked dataset will be generated in the case study (Chapter 8), the KPIs will be calculated through querying the generated linked dataset and the exploitation of the generated linked dataset for multi-level energy performance analysis will be performed.

8 CASE STUDY

8.1 INTRODUCTION

In order to demonstrate the feasibility and benefits of the proposed methodology, ranging from the stakeholders' identification and the selection of KPIs, via the identification of master data, to the linked data generation and exploitation, a case study is carried out in this chapter. The selected case is a small district containing 18 solar houses and several public service buildings. All of the buildings were connected together with a microgrid, which was further connected to the external electricity network. Both the buildings and the microgrid were monitored by their energy management systems, but initially without information exchange across different scales and across different buildings.

The case study in this chapter is carried out in two parts: the first part aims to demonstrate the feasibility of the proposed methodology for extracting, interchanging and analysing the key performance information and master data, in order to find the energy performance problems and the areas for improvement; the second part comprises the comparison analysis between the proposed methodology (with information exchange among the stakeholders) and the current used method (without effective information exchange among various stakeholders), in order to validate the energy and cost benefits of the proposed methodology for informed decision-making in energy performance improvement.

The feasibility of the proposed methodology is demonstrated in Section 8.3. Firstly, the identification and prioritization of the stakeholders is carried out in Section 8.3.1, using the three-task method. Secondly, in Section 8.3.2, a pre-list of 35 energy PIs is proposed based on the energy structure, systems and flow analysis in the district; the KPIs that underpin stakeholders' performance goals and represent the multi-level key performance information are selected among the list of PIs using the bi-index method. With the selected KPIs, the related master data sources are identified in Section 8.3.3. Afterwards, an example linked datasets of the ontology is constructed by integrating the selected KPIs and the collected master data sources in Section 8.3.4. Three representative KPIs related to the energy balance performance and their needed datum sources are instantiated to the ontology; linked data is generated in order to realise the data exchange and exploitation. The calculation and benchmarking of the three KPIs are carried out in Section 8.3.5. Finally, a multi-level energy performance analysis with the calculated KPIs and the generated linked data is performed in Section 8.3.6, in order to identify key performance problems and knowledge or insights for improvement.

Different decisions for energy performance improvement can be made using the proposed methodology and the current used method. In order to validate the benefits of proposed

methodology, Section 8.4 compares the two methodologies and analyses their decision making in three different scenarios. Firstly, Section 8.4.1 carries out a general comparison between the proposed methodology and the current used method, including their processes for energy performance analysis and decision making. Subsequently, in Section 8.4.2, the effect for energy performance improvement with different decisions in three scenarios that aim to improve energy balance at different levels is analysed and compared. The cost benefits of using the proposed methodology is also validated.

8.2 THE SELECTED CASE

Taking into account the smart city context, the district, including its buildings, equipped with distributed energy generation and ICTs for energy management and monitoring is the best option for the case study. Therefore, the competition site of the Solar Decathlon Europe (SDE) 2012⁷³ is selected.

SDE 2012 is a global competition involving high-efficiency solar houses, took place in Madrid, Spain. All of the solar houses were installed with PV panels and low energy efficiency measures, in order to achieve nearly zero energy buildings. In total, there were 18 solar houses participating the competition. Together with the public service buildings, including offices, restaurants and conference centres, it formed a small district called Villa Solar, as shown in Figure 42. The buildings in Villa Solar were connected through a smart microgrid, which is monitored and controlled by a smart centre. All of the solar houses were installed with building energy management systems. They were monitored by meters and sensors during the competition period from September 17th to 28th, 2012, as was the microgrid.

Figure 42: Selected district for case study titled Villa Solar.

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⁷³ Solar Decathlon Europe 2012, for more information see: <http://www.sdeurope.org/>.

The details of the electric system and the buildings in the Villa Solar can be depicted as follows:

- The solar houses are detached and single-family houses, which do not only use solar energy generation, but also apply energy efficient measures to reduce energy consumption. The energy balance in the solar houses should be positive, which means that they should consume less energy than the generated energy.
- The microgrid is the electricity distribution network in the district that allows multidirectional connection between consumers and self-sufficient prosumers. It connects and controls the entire electrical system linking the 18 solar houses, as well as the public service buildings. Through a MV/LV (Medium Voltage/ Low Voltage) substation, the microgrid is connected to city grid.
- The public service buildings include offices, restaurant, the conference centre, etc. There is also a photovoltaic pergola in the public area which generates energy. The surplus energy generated through the renewable energy resources during the day are primarily self-consumed for public services.
- Since the microgrid is connected to the city grid through the district substation, the surplus energy of the Villa Solar can be supplied to another site in the city. A smart centre monitors the generation and consumption of each element in Villa Solar, globally through the SCADA (Supervisory Control and Data Acquisition) technology.

Although the microgrid and the solar houses had their respective energy management systems, there is no information exchange and stakeholders' interaction across the district and building levels and across the different buildings. Therefore, the proposed KPI-based linked data methodology is used to facilitate the extraction, exchange and exploitation of key performance information and master data for different stakeholders.

8.3 THE IMPLEMENTATION OF KPI-BASED LINKED DATA METHODOLOGY

The implementation of the KPI-based linked data methodology aims to demonstrate its feasibility and benefits for extracting and exchanging key performance information and master data and facilitating multi-level energy performance analysis.

The implementation follows the general tasks of the proposed methodology, which is conducted by the following steps:

1. Stakeholders identification and prioritization analysis in Section 8.3.1 targets to identify the various stakeholders involved in the energy management of the Villa Solar and the solar houses, and to find the key stakeholders that influence and benefit from the energy management.

2. PI identification and KPIs selection in Section 8.3.2 aims to extract key performance information that underpin the identified stakeholders' performance goals. A hierarchy of 35 energy PIs that represent the different energy aspects of the Villa Solar and the solar houses are identified. Among these PIs, the KPIs are selected through stakeholders' involvement, considering both their votes and prioritization.
3. Master data identification in Section 8.3.3 aims to collect the core data sources that contain the valuable information which supports the calculation and analysis of the selected KPIs.
4. EM-KPI ontology instantiation and linked data generation in Section 8.3.4 maps the collected data sources to the ontology and interchanges the key performance information and the master data sources between the various stakeholders.
5. KPI calculation and benchmarking in Section 8.3.5 calculates three representative KPIs using the data and information from the generated linked data and benchmarks the KPIs in order to evaluate the targeted energy performance.
6. Multi-level energy performance analysis in Section 8.3.6 aims to exploit the cross-domain data and identify the energy performance problems at different levels and key areas for improvement through the linked data analysis.

8.3.1 Stakeholders Identification and Prioritization Analysis

This section illustrates the stakeholders' identification and prioritization analysis in the case using the proposed three-task method, including (1) the identification of intervention points for energy performance, (2) the identification of stakeholders' roles pertaining to the various intervention points and (3) the prioritization analysis of stakeholders based on their importance levels to the intervention points.

8.3.1.1 Identify Intervention Points for Multi-level Energy Performance

As introduced in Section 4.2.1, the intervention points with different intervention mechanisms for energy performance can be identified at three levels, namely the district level, the building and system level and the zone and equipment level.

As regards the proposed typical intervention points, the points at the district level that intervene the energy performance in the Villa Solar are identified as a district energy profile, which comprises both the building stock form and the district energy system form. As the buildings in Villa Solar have different functions, the building stock form indicates their functional type, density and constructed year, which influence the energy aspects such as energy use, energy demand and energy balance in the district. In addition, the district energy system form represents the energy types and features of energy generation, delivery and consumption systems, which influence the aspects such as renewable energy share, energy supply and CO₂ emissions in the Villa Solar.

At the whole building and system level, the main intervention points for the energy performance are identified as the building performance and the systems' efficiency. Since the building performance depends on the aspects of passive building design as well as the realization of the building's comfort and function during the post-occupancy period, the passive energy efficiency, indoor comfort and building function are identified as three sub-intervention points of building performance. Meanwhile, the systems' efficiency is divided into district energy systems' efficiency and building energy systems' efficiency. The district energy systems include the energy distribution network (i.e., microgrid) and the distributed energy resources used in Villa Solar. The building energy systems include the energy consumption systems such as HVAC systems and lighting systems and the integrated energy production systems such as PV systems in the solar houses.

Furthermore, a system is composed of different equipment. The inefficient equipment will cause additional energy waste, and the inappropriate operation of the equipment will also impact significantly to the systems' efficiency. Therefore, the efficiency of the equipment is considered as one of the intervention points at the zone and equipment level. It is essential to use high energy-rating equipment and keep a timely maintenance for the equipment. Meanwhile, the buildings consist of various zones; in such zones, there are occupants who have different energy use behaviours due to their income level, age or gender. The occupants' behaviour is one of the most important factors that impact upon the energy demand, and has a significant impact on the energy balance of Villa Solar and the solar houses. Therefore, the occupants' behaviour is taken as one of the most important intervention points.

To conclude, the overall intervention points used in the Villa Solar are as follows:

- the district energy profile (building stock form and district energy system form);
- the building performance (passive energy efficiency, indoor comfort and building function);
- the systems' efficiency (district energy systems' efficiency and building energy systems' efficiency);
- the equipment efficiency; and
- the occupants' behaviour.

8.3.1.2 Identification of the Stakeholders' Role

The stakeholders' roles are identified according to a space dimension created by the different intervention points and a time dimension, which involves different life cycle stages. The invention points are where the stakeholders involved in the energy management at the district and/or building levels; and the different life cycle stages impact the energy performance to different extents in the Villa Solar, solar houses and

energy systems. In this section, a list of stakeholders' roles is identified; and according to each of the roles, the related stakeholder individuals and groups are identified.

At the district scale, during the plan and design stage, the stakeholders who play the role of district planners are a planning group of Villa Solar; they allocate the construction site and plot area of each solar house and public service buildings. The stakeholders who act as energy planners are several district energy engineers; they design the electricity distribution network of Villa Solar, including the connection of distributed generation resources and the allocation of energy storage and EV charging points. These district energy engineers also take charge of the microgrid management at the operation and maintenance stage, hence they also act as district energy managers. The products and the installation of the microgrid are provided by an electrical company, which is the manufacture and also played the role of asset manager. The buildings in Villa Solar are the energy end-users, but also generate surplus energy with the installed PV systems. The surplus energy of the solar houses is received by the energy supplier, who also supplies electricity to the buildings when the energy generation unable to cover the energy consumption in buildings.

Therefore, the following stakeholders engage in the district-scale energy management: 1) the district planning group, which plays the role of district planner and intervenes in the building stock form; 2) the district energy engineers, who act as district energy planners and managers and who intervene in the district energy profile and the district energy systems' efficiency; 3) the microgrid system company, which is the manufacture, installer and asset manager of the microgrid and which influence the systems' and equipment efficiency; 4) the energy supplier, which is influenced by the microgrid operation but also the financial beneficiary of the surplus energy; 5) the building owners, who are energy end-users and financial beneficiaries intervening in the building performance and the efficiency of systems and equipment.

At the building scale, during the plan and design stage, each solar house and public service building has their own architects for the building design and their own electrical and mechanical engineers for the building systems' design. At the construction and installation stage, each building has a technical construction company for building construction and energy system installation and commissioning. The products for the buildings and systems are provided by different manufactures. During the operation period, the solar houses are operated by their own building energy managers for the energy optimization. Such energy managers also act as facility managers for the equipment maintenance. Additionally, the occupants in each building are also the energy consumers, whose behaviour has a direct effect on the building's performance.

Therefore, the following stakeholders engage in the building-scale energy management: 1) the architects, who intervene in the passive energy efficiency of the buildings; 2) the

electrical and mechanical engineers, who intervene in the building energy systems' efficiency; 3) the construction and system installation companies, who influence the building performance and systems' efficiency; 4) the equipment manufacturers, who impact the equipment efficiency; 5) the building energy managers, who are key to the efficiency of the systems and equipment, the indoor comfort and the building function; 6) the occupants, who decide the energy use behaviours and impact upon the overall building performance.

In order to show clearly the internal stakeholders aligning to the space dimension and the time dimension, Figure 43 illustrates the identified stakeholders according to their involved life cycle stages and intervention points on a two-dimensional coordinate map. The stakeholders in grey squares represent those who engage in energy management at district scale; and the stakeholders in light orange squares refer to those who pertain to energy management at building scale. The building owners in green squares means that they involve in both the district and the building energy management.

Figure 43: Internal stakeholders identified for multi-level energy management in Villa Solar.

With regards to the external stakeholders, the most important one is the organizing committee of the competition, which deploys the competition rules (i.e., energy policies) that each solar house should fulfil. Such rules should be implemented not only for the building design but also for the operation of the solar houses.

Table 20 lists all of the stakeholders involved in multi-level energy management in Villa Solar.

Table 20: Stakeholders identified in Villa Solar and the buildings

Type	Scale	Stakeholder
Internal	District	The district planning group, the district electrical engineers, the electrical company, the energy supplier
	Building	The architects, the electrical and mechanical engineers, the construction companies, the equipment manufacturers, the building energy managers, the occupants
External		The organizing committee of the competition

8.3.1.3 Analysis of Key Stakeholders

Once the stakeholders have been identified, the next step is to analyse their prioritization. The prioritization of the identified stakeholders is determined by calculating the SPI (Stakeholder Prioritization Index) as proposed in Chapter 4.2.3. SPI is a summated rating scale considering comprehensively the stakeholders' importance levels in the different intervention points. Therefore, the stakeholders' importance levels in the district energy profile, building performance, systems' efficiency, equipment efficiency and occupants' behaviour should be decided in this case, which are, respectively, represented as L_{DEP} , L_{BP} , L_{SE} , L_{EE} and $L_{O/CB}$. Each stakeholder has respective values of L_{DEP} , L_{BP} , L_{SE} , L_{EE} and $L_{O/CB}$, which ranges from 0 to 5. The higher the value, the more importance the stakeholder has.

Figure 44: Levels of stakeholders' importance in regard to the district energy profile (L_{DEP}).

Using the impact/interest matrix, the stakeholders' importance levels in the district energy profile are shown in Figure 44. The district planning group and the district energy engineers are key players at this intervention point as they directly influence and have a high level of interest in building stock form and district energy system form. Thereby, they have a rating value of 5. In addition, the energy supplier and the microgrid system

company have a high level of interest in the district energy profile but have a low level of impact at this point; thus, they are assigned a rating value of 3. Finally, the building owners need to know the district energy profile in order to fulfil the building's requirements but their interest in the overall district energy profile is not as high as the energy supplier or the microgrid system company. Moreover, building owners have a low impact at this intervention point. Thus, they are considered to have the least importance, and are assigned a rating value of 2. The organizing committee of the competition makes the rules for the Villa Solar and the solar houses; therefore, it has a high level of interest in and a high impact at this intervention point.

Figure 45: Levels of stakeholders' importance in regard to the building performance (L_{BP}).

Another example is the analysis of the stakeholders' importance in relation to the building performance, as shown in Figure 45. The stakeholders, who are key players for such point, include the building owners, architects, occupants, and building energy managers. They have a rating value of 5. The building owners have a high level of interest in the overall building performance, as well as a high level of impact on this point. The architects impact significantly on the passive energy efficiency of the buildings; the occupants and the building energy managers are main actors for the building function and indoor comfort. All of them have a high level of interest in the building performance. Thereby, they are also assigned rating value of 5. Additionally, the construction and installation companies also have a major impact on this point, since their tasks, such as the treatment of thermal bridges and the commissioning of energy systems, are important; however, these stakeholders show lower interest in this point. Thus, they are assigned the value of 3. Furthermore, the equipment manufacturers and the electrical and mechanical engineers have a high level of interest in the point, but their impact is not as high as the building energy managers; therefore, they are assigned the rating value of 4. Other stakeholders, including the district planning group, the microgrid system company and the district

energy engineers, have low level of interest in, and a low impact on, the building performance; thus, they have the rating value of 2.

With a similar analysis, the levels of stakeholders' importance at the other three intervention points have also been identified, and are summarized in Table 21. The SPI is calculated using **Equation 1**. The result of the SPI indicates that the stakeholders who only undertake the design and construction stages have a lower priority, while the stakeholders who are maintenance and operations staff, end-users and financial beneficiaries are of more importance. Six groups of stakeholders have SPI values higher than the average; therefore, they are identified as key stakeholders.

The identified key stakeholders are listed as following:

- the district energy engineers;
- the microgrid system company;
- the building owners;
- the building energy managers;
- the occupants and
- the organizing committee of the competition.

Table 21: Prioritization analysis for the identification of key stakeholders

Scale	Stakeholder	Importance levels to the intervention points					SPI
		L_{DP}	L_{BP}	L_{SE}	L_{EE}	$L_{O/CB}$	
District	District planning group	5	2	0	0	0	1.4
	District energy engineers	5	2	5	4	3	3.8
	Microgrid system company	3	2	5	5	0	3
	Energy supplier of the main grid	3	0	3	2	3	2.2
	Building owners	2	5	4	3	4	3.6
Building	Architects	0	5	0	0	0	1.0
	Electrical and mechanical engineers	0	4	5	5	0	2.8
	Construction and system installation companies	0	3	4	3	0	2.0
	Equipment manufacturers	0	4	3	4	0	2.2
	Building energy managers	0	5	5	5	4	3.8
	Occupants	0	5	4	4	5	3.6
	Organizing committee of the competition	5	5	5	5	0	4.0

8.3.2 PIs Identification and KPIs Selection

This step aims at identifying PIs and selecting the KPIs that underpin the stakeholders' performance goals and that represent the multi-level key performance information.

Firstly, the pre-list of PIs is drawn up to facilitate the selection of the KPIs. It is carried out using a preliminary review of the district's energy structure, energy flow and energy systems. Electricity is the only type of energy consumed in the Villa Solar. The electricity is provided via two sources: PV panels on site and the external grid. The latter complements the energy demand only when the energy generated by the PV panels is not sufficient to satisfy the demand. The two sources of electricity are distributed via a micro-grid to their end-users. During the distribution, some energy losses are to be expected. The end-users of the electricity are the energy-consuming systems in both the solar houses and the public service buildings. In the solar houses, the most significant forms of energy use include the HVAC systems, the lighting systems and the kitchen appliances. The surplus energy of the solar houses is supplied to the public service buildings when needed. When it is not needed, the energy is fed back to the external grid. The public service buildings have few PV panels integrated, and they account for a large portion of the total energy use. The main energy flow in the Villa Solar is illustrated in Figure 46.

Figure 46: Energy flow analysis for identifying energy performance indicators.

Through the preliminary energy review, the related PIs can be found. Furthermore, the review of literatures provides some indicators that could be reused. For example, Balducci

et al. [337] and Personal et al. [248] offered several indicators about smart grid; O'Donnell [307], Siemens [245] and Harris and Higgins [338] provided some indicators for building performance assessment. In addition, new PIs are also developed. In total, a pre-list of 35 PIs is identified, as listed in Appendix E. These PIs cover different aspects of energy performance in this case.

To select the KPIs among the proposed PIs, the comprehensive index (CI) is calculated to weight each indicator. In doing this, the values of the SPI (Stakeholder Prioritization Index) and SVI (Stakeholder Vote Index) are necessary. The value of the SPI for each stakeholder has been indicated in previous Section 8.3.1.3. Therefore, the SVI should be decided through interviews involving the participation of stakeholders. Since the case scenario originated in 2012, many of the stakeholders could not complete this task. Therefore, only the representatives of the key stakeholders participated in the vote on the PIs.

Table 22 reveals the values of the SVI from the key stakeholders. The weighting factors for the SVI of each stakeholder is calculated. As a result, the weighting factors for the relevant stakeholders are as follows: district energy engineers ($S1=0.174$), microgrid system company ($S2=0.138$), building owners ($S3=0.165$), building energy managers ($S4=0.174$), occupants ($S5=0.165$), the organizing committee ($S6=0.183$). Afterwards, the values of the CI are obtained, as listed in Table 22.

The values of the CI indicate that 23 indicators have a higher value than the average of the rating scale. They are chosen as the KPIs, including four strategic ones (I01, I02, I03, I04), 12 tactical ones (I05, I07, I09, I10, I11, I12, I15, I16, I17, I18, I19, I20) and seven operational ones (I26, I29, I30, I31, I32, I33, I34). Remaining PIs are treated as supporting indicators. Figure 47 illustrates the hierarchy of the selected KPIs.

Table 22: Values of the SVI from key stakeholders and the CI for weighting the KPIs

Tag	Performance Indicators (PIs)	SVI						CI
		S1	S2	S3	S4	S5	S6	
I01	Reduction in CO ₂ emissions	5	2	4	5	3	5	4.1
I02	Energy cost saving	4	5	5	5	5	5	4.8
I03	District energy balance	5	4	1	3	1	5	3.2
I04	Overall energy use reduction	5	4	5	5	5	5	4.9
I05	Individual building energy balance	1	3	5	5	1	5	3.4
I06	Inter-building energy balance	3	3	2	3	1	2	2.3
I07	Time correlation between energy generation and use	5	3	5	5	5	5	4.7
I08	Peak demand reduction	5	3	1	3	1	2	2.5
I09	Renewable energy share	5	2	5	5	4	5	4.4
I10	System performance	4	5	4	5	4	4	4.3
I11	Energy loss reduction	5	4	3	4	2	1	3.1
I12	Generation system efficiency	4	5	3	5	3	3	3.8
I13	Storage system efficiency	4	5	2	2	1	1	2.4
I14	Distribution system efficiency	5	5	1	1	1	1	2.2
I15	Consumption system efficiency	3	2	4	4	4	4	3.6
I16	Single-building energy use reduction	2	1	5	5	5	5	3.9
I17	Significant energy use reduction	3	1	5	5	5	3	3.7
I18	Building functionality	3	3	5	5	5	5	4.4
I19	Building comfort	1	1	4	5	5	5	3.6
I20	Purchased energy use reduction	4	4	5	5	5	1	4.0
I21	Purchased energy at a lower price	1	1	1	1	1	1	1.0
I22	Influence of energy storage on cutting peak demand	4	3	1	2	1	1	2.0
I23	Influence of TOU energy price on cutting peak demand	1	1	1	1	1	1	1.0
I24	Accuracy of the prediction of the energy supply and demand	5	1	1	3	1	1	2.0
I25	Capacity factor	4	5	1	1	1	1	2.1
I26	Equipment energy efficiency	4	5	4	5	5	4	4.5
I27	Operational schedule and occupancy consistency	3	1	2	5	3	1	2.5
I28	Occupancy stability indicator	3	1	2	4	1	1	2.0
I29	Thermal load reduction	3	1	5	5	5	5	4.1
I30	Thermal comfort	1	1	3	5	5	5	3.4
I31	Light comfort	1	1	3	5	5	5	3.4
I32	Appropriate temperature	1	1	3	5	5	5	3.4
I33	Appropriate humidity	1	1	3	5	5	5	3.4
I34	Appropriate amount of fresh air	1	1	3	5	5	5	3.4
I35	Consumers' participation	5	2	1	5	1	1	2.5

Note: S1: district energy engineers; S2: microgrid system company; S3: building owners; S4: building energy managers; S5: occupants; S6: organizing committee of the competition.

The selected KPIs and the supporting indicators are represented in the three-level hierarchy, as shown in Figure 47, where KPIs are highlighted in yellow. The strategic

KPIs I01 to I04 are hyper-aggregated at the district level. These KPIs represent the four main energy performance aspects in energy management, namely: CO₂ emissions reduction, energy cost saving, energy balance and energy use reduction. Meanwhile, I05 to I21 are disaggregated from the strategic KPIs at the building and system level, and I22 to I35 are the underlying PIs at the operational level. The interrelationship between indicators at different levels is included. For example, I03, district energy balance, evaluates the district's capacity for energy self-sufficiency, and can be disaggregated into two categories: I05 (individual building energy balance, which evaluates buildings' energy self-efficiency) and I07 (time correlation between generation and consumption, which evaluates whether the time of energy use is consistent with that of energy generation or not, and whether the in-situ energy balance is achieved or not).

Figure 47: Hierarchy of KPIs (highlighted in yellow) and supporting indicators.

In addition to the KPI hierarchy, new KPIs are also defined. One example is I02 (energy cost saving), which calculates the energy cost by considering both the energy purchase from the external grid and the energy sale to the external grid (Equation 4). The total energy cost is the difference between the cost of purchasing energy and the benefits of selling energy, which are, respectively, determined by the energy cost tariff and the feed-in tariff. When the value is negative, it means that economic profits have been obtained from the surplus energy.

$$\text{Equation 4: } I02 = E_{Purchase} \times Tariff_{Energy\_cost} - E_{Sale} \times Tariff_{Feed\_in}$$

Another new KPI is I07 (time correlation between energy generation and use) where T represents the time interval in which the power generated behind the meter did not cover the demand (Equation 5). I07 measures the total amount of unidirectional energy imported from the external grid. When its value is 0, no external power is imported, thereby achieving the targeted level of performance.

Equation 5: $I07 = \int_0^T P_{Demand\_uncovered\_by\_site\_generation} dt$

8.3.3 Mater Data Identification

Using the identified KPIs, the master data should be collected for the KPIs' calculation and performance analysis. The master data domains, objects and elements are identified, as listed in Table 23. As can be seen, the related master data objects include district, buildings, energy systems, equipment, building zone and occupant. The energy systems contain energy generation systems, energy storage systems, energy distribution systems and energy consumption systems. In addition, the master data elements are mainly related to energy production, supply, storage, use and cost in the district, buildings and/or systems, the location, the climate and weather, the static information of district, building and systems, the occupant, and the measurement of each parameters.

Table 23: Identified master data sources in Villa Solar

KPI	Master data domain	Master data object	Master data element
I01	Energy, district, measurement	Villa Solar, MV/LV substation	District non-renewable and renewable energy generation and consumption measurement, CO ₂ conversion factors
I02	Energy, measurement	Villa Solar	Energy billing, energy tariff, district energy consumption measurement
I03	Energy, measurement	Villa Solar	District total energy generation measurement and energy consumption measurement
I04	Energy, measurement	Villa Solar	District static data, district total energy consumption measurement
I05	Energy, measurement	Solar house	Building energy generation measurement, building energy consumption measurement
I07	Energy, measurement	Solar house	Power imported from external grid, generating power measurement, energy demand measurement
I09	Energy, measurement	Solar house	Renewable energy generation measurement, consumption measurement
I10	Utility, facility, measurement	Microgrid, energy facility in solar house	Utility and facility static data, system energy parameters monitoring
I11	Energy, measurement	Microgrid, energy facility in solar house	Energy supply measurement, energy consumption measurement
I12	Utility, facility,	Energy generation unit, energy generation facility	Energy generation unit and facility static data, generating power measurement, outdoor solar radiation

KPI	Master data domain	Master data object	Master data element
	environment, measurement		
I15	Utility, facility, measurement	Energy consumer, energy consumption facility	Energy consumer and consumption facility static data, consumption system energy parameters monitoring
I16	Energy, building, measurement	Solar house	Building energy consumption measurement, building static data, such as air-conditioned volume
I17	Energy, facility, measurement	HVAC system, lighting system, house appliances	Energy system consumption monitoring
I18	Building, occupant	Solar house, occupant	Occupants' votes in overall building function
I19	Building, occupant	Solar house, occupant	Occupants' votes in overall building comfort
I20	Energy, measurement	Solar house	Energy bill, energy tariff, energy consumption monitoring
I26	Equipment, device, measurement	Equipment	Equipment or device static data, equipment parameter monitoring
I29	Building, measurement	Solar house, building elements in solar house	Building static data, U-value, wall, window, roof, floor, etc
I30	Building, environment, measurement	Solar house, zones in solar house	Occupancy, temperature, humidity, air speed, fresh air measurement
I31	Building, environment, measurement	Solar house, zones in solar house	Illuminance intensity measurement
I32	Building, environment, measurement	Solar house, zones in solar house	Temperature measurement
I33	Building, environment, measurement	Solar house, zones in solar house	Humidity measurement
I34	Building, environment, measurement	Solar house, zones in solar house	CO ₂ concentration measurement

After identifying the master data, the next step is to collect them from different sources. Among all of the identified master data, the existing data sources include (1) district, building and energy system static data; (2) energy generation, supply and consumption data of each solar house and the district substation, (3) building comfort data of indoor temperature, humidity, illuminance and CO₂ concentration, and (4) outdoor environment data. The sub-meter data and other system and equipment monitoring data are not available. They need to be collected by further data capture. The district energy supply data were measured and collected separately, not through the aggregation of building-

level data. Generally, the monitored data have good quality and consistency, due to its purpose for the competition; for this reason, the definition of methods to deal with potential data inconsistency issues is beyond the scope of this work.

8.3.4 EM-KPI Ontology Instantiation and Linked Data Generation

In this section, the developed EM-KPI ontology is used to facilitate the interchange of key performance information and master data sources. An example linked dataset is constructed using the ontology in order to demonstrate its feasibility for data interchange and exploitation.

The original data sources gathered from the different stakeholders in this scenario are all stored in separate Excel files, including the list of KPIs, buildings static and their monitored energy demand data, energy production data, energy supply data and indoor comfort data, as well as the outdoor weather data.

Figure 48: Process used to map the data sources to the ontology and generate linked data in the real scenario.

The dispersed data sources should be firstly converted into RDF (Resource Description Framework) in order to instantiate the ontology. Figure 48 shows the process adopted to map the data sources to the EM-KPI ontology and to generate the linked data for application. The tool OpenRefine is used to clean and transform the Excel data, to create the instances for the classes and to assign values to the properties for each instance. In total, 27 Excel data files are converted, including the KPIs and the required datum sources. The converted RDF data and the ontology are gathered together in a triple store. The tool RDF4j is used to integrate the various RDF files and to query the linked datasets. A support service for the calculation of KPIs is needed, since the linked data only provides the solution to integrate data, not for the calculation.

As an example, three representative KPIs related to the energy balance are studied, namely I03 district energy balance, I05 individual building energy balance and I07 time correlation between generation and consumption. The related information about these KPIs and their associated master data sources are mapped to the ontology.

List 1, below, shows a code snippet of I03 and its relationship with I05 and I07, which is written in Turtle. The snippet shows that I03 is a strategic KPI and that its definition is the district energy balance between energy generation and consumption during a given time step. The stakeholders, including the district energy engineers and the building energy managers, have a performance goal (i.e., energy self-sufficiency). The performance goal has associated KPIs, including I03, I05 and I07. In addition, I05 and I07 are the disaggregation of I03.

```
@prefix dct: <http://purl.org/dc/terms/>.
@prefix eko: <http://energy.linkeddata.es/em-kpi/ontology#>.
@prefix xsd: <http://www.w3.org/2001/XMLSchema#>.
eko:I03 a eko:StrategicKPI.
    dct:identifier "District energy balance"^^xsd:string;
    eko:hasKPIDefinition "District energy balance between generation and
consumption during given time step (TS)"^^xsd:string.
eko:DistrictEnergyEngineers a eko:Stakeholder;
    eko:hasPerformanceGoal eko:EnergySelfsufficiency.
eko:BuildingEnergyManagers a eko:Stakeholder;
    eko:hasPerformanceGoal eko:EnergySelfsufficiency.
eko:EnergySelfsufficiency a eko:PerformanceGoal;
    eko:hasAssociatedKPI eko:I03, eko:I05, eko:I07.
eko:I05 a eko:TacticalKPI.
eko:I07 a eko:TacticalKPI.
eko:I03 eko:hasDisaggregation eko:I05, eko:I07.
```

Listing 1: A code snippet in Turtle regarding the KPI I03 and its relationship with I05 and I07.

Figure 49 shows a capture of the RDF4j repository that integrate the 27 RDF files with the ontology. Therefore, the generated linked data is available. The integrated RDF is also exported to make it accessible for further exploration and analysis.

Repositories	Context
New repository	<file:///C:/fakepath/EM-KPI_Ontology_Version1.1.owl>
Delete repository	<file:///C:/fakepath/Io3-District-energy-balance-calculation-results.xlsx.ttl>
Explore	<file:///C:/fakepath/VillaSolar-energy-supply-external-kW.xlsx.ttl>
Summary	<file:///C:/fakepath/Building-basic-information.xlsx.ttl>
Namespaces	<file:///C:/fakepath/Weather-data.xlsx.ttl>
Contexts	<file:///C:/fakepath/Strategic-KPI.xlsx.ttl>
Types	<file:///C:/fakepath/Io5-Individual-building-energy-balance-calculation-results.xlsx.ttl>
Explore	<file:///C:/fakepath/Io7-calculation-results.xlsx.ttl>
Query	<file:///C:/fakepath/Tactical-KPI.xlsx.ttl>
Saved Queries	<file:///C:/fakepath/Solar-house-2-STSH-astonyshine-Refine.xlsx.ttl>
Export	<file:///C:/fakepath/Solar-house-1-DTU-Fold.xlsx.ttl>
Modify	<file:///C:/fakepath/Solar-house-3-HTWG-Ecolar-Home-Refine.xlsx.ttl>
SPARQL Update	<file:///C:/fakepath/Solar-house-4-EHU-Ekihouse-Refine.xlsx.ttl>
Add	<file:///C:/fakepath/Solar-house-5-ABC-Sumbiosi-Refine.xlsx.ttl>
Remove	<file:///C:/fakepath/Solar-house-6-RWTH-Counter-Entropy-House-Refine.xlsx.ttl>
Clear	<file:///C:/fakepath/Solar-house-7-BRA-Ek-House-Refine.xlsx.ttl>
System	<file:///C:/fakepath/Solar-house-8-ROME-Med-in-Italy-Refine.xlsx.ttl>
Information	<file:///C:/fakepath/Solar-house-9-FAUP-cem-casas-em-movimento-Refine.xlsx.ttl>
	<file:///C:/fakepath/Solar-house-10-CEU-SMLsystem-Refine.xlsx.ttl>
	<file:///C:/fakepath/Solar-house-11-AND-Patio-2-12-Refine.xlsx.ttl>
	<file:///C:/fakepath/Solar-house-12-UPC-e-co-Refine.xlsx.ttl>
	<file:///C:/fakepath/Solar-house-13-CUJ-Omotenashi-House-Refine.xlsx.ttl>
	<file:///C:/fakepath/Solar-house-14-UDZ-Casa-pi-Unizar-Refine.xlsx.ttl>
	<file:///C:/fakepath/Solar-house-15-BUC-Prispa-Refine.xlsx.ttl>
	<file:///C:/fakepath/Solar-house-16-BME-Odoo-Refine.xlsx.ttl>
	<file:///C:/fakepath/Solar-house-17-TJU-Para-Eco-House-Refine.xlsx.ttl>
	<file:///C:/fakepath/Solar-house-18-TRA-Canopea-Refine.xlsx.ttl>
	<file:///C:/fakepath/Operational-KPI.xlsx.ttl>

Figure 49: Contexts of the integrated RDF files in the RDF4j repository.

RDF4j can also provide database server and SPARQL endpoint services. The RDF4j Workbench is a web-based client UI for managing knowledge bases and executing queries. It can authorize users who can access to the repository, and pre-define and save the SPARQL queries for easy data retrieve. Figure 50 shows a screenshot of the user definition and Figure 51 illustrates a screenshot of the pre-defined queries.

Repositories	
New repository	
Delete repository	
Explore	
Summary	
Namespaces	
Contexts	
Types	
Explore	
Query	
Saved Queries	
Export	

RDF4J Server URL:

for example: http://localhost:8080/rdf4j-server

User (optional):

Password (optional):

Figure 50: Screenshot of the user definition for RDF4j Server.

Figure 51: Screenshot of saved SPARQL queries for easy data retrieve.

With the generated linked data, SPARQL query language can be used to retrieve the KPIs and the related cross-domain data sources for the insight exploration. In order to gain an overview of the stakeholders and their performance goals in this case, a simple query of the stakeholders and their energy performance goals is conducted firstly, as Listing 2.

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX eko: <http://energy.linkeddata.es/em-kpi/ontology#>
SELECT ?Stakeholder ?PerformanceGoal
WHERE
{
  ?Stakeholder rdf:type eko:Stakeholder.
  ?Stakeholder eko:hasPerformanceGoal ?PerformanceGoal.
}
```

Listing 2: The SPARQL query of the stakeholders and their performance goals.

Table 24 lists the SPARQL query result of Listing 2, which shows that there are six groups of stakeholders instantiated in the ontology, who have performance goals such as energy self-sufficiency, house function and comfort, multi-level energy efficiency improvement, renewable energy use increase and energy cost-saving.

Table 24: Query result of the stakeholders and their performance goals

Stakeholder	PerformanceGoal
eko:BuildingEnergyManagers	eko:EnergySelfsufficiency
eko:BuildingEnergyManagers	eko:HouseFunctioningAndComfort
eko:BuildingEnergyManagers	eko:Multi-levelEnergyEfficiencyBy20Percent
eko:BuildingOwners	eko:EnergyCostSavingWithMinimumEnergyPurchase
eko:CompetitionOrganizingCommittee	eko:Multi-levelEnergyEfficiencyBy20Percent
eko:CompetitionOrganizingCommittee	eko:CO2EmissionsReductionBy20Percent
eko:CompetitionOrganizingCommittee	eko:RenewableEnergyUseBy20Percent
eko:DistrictEnergyEngineers	eko:EnergySelfsufficiency
eko:DistrictEnergyEngineers	eko:Multi-levelEnergyEfficiencyBy20Percent
eko:MicrogridCompany	eko:Multi-levelEnergyEfficiencyBy20Percent
eko:MicrogridCompany	eko:EnergyCostSavingWithMinimumEnergyPurchase
eko:Occupants	eko:HouseFunctioningAndComfort

Since energy self-sufficiency is one of the most important targets in the Villa Solar, its associated KPIs are selected as an example for further analysis, which are requested as the following Listing 3. The related stakeholders include the district energy engineers and building energy managers.

```

PREFIX eko: <http://energy.linkeddata.es/em-kpi/ontology#>
PREFIX dct: <http://purl.org/dc/terms/>
SELECT ?KPI ?identifier1 ?DisaggregatedKPI ?identifier2
WHERE
{
  eko:EnergySelfsufficiency eko:hasAssociatedKPI ?KPI.
  ?KPI eko:hasDisaggregation ?DisaggregatedKPI.
  ?KPI dct:identifier ?identifier1.
  ?DisaggregatedKPI dct:identifier ?identifier2 }

```

Listing 3: The SPARQL query of the KPIs associated to energy self-sufficiency.

The query result of Listing 3 is presented in Table 25, showing that the KPIs associated to energy self-sufficiency include I03 (district energy balance), I05 (individual building energy balance) and I07 (time correlation between generation and use), among which I05 and I07 are disaggregated from I03.

Table 25: Query result of the KPIs associated to energy self-sufficiency

KPI	Identifier1	DisaggregatedKPI	Identifier2
eko:I03	"District energy balance "	eko:I05	"Individual building energy balance"
eko:I03	"District energy balance "	eko:I07	"Time correlation between use and generation "

8.3.5 KPI Calculation and Benchmarking

In this section, the three representative KPIs in relation to the energy self-sufficiency will be calculated through retrieving their mathematical model and needed datum sources from the linked data; in addition, these KPIs are also benchmarked to indicate whether the target performance is achieved or not.

The mathematical model and datum sources for the calculation of I03 are queried as the following Listing 4.

```
PREFIX eko: <http://energy.linkeddata.es/em-kpi/ontology#>
PREFIX ssn: <http://purl.oclc.org/NET/ssnx/ssn#>
PREFIX dul: <http://www.ontologydesignpatterns.org/ont/dul/DUL.owl#>
PREFIX bio:
<https://www.auto.tuwien.ac.at/downloads/thinkhome/ontology/gbBuildingOntology
.owl#>
SELECT DISTINCT ?MathematicalModel ?Equation ?mathML ?DatumSource
WHERE
{
  eko:I03 eko:hasCalculation ?I03Calculation.
  ?I03Calculation ssn:hasInput ?DatumSource.
  ?I03Calculation eko:hasCalculationModel ?MathematicalModel.
  ?MathematicalModel bio:containsEquation ?Equation.
  ?Equation eko:hasMathML ?mathML.
}
```

Listing 4: The SPARQL query of the mathematical model and datum sources for I03 calculation.

Table 26 lists the query result of the datum sources, in addition to the mathematical model including its equation.

Table 26: Query result of the datum sources for I03 calculation

MathematicalModel	Equation	MathML	DatumSource
eko:Math_model_I03	eko:Equation_I03	$ \begin{matrix} \text{D} & \text{I} & \text{S} & \text{T} \\ \text{r} & \text{i} & \text{c} & \text{t} \\ \text{g} & \text{e} & \text{n} & \text{e} \\ \text{m} & \text{t} & \text{i} & \text{o} & \text{n} \end{matrix} $	eko:DatumSource_EnergySupplyExternalkW_VillaSolar

I03 (district energy balance) is calculated using *eko:Equation_I03*, the MathML translated to normal expression is as shown in **Equation 6**, where $P_{District\ generation}$ and $P_{District\ consumption}$, respectively, represent the power generated and consumed in the

district at a specific time. The integral of the power generated and consumed, respectively, represent the total amount of energy generation and consumption in the district during the time step (TS).

$$\textbf{Equation 6: } I03 = \int_0^{TS} P_{District\ generation} dt - \int_0^{TS} P_{District\ consumption} dt \text{ (kWh)}$$

The datum sources needed for the calculation is:

eko:DatumSource_EnergySupplyExternalkW_VillaSolar, which is the difference between $P_{District\ generation}$ and $P_{District\ consumption}$, and these data sources are available and provided by the observation of external energy supply in the district.

Since I03 reflects the difference between the energy generation and consumption in Villa Solar, if the result is 0, the district's energy balance is achieved. If the result is positive, the surplus energy will be exported to the external grid. Finally, if the result is negative, the performance target is not considered to be fulfilled.

Using the linked data, the mathematical models and the needed datum sources for the calculation of I05 and I07 has also been retrieved. The disaggregated indicator I05 (individual building energy balance) is calculated using *eko:Equation_I05*, the MathML translated to normal expression is as shown in the following **Equation 7**. $P_{Building\ generation}$ and $P_{Building\ consumption}$, respectively, represent the generated and consumed power in the specific solar house at specific time. The integral of the $P_{Building\ generation}$ and $P_{Building\ consumption}$, respectively, represent the total amount of energy generation and consumption in the solar house during the time step (TS).

$$\textbf{Equation 7: } I05 = \int_0^{TS} P_{Building\ generation} dt - \int_0^{TS} P_{Building\ consumption} dt \text{ (kWh)}$$

The datum sources needed to calculate I05 include the external energy supply data of each solar house. The external energy supply is the difference between $P_{Building\ generation}$ and $P_{Building\ consumption}$, which is available and can be provided by the observation data of building energy supply.

I05 represents the difference between the energy generation and consumption in a single building, if the result is 0, the solar house's energy balance is achieved. If the result is positive, surplus energy is generated and it will be exported to the external grid. Finally, if the result is negative, the performance target of building energy balance is not considered to be fulfilled.

Lastly, the mathematical model and datum sources of I07 (time correlation between energy generation and use) is requested. I07 evaluates whether the energy generation is consumed in situ or not. I07 is calculated using *eko:Equation_I07*, as shown in the

following **Equation 8**, where T represents the time interval in which the power generated did not cover the demand, and this meant that some energy needed to be imported from the external grid. The integral of $P_{Demand\ uncovered\ by\ generation}$ means the total amount of energy supply from the external grid.

Equation 8: $I07 = \int_0^T P_{Demand\ uncovered\ by\ site\ generation} dT \text{ (kWh)}$

I07 measures the total amount of unidirectional energy imported from the external grid, therefore its value is non-negative. When the value is 0, this means that the solar house uses no external power to meet its demand, thereby achieving the targeted level of performance. When the value is above 0, the time correlation cannot be considered to be fulfilled.

The needed datum sources of I07 are provided by the observation data of the total amount of energy supply from the external grid in each solar house, with the unit of kWh. These data are available from the smart meter installed in the solar houses.

After retrieving the mathematical model and datum source for each KPI, they are exported to the support tool for implementing the calculation.

8.3.6 Multi-level Energy Performance Analysis

The results of KPI calculation are illustrated in this section; and a comprehensive multi-level energy performance analysis based on the results of KPI calculation and their related master data is carried out. This aims to find energy performance problem, identify key areas for improvement and explore the insights for improvement.

To enable a deeper analysis of energy balance performance, firstly the calculation results of each KPI is retrieved, including their calculated value, their evaluated objects, the evaluation time step and the unit of the value. As an example, the following Listing 5 shows the query of the calculation result of I03.

The query result of I03 is shown in Table 27. It implies that I03 evaluates the object Villa Solar and that it takes the evaluation time step as one day. For example, *eko:Interval20120917* means the day September 17th, 2012. In addition, the start time instant and the end time instant are also presented. In total, there are 12 calculations for I03, from September 17th to September 28th. The unit of the calculation value is kWh. The values of I03 implies that the energy balance performance of Villa Solar is unsatisfactory, because each value is negative, which means that the energy self-sufficiency target has not been achieved.

```
PREFIX eko: <http://energy.linkeddata.es/em-kpi/ontology#>
PREFIX time: <http://www.w3.org/2006/time#>
PREFIX ssn: <http://purl.oclc.org/NET/ssnx/ssn#>
```

```

PREFIX dul: <http://www.ontologydesignpatterns.org/ont/dul/DUL.owl#>
SELECT DISTINCT ?KPIEvaluatedObject ?dateTimeStart ?dateTimeEnd ?value_I03 ?Unit
WHERE
{
  eko:I03 eko:hasCalculation ?I03Calculation.
  ?I03Calculation eko:hasAssociatedObject ?KPIEvaluatedObject.
  ?I03Calculation eko:hasEvaluationTimeStep ?Interval.
  ?Interval time:hasBeginning ?InstantStart.
  ?InstantStart time:inXSDDateTime ?dateTimeStart.
  ?Interval time:hasEnd ?InstantEnd.
  ?InstantEnd time:inXSDDateTime ?dateTimeEnd.
  ?I03Calculation ssn:hasOutput ?KPIValue.
  ?KPIValue dul:hasValue ?value_I03.
  ?KPIValue eko:hasUnit ?Unit. }
ORDER BY ?Interval

```

Listing 5: The SPARQL query of the I03 calculation result.

Table 27: Query result of I03, including the evaluation interval, the value and the unit

I03Calculation	Interval	DateTimeStart	DateTimeEnd	Value_I03	Unit
eko:Calcu01_I03_VillaSolar	eko:Interval20120917	2012-09-17T00:14:00	2012-09-17T23:59:00	-747.535	eko:kilowatt_hour
eko:Calcu02_I03_VillaSolar	eko:Interval20120918	2012-09-18T00:14:00	2012-09-18T23:59:00	-802.770	eko:kilowatt_hour
eko:Calcu03_I03_VillaSolar	eko:Interval20120919	2012-09-19T00:14:00	2012-09-19T23:59:00	-787.730	eko:kilowatt_hour
eko:Calcu04_I03_VillaSolar	eko:Interval20120920	2012-09-20T00:14:00	2012-09-20T23:59:00	-857.385	eko:kilowatt_hour
eko:Calcu05_I03_VillaSolar	eko:Interval20120921	2012-09-21T00:14:00	2012-09-21T23:59:00	-628.870	eko:kilowatt_hour
eko:Calcu06_I03_VillaSolar	eko:Interval20120922	2012-09-22T00:14:00	2012-09-22T23:59:00	-458.180	eko:kilowatt_hour
eko:Calcu07_I03_VillaSolar	eko:Interval20120923	2012-09-23T00:14:00	2012-09-23T23:59:00	-359.555	eko:kilowatt_hour
eko:Calcu08_I03_VillaSolar	eko:Interval20120924	2012-09-24T00:14:00	2012-09-24T23:59:00	-310.020	eko:kilowatt_hour
eko:Calcu09_I03_VillaSolar	eko:Interval20120925	2012-09-25T00:14:00	2012-09-25T23:59:00	-483.635	eko:kilowatt_hour
eko:Calcu10_I03_VillaSolar	eko:Interval20120926	2012-09-26T00:14:00	2012-09-26T23:59:00	-495.795	eko:kilowatt_hour
eko:Calcu11_I03_VillaSolar	eko:Interval20120927	2012-09-27T00:14:00	2012-09-27T23:59:00	-827.310	eko:kilowatt_hour
eko:Calcu12_I03_VillaSolar	eko:Interval20120928	2012-09-28T00:14:00	2012-09-28T23:59:00	-845.055	eko:kilowatt_hour

Figure 52 visualizes the calculation result of I03. Additionally, the energy balance data of the public service buildings and the 18 solar houses are also presented in order to compare and analyse the energy balance performance of the Villa Solar. The result implies that the district energy balance has not been achieved, especially in the dates 18th, 20th, 27th and 28th September. The reason behind the undesirable energy performance is that the energy demand of the public service buildings is much higher than the surplus energy generated by the 18 solar houses. The surplus energy of the solar houses was supplied to the public service buildings, but it did not suffice to cover their demand. On September 23rd and 24th, the district energy balance had the best performance, primarily due to the lower demand of the public service buildings and the surplus energy supplied by the solar houses on those days. In additional, the solar houses always generated surplus energy, with the exception of two days: September 27th and 28th.

Figure 52: Result for I03 (district energy balance) and its contrast with the public service buildings and the 18 solar houses

A further analysis of the factors which influence the energy production in these two days is conducted to ascertain the reason behind the undesirable performance. The SPARQL query of the factors which influence energy production is detailed below in Listing 6.

```
PREFIX eko: <http://energy.linkeddata.es/em-kpi/ontology#>
PREFIX po:
<https://www.auto.tuwien.ac.at/downloads/thinkhome/ontology/ProcessOntology.owl#>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
CONSTRUCT {?y po:hasInfluenceOn ?EnergyProduction}
WHERE
{
  ?y po:hasInfluenceOn ?EnergyProduction.
  ?EnergyProduction rdf:type eko:EnergyProduction }

```

Listing 6: The SPARQL query of the factors which influence energy production.

The query result of Listing 6 implies that solar irradiance has a direct influence on energy production. Therefore, the observation data of the solar irradiance are retrieved, including the global horizontal solar irradiance and global inclined 40° (best angel in Madrid) solar radiation. Figure 53 visualises the retrieved data of the solar irradiance. It shows that the solar irradiance in *Interval20120927* and *Interval20120928* is much lower than the other days, with an intensity of less than 300 W/m^2 , which is unfavourable for energy production, and therefore leads to a bad energy balance performance in these days.

Figure 53: Global horizontal solar radiation ($G(0)$) and global inclined 41° solar radiation ($G(41)$) in Madrid

In order to evaluate and compare the energy balance performance in each solar house, the disaggregated indicator I05 (individual building energy balance) is analysed and its calculation results is also retrieved. The calculation also takes one day as evaluated time step and the unit is kWh. However, unlike to I03, which only has one evaluated object (i.e., Villa Solar), the indicator I05 has calculations associated to different solar houses. Each solar house has 12 calculations during the monitored days. The value can be compared with each other to understand better the performance in various solar houses.

Table 28 presents the calculation value of I05, which are visualized in different colours. The values and the colour gradient show the amount of surplus energy generated. The darker the shade of green, the more surplus energy generated. Similarly, the darker the shade of red, the more energy needed to be imported from the external grid. It indicates that the required energy balance performance was not achieved by any of the solar houses on September 27th and 28th, due to the bad weather conditions mentioned previously. However, most solar houses achieved the energy balance performance on most days, except for Solar House 2 and Solar House 14, which had the worst performance in terms of energy balance.

Table 28: Calculation result of I05 individual building energy balance (unit: kWh)

Day-month Object	17-Sep	18-Sep	19-Sep	20-Sep	21-Sep	22-Sep	23-Sep	24-Sep	25-Sep	26-Sep	27-Sep	28-Sep
Solar House 1	-3.7	-0.3	8.5	-2.0	10.7	20.6	10.6	19.7	13.2	14.5	-3.9	-9.3
Solar House 2	-6.3	-10.6	-9.3	-12.4	-6.9	-1.0	-1.2	-9.0	-7.7	-8.9	-15.9	-10.8
Solar House 3	7.0	3.3	22.5	2.1	33.7	49.9	36.6	43.4	31.9	32.4	3.9	-1.4
Solar House 4	14.8	7.0	27.0	21.1	35.7	41.6	27.8	37.9	18.3	24.1	-1.3	-14.9
Solar House 5	-3.7	1.9	3.1	-4.1	1.2	15.3	10.2	12.7	8.2	6.1	-4.5	-7.3
Solar House 6	5.2	4.3	8.1	2.4	20.3	12.2	15.3	17.3	5.0	11.5	-4.1	-6.4
Solar House 7	19.0	21.5	36.7	20.1	41.0	46.3	32.9	48.1	30.6	32.4	-8.8	-9.8
Solar House 8	14.1	13.9	24.1	14.5	29.5	34.9	30.0	34.3	22.4	21.2	1.1	-5.3
Solar House 9	17.6	20.7	29.2	21.8	32.2	38.2	29.0	35.1	23.2	23.9	1.6	1.0
Solar House 10	-12.0	-9.6	2.2	-5.0	4.4	11.6	6.5	7.9	6.3	7.8	-1.7	-3.7
Solar House 11	13.4	18.4	31.9	16.2	35.2	38.5	27.0	35.8	21.4	23.8	4.2	-0.4
Solar House 12	-1.5	1.7	8.5	2.9	11.1	18.5	12.9	12.8	5.7	6.5	-6.5	-5.0
Solar House 13	1.9	0.3	14.3	10.9	26.0	25.3	10.9	19.5	20.8	11.2	-3.1	-14.6
Solar House 14	-1.3	-10.2	-5.6	-9.1	-1.6	3.5	1.0	-2.7	-0.4	-9.1	-16.6	-7.1
Solar House 15	5.8	10.4	26.4	16.0	29.0	36.3	25.6	30.8	18.3	21.7	-6.2	-4.0
Solar House 16	2.5	8.4	19.3	4.0	14.0	28.3	18.0	23.6	11.1	11.1	-14.9	-15.8
Solar House 17	11.0	13.9	30.3	15.6	33.0	34.9	24.2	41.4	21.6	23.6	-8.4	-11.9
Solar House 18	9.8	9.5	22.2	12.7	24.5	23.4	20.3	34.0	20.6	18.0	-5.3	-9.7

In order to determine the reason for the undesirable performance in Solar House 2 and Solar House 14, the master data of the generated and consumed power in these two houses were retrieved and analysed. The following Listing 7 shows the query of the observation data of energy production in Solar House 2.

```

PREFIX ssn: <http://purl.oclc.org/NET/ssnx/ssn#>
PREFIX eko: <http://energy.linkeddata.es/em-kpi/ontology#>
PREFIX dul: <http://www.ontologydesignpatterns.org/ont/dul/DUL.owl#>
PREFIX time: <http://www.w3.org/2006/time#>
SELECT DISTINCT ?dateTime ?energyProduction ?Unit
WHERE
{
  ?Observation ssn:observedProperty eko:EnergyProductionW_Solarhouse_2.
  ?Observation ssn:featureOfInterest ?FeatureOfInterest.
  ?Observation ssn:observationSamplingTime ?Instant.
  ?Instant time:inXSDDateTime ?dateTime.
  ?Observation ssn:observationResult ?ObservationValue.
  ?ObservationValue dul:hasValue ?energyProduction.
  ?ObservationValue eko:hasUnit ?Unit.
}
ORDER BY ?dateTime

```

Listing 7: The SPARQL query of the observation data of energy production in Solar House 2.

The requested master data of Solar House 2 is exported and visualized as shown in Figure 54. It can be seen that the energy generation power is very low during the monitoring days that can be almost neglected. It is far from sufficient to cover the energy demand.

Figure 54: Power generated and consumed in Solar House 2 from September 17th to 28th.

Excluding the outdoor weather factors, this implies that Solar House 2 may have problems with its energy producer facility. Hence the energy producer facility that produce energy in Solar House 2 is requested as the below Listing 8.

```
PREFIX ero:
<https://www.auto.tuwien.ac.at/downloads/thinkhome/ontology/EnergyResourceOntology.owl#>
SELECT ?Facility ?EnergyProduction ?EnergyType
WHERE
{
  ?Facility ero:producesEnergy ?EnergyProduction.
  ?Facility ero:producesEnergyType ?EnergyType
}
```

Listing 8: The SPARQL query of the energy producer facility in Solar House 2.

It has been found that a PV system is the facility that generates energy in Solar House 2. Such PV system contains a PV unit, which has the type of microcrystalline silicon and the installed power is 11.35 kW, which is much higher than the actual generated power. Therefore, it can be inferred that there were some problems or a system failure happened to the PV unit, which resulted to such a low generating efficiency.

With the similar process, the energy performance problem in Solar House 14 can also be analysed. Figure 55 visualizes the observation data of the generated and consumed power in Solar House 14.

Figure 55: Power generated and consumed in Solar House 14 from September 17th to 28th.

A further query of the energy producer facility in Solar House 14 shows that a PV unit of the type polycrystalline silicon was installed in the building, its installed power is 8.8 kW. However, the actual power output was less than 2.5 kW, which was not sufficient to satisfy the energy demand. The PV system of Solar House 14 ran very inefficiently on the days monitored.

I03 and I05 calculate the difference between the total amounts of generated and consumed energy during the day, without considering the time consistency between generation and consumption. Thereby, another disaggregated indicator I07 (time correlation between energy generation and use) is analysed.

Table 29 presents the calculation result of I07. The evaluated time step of I07 is also one day, and the unit of I07 value is kWh. Compared to I05, the values of I07 imply that, although most of the solar houses generated surplus energy during the day, some power still needed to be imported from the external grid, since they did not achieve the required time correlation between energy generation and use. Time correlation is one of the most difficult challenges. Taking Solar House 13 as an example, it had the worst performance in terms of time correlation, importing 162 kWh in total during the days monitored, while, according to I05, it had 123.4 kWh of surplus energy. If the desirable time correlation performance is achieved, it did not need to import any energy from the external grid, but export 123.4 kWh back to the grid.

Table 29: Calculation result of I07 (time correlation between generation and consumption)
(unit: kWh)

Day-month Object	17- Sep	18- Sep	19- Sep	20- Sep	21- Sep	22- Sep	23- Sep	24- Sep	25- Sep	26- Sep	27- Sep	28- Sep
Solar House 1	13	12	11	15	10	6	3	5	3	6	8	10
Solar House 2	5	11	9	13	8	2	1	10	8	9	17	11
Solar House 3	14	17	12	25	9	2	3	2	3	3	7	5
Solar House 4	10	15	9	7	2	6	8	6	7	6	10	15
Solar House 5	11	8	9	14	12	3	4	3	3	5	8	8
Solar House 6	10	11	10	11	5	15	5	6	11	6	9	8
Solar House 7	11	9	9	14	7	6	5	4	4	8	15	14
Solar House 8	4	4	3	5	3	2	1	2	4	3	5	8
Solar House 9	8	4	8	7	4	2	1	3	6	4	9	3
Solar House 10	15	10	9	8	4	3	3	3	5	3	4	4
Solar House 11	10	3	0	2	0	0	0	1	0	2	3	3
Solar House 12	4	5	3	6	2	2	1	4	5	5	9	6
Solar House 13	15	13	14	12	10	11	12	15	12	17	16	15
Solar House 14	0	6	11	13	9	7	6	10	6	13	17	7
Solar House 15	13	7	4	7	4	2	3	2	3	4	12	5
Solar House 16	14	10	10	12	13	9	8	8	8	13	18	16
Solar House 17	9	8	9	12	7	10	6	3	5	10	13	12
Solar House 18	14	13	12	15	10	11	8	1	2	3	9	11

In order to enable a detailed analysis of the time uncorrelation between energy generation and use in Solar House 13, the observation data of its generated and consumed power from September 21st to 25th are retrieved and analysed. Figure 56 presents the related observation data. It reveals that the PV system worked properly; the power generated was much higher than the power consumed, which should entirely satisfy the energy demand. However, most of the energy consumption occurred during times that involved no energy generation; and this part of energy consumption should be imported from external grid. To improve the performance in this case, adjustments in the occupants' behaviour or the utilization of energy storage are possible solutions.

Figure 56: Power generated and consumed in Solar House 13 from 21st Sep to 25th Sep

The results and analyses of I03, I05 and I07 demonstrate the interrelationship between high-level aggregated KPIs and low-level disaggregated KPIs, in addition to the advantages they offer for multi-level energy performance analysis. The real scenario analysis validates the feasibility of the proposed methodology, especially the feasibility of the EM-KPI ontology and its generated linked data in exchanging cross-domain master data and multi-level key performance information and exploiting the knowledge and insights for performance improvement. It proves the convenience of the linked data analysis for identifying performance problems and key areas for improvement.

8.4 COMPARISON OF THE CURRENT AND KPI-BASED LINKED DATA METHODOLOGY

In this section, a further comparison analysis between the KPI-based linked data methodology and the current used methodology is carried out in terms of the decision-making in energy performance improvement. The KPI-based linked data methodology facilitates the exchange and sharing of multi-level energy performance information and cross-domain data among different stakeholders; while the current method used in the case has no effective interaction and information exchange between building and district stakeholders as well as between stakeholders from different buildings. Building energy management systems and microgrid energy management systems are standalone. The comparison analysis of these two methodologies will focus on the effect of energy performance improvement resulted by different decisions made and actions taken by stakeholders when using the two different methodologies.

To conduct the comparison analysis, firstly the general differences between the current used methodology and the KPI-based linked data methodology is illustrated in Section 8.4.1. Afterwards, the comparison analysis in terms of energy performance improvement is conducted in Section 8.4.2. The improvement analysis is carried out based on three

scenarios: the first scenario considers the improvement of energy balance at the district level, which contains both building consumers and prosumers; the second scenario studies the energy balance among a cluster of building prosumers; and the third scenario considers the energy balance in a single building prosumer. Finally, a comprehensive cost benefit analysis of the KPI-based linked data methodology is carried out.

8.4.1 Current Methodology vs. KPI-based Linked Data Methodology

The main differences between the current methodology and the KPI-based the linked data methodology lie in the processes for engagement of stakeholders, selection of KPIs, interchange and sharing of multi-level performance information and cross-domain data. Therefore, when there are undesirable performance problems, the improvement decisions and actions taken by the different stakeholders using the two methodologies will be different. In this section, a general comparison between the two methodologies is performed. Figure 57 shows the main aspects for comparison.

Figure 57: Main aspects for comparison between the current methodology and KPI-based linked data methodology.

Figure 58 summarizes the different aspects of interaction at district and building levels with the current used methodology. The energy management at the district level and at the building level are standalone. In addition, the energy management in different buildings is also separated. District stakeholders and building stakeholders as well as the stakeholders from different buildings are not involved to promote an integrated multi-level energy management. Therefore, there is no interaction among the stakeholders across the district and building levels, neither across the different buildings. The selected KPIs at district level represent district energy performance without hierarchical relation with the KPIs at building level. Furthermore, there are no standard KPIs for different buildings, which means that different buildings may choose different KPIs to represent their performance. Thus, it is difficult to compare the performance of various buildings. Furthermore, the data are not shared and exchanged at the district and building levels for energy performance analysis due to cross-domain data heterogenous problem. In terms

of energy performance analysis, district energy managers analyse the district energy performance and usually have no access to the detailed performance information of single buildings. One building also has no access to the performance information of other buildings. Thus, when encountering performance problems, the improvement decisions and actions can be only performed at their own level of control.

Figure 58: Interaction at district and building levels using the current methodology.

In contrast, the KPI-based linked data methodology provides an effective engagement mechanism for various stakeholders at different levels and a sharing approach for key performance information and heterogeneous data from different scales and domains. Figure 59 illustrates the different aspects of interaction at district and building levels using the KPI-based linked data methodology. With the proposed methodology, the district energy managers can interact with the building energy managers; and the stakeholders at district level can interact with the stakeholders at single building level. Furthermore, the stakeholders at different buildings can also interact with each other for performance information and data exchange. Furthermore, the KPIs at different level are represented in a multi-level hierarchical structure. The KPIs at district level can be disaggregated to the KPIs at building and system level, and then at zone and equipment level. The different buildings use the standard KPIs, thereby the energy performance of various buildings is comparable. Moreover, there is data sharing across different levels and among different buildings. The stakeholders are informed of their concerned performance and also able to analyse the performance using the shared data. The shared cross-domain data can enable a more comprehensive analysis in performance problems identification. Furthermore, the stakeholders can engage in the decision making for energy performance improvement and interact with each other. Therefore, the final improvement decisions to resolve the

performance problems is a result of stakeholders' engagement. One stakeholder can influence or benefit from the others.

Figure 59: Interaction at district and building levels using the KPI-based linked data methodology.

To conclude, the main differences of the current used methodology and the proposed methodology are listed in Table 30. It shows that the proposed methodology has various advantages over the current methodology in terms of stakeholders' engagement, KPI selection and information exchange.

Table 30: Summary of the main differences between current and linked data methodology

	Current methodology	KPI-based linked data methodology
1. Interaction between district and building energy management	No	Yes
2. Stakeholders interaction at district and building levels	No	Yes
3. Integrated hierarchy of multi-level KPIs	No	Yes
4. Standard KPIs for different buildings	No	Yes
5. Performance information sharing and exchange across different levels and among different buildings	No	Yes
6. Heterogeneous data interoperability	Limited	Yes
7. Multi-level energy performance analysis	No	Yes
8. Performance comparison between different buildings	Limited	Yes
9. Improvement decisions and actions with stakeholders' engagement	Limited	Yes

8.4.2 Comparison Analysis for Energy Performance Improvement

The comparison analysis of energy performance focuses on the different potential improvement decisions and actions that could be taken by stakeholders using the two different methodologies. The final energy performance resulted by the different decisions will be analysed and compared.

Considering the Villa Solar contains 18 solar houses connected to the grid, which are all aimed to be Net Zero Energy Buildings (NetZEBs)⁷⁴, the concept Net Zero Energy Cluster (NetZEC)⁷⁵ [339] is introduced to describe the group of 18 solar houses. The 18 solar houses are actually a cluster of prosumers with integrated PV, while the public service buildings are a group of consumers. In order to enable a systematic comparison study, three scenarios which aims to improve energy balance at different levels are defined. These three scenarios are, respectively,

- Scenario 1: energy balance at the district level, including both the NetZEC (solar houses) and the other building consumers (public service buildings).
- Scenario 2: energy balance at the NetZEC level, which considers only the various NetZEBs (solar houses).
- Scenario 3: energy balance at the NetZEB level, which only considers a single NetZEB (solar house).

Within each of the scenarios, different decisions for energy performance improvement may be made using the different methodologies. Therefore, sub-scenarios are defined according to the two methodologies in order to enable comparison analysis (Figure 60).

The sub-scenario C1 aims to improve energy balance at the district level using the current methodology, which has no stakeholders' interaction and information exchange across the district and building levels; while, the sub-scenario K1 improves the district energy balance using the KPI-based linked data methodology. Similarly, the sub-scenario C2 aims to improve energy balance of the NetZEC using the current methodology; while sub-scenario K2 studies the energy balance of the NetZEC using the proposed methodology with stakeholder interaction among different buildings. Finally, the sub-scenario C3 uses the current methodology to improve energy balance of a NetZEB; and the sub-scenario K3 improves the building energy balance using the proposed

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⁷⁴ A NetZEB is a building that reduces its energy needs thanks to high energy efficient measures and use of renewable energy resources, in order to get a zero-energy balance between energy consumption and generation. The term "Net" means the connection with the electricity grid.

⁷⁵ Within a certain boundary domain, buildings that are not NetZEBs as singles can perform to reach the zero-energy balance as a whole, thanks to buildings with a positive energy balance which can compensate such ones with negative balances. This lead to the concept of Net Zero Energy Clusters (NetZECs).

methodology with performance comparison among different buildings. The comparison of the sub-scenarios will be elaborated in the following sections.

	Current Methodology	KPI-based linked data methodology
Scenario 1 Energy balance at the district level (a NetZEC and other building consumers)	Sub-scenario C1 no stakeholders' interaction between district and buildings	Sub-scenario K1 stakeholders' interaction between district and buildings
Scenario 2 Energy balance at a NetZEC level	Sub-scenario C2 no stakeholders' interaction among different buildings	Sub-scenario K2 stakeholders' interaction among different buildings
Scenario 3 Energy balance at a NetZEB level	Sub-scenario C3 no performance comparison among different buildings	Sub-scenario K3 performance comparison among different buildings

Figure 60: Scenario definition for comparison using the current and KPI-based linked data methodology.

8.4.2.1 Scenario 1: Energy balance at the district level

As the previous multi-level energy performance analysis conducted in Section 8.3.6, the district energy balance (I03) has not been achieved during the monitored days. One of the main reasons is the high energy demand of public service buildings, which is unable to be covered by the surplus energy generated by the 18 solar houses. This analysis takes the one day as evaluation time step. However, this section aims to improve the district energy balance in the real-time for curtailing the peak and filling the trough.

The data of the external energy supply at the district level is extracted, which is shown in Figure 61. The external energy supply represents the consumed power minus the generated power, which can be presented as $(P_{District\ consumption} - P_{District\ generation})$. These values represent the status of district energy balance in real-time. When the value is positive, external power is supplied to the district; when the value is negative, surplus energy is exported to the external grid.

Figure 61: External energy supply (real-time energy balance) of the district.

As can be seen in Figure 61, during the monitored days, the external energy supply is positive in most of the time, which means that the real-time energy balance has not been achieved. The peak for the energy supply reaches to the highest value of 80 kW during the night, and the trough that exports energy to the external grid reached to -40 kW. The difference between the peak and the trough is approximately 120 kW. This sharp fluctuation of energy demand is considered unfavourable to the stability of grid. To improve this, it is possible to take measures to make full use of the surplus energy for reducing the peak demand and filling the trough at the district level, so as to achieve better energy balance performance.

The solar houses and the public service buildings are two types of buildings. They have different energy use features. For example, residential buildings have a peak of energy demand during the night, while the public service buildings are mainly used during the day. In order to find out the contribution of each building type to the high fluctuation of district energy supply, the observation data of energy supply in both the public service buildings and the 18 solar houses are extracted, as visualized in Figure 62.

It can be seen that the energy supply of the public service buildings is smoother than that of the solar houses. During the night, the energy supply is between 10 – 20 kW, and during the day, it is between 30 – 50 kW. The value is stable in the monitored days. However, the energy supply of the solar houses is quite different during the day and the night. There is surplus energy exported to the external grid during the day, which sometimes reaches to approximately -70 kW. However, during the night, there is a peak of energy demand, especially on September 17th to September 20th, which reaches to more than 40 kW. The fluctuation of the energy supply of solar houses varies from -70 kW to 40 kW, a difference of 110 kW.

Figure 62: External energy supply (real-time energy balance) of the public service buildings and the solar houses.

The surplus energy generated by the solar houses can compensate a part of energy demand of the public service buildings during the day. Hence, it results to a curve of district energy supply as shown in Figure 61. In order to see clearly the synergy effect of solar houses and public services buildings, taking the day September 17th as an example, the energy supplies of the district, the public service buildings and the solar houses are illustrated together in Figure 63. It implies that the fluctuation of the district energy supply is mainly due to the solar houses, because the district curve follows the similar trend as the curve of the solar houses. In order to achieve a better district energy balance, the related measures could be taken in the solar houses to adjust their energy use.

Figure 63: External energy supply (real-time energy balance) of the whole district, the public service buildings and the solar houses on September 17th.

8.4.2.1.1 Sub-scenario C1

Since the current used methodology has no engagement mechanism among district and building stakeholders, performance information and data across different levels cannot be exchanged. Therefore, the district energy managers are unable to change the energy use of the solar houses, since they are dependent on the building stakeholders. District stakeholders could only take energy storage measures for utilizing the surplus energy at the district level in order to improve the energy balance. An achievable result is shown in Figure 64. The stored surplus energy can help to cut a part of peak demand during the night.

Figure 64: External energy supply (real-time energy balance) of the whole district in sub-scenario T1.

8.4.2.1.2 Sub-scenario K1

Using the proposed methodology with stakeholders' interaction and information exchange across the district and building levels, the district energy managers can interact with the building energy managers or occupants/consumers, taking measures for the peak demand shift or using energy storage in the associated solar houses to adjust their energy use.

Two solutions for the improvement are possible, which are as follows:

Solution 1. adjust occupants/consumers' behaviour in the solar houses by changing their time of energy use. The advantage of this solution is that there is no need for additional investment. However, the disadvantage is that the energy consumers are needed to change their energy use habits, which may be not preferable for several building consumers.

Solution 2. use energy storage as a demand side measure for the solar houses to reduce peak demand and adjust real-time energy balance. The main advantage of this solution is that it has no need to change occupants' energy use behaviours. The energy storage can

complement photovoltaic panels in promoting the self-consumption, helping the solar houses take advantage of self-produced energy when they need it, not just when the sun generates it. However, the disadvantage is that additional investment is needed for energy batteries.

In order to understand well the energy generation and consumption pattern in the solar houses, the observation data of their power generation and consumption are retrieved. Figure 65 visualizes the observation data. It can be seen that there are two peaks of energy consumption in the 18 solar houses during the day. The first peak is in the day; while, the second peak occurs in the evening when there is no energy generation. It is the second peak that results in the high energy supply of the solar houses and the district during the night. Therefore, measures should be taken to shift the second peak of power consumption.

Figure 65: Power consumed and generated by the 18 solar houses.

Taking the day September 17th for detailed analysis, the monitored data of power consumed and generated by the solar houses, as well as their resulted energy supply, are extracted and visualized together in Figure 66. It can be seen that the surplus energy could totally cover the energy consumption. The external energy supply is due to the time uncorrelation between energy generation and use in the solar houses.

Figure 66: Power consumed and generated by the solar houses and external power supply to solar houses in September 17th.

During the second peak of energy consumption, the main energy uses in the solar houses may include lighting, cooking, laundry, domestic hot water, air conditioning among others. By using the solution to adjust occupants' behaviour, some of the energy uses could be shifted. However, it is hard to estimate the possible effect of peak demand reduction by using such solution. Therefore, the analysis will be focused on the improvement of energy balance using energy storage measures.

In order to decide the capacity of energy batteries for the solar houses, the daily external energy supply (total energy imported from external grid during the day) and the daily energy gain (total energy exported to external grid during the day) of each solar house are retrieved, which are respectively calculated by $(\int_0^{TS} P_{imported\ from\ external\ grid} dt)$ and $(\int_0^{TS} P_{exported\ to\ external\ grid} dt)$, where TS is the time step of one day. Table 31 lists the results of the total energy supply and energy gain of each solar house in the studied day.

As can be seen in Table 31, the daily energy supply of the single solar house varies from 4 – 15 kWh. The amount of energy gain of each solar house is also quite different. Solar House 2 and Solar House 14 has no energy gain, which means no energy has been exported to grid. In addition, some solar houses have energy gain more than external energy supply, which means that if the generated energy is fully self-consumed, there is no need to use external energy. Reversely, there are also some other solar houses have energy gain less than external energy supply, which means that although the generated energy is fully self-consumed, there is still a need to import energy from the external grid. Considering together the amount of external energy supply and energy gain, a set of 13 batteries is chosen to provide energy storage for the 13 solar houses with desirable daily energy gain. The capacity of each battery is 14 kW. Therefore, the total capacity of the

set of batteries is 182 kWh, which is able to cover the daily external energy supply of the solar houses.

Table 31: External energy supply and energy gain of each solar house monitored by microgrid management system on September 17th.

	Daily external energy supply (kWh)	Daily energy gain (kWh)
Solar House 1	13	10
Solar House 2	5	0
Solar House 3	14	21
Solar House 4	10	25
Solar House 5	11	6
Solar House 6	10	15
Solar House 7	11	29
Solar House 8	4	17
Solar House 9	8	25
Solar House 10	15	3
Solar House 11	10	23
Solar House 12	4	6
Solar House 13	15	16
Solar House 14	0	0
Solar House 15	13	19
Solar House 16	14	18
Solar House 17	9	19
Solar House 18	14	24
Total	180	276

Using the energy storage, most of the solar houses can achieve energy self-consumption, which has no need to import energy from the external grid. In addition, the part of surplus energy that is not stored will be exported to the grid as usual. As an example, Figure 67 and Figure 68, respectively, show the external energy supply of Solar House 1 and Solar House 3 when using energy storage. It can be seen that if the energy storage is used in the associated solar houses, the performance of energy balance in such houses will be improved greatly.

Figure 67: External energy supply (real-time energy balance) of Solar House 1 in sub-scenario K1 on September 17th.

Figure 68: External energy supply (real-time energy balance) of Solar House 3 in sub-scenario K1 on September 17th.

The potential external energy supply at the whole district level is shown in Figure 69. It implies that the sub-scenario K1 with stakeholder interaction and information exchange from district to building level can achieve much better performance in energy balance than that of sub-scenario C1. The curve of the district energy supply is much smoother in sub-scenario K1. Therefore, the proposed methodology help achieve better energy balance performance.

Figure 69: External energy supply (real-time energy balance) of the district in sub-scenario K1 on September 17th.

8.4.2.2 Scenario 2: Energy balance at a NetZEC level

In this scenario, the interaction of stakeholders and information exchange among different building prosumers is considered, in order to improve the energy balance at the NetZEC level.

The calculation of I05 (single building energy balance) in Section 8.3.6 shows that not all of solar houses have achieved individual building energy balance during the monitored days. In some solar houses, the total energy generation is not able to cover the total energy consumption.

Taking September 17th as example, the result of single building energy balance (I05) is illustrated in Figure 70, which is calculated by $(\int_0^{TS} P_{Building\ generation} dt - \int_0^{TS} P_{Building\ consumption} dt)$, taking the calculated time step (TS) as one day. It can be seen that Solar House 1, 2, 5, 10, 12 and 14 have not achieved energy balance on September 17th, while the other solar houses have surplus energy varying from 1.9 to 19 kWh.

In order to improve energy balance of the NetZEC, sub-scenarios C2 and sub-scenario K2 are analysed as following.

Figure 70: Single building energy balance (I05) of different solar houses in September 17th.

8.4.2.2.1 Sub-scenario C2

Using the current used methodology, there is no stakeholders' interaction and information exchange among different buildings. The solar houses cannot benefit the surplus energy from another house. They can only resolve the energy balance problem at the scale of their own buildings. The possible solutions include:

- 1) Increasing the amount of energy generation, which can be done by enlarging the capacity of energy generation system, or improving the generation efficiency if there are some efficiency problems of the energy generation system due to various factors, such as the dust coverage on the surface of PV panels and the high temperature for PV cells.
- 2) Reducing the energy consumption, which can be done by conserving the energy use or improving the energy efficiency of the building and its energy consumption systems if there exist some energy performance problems.

However, the measures to enlarge the capacity of energy generation system may unnecessarily increase the investment; and the conservation of energy use at the expense of occupants' life quality is usually not preferred. Furthermore, the energy efficiency problems of the generation systems, buildings and energy consumption systems can be found out more easily if different buildings can exchange their performance information and compare it. This will be analysed in Scenario 3.

The solar houses which implement the energy storage measures in each of their buildings could lead to a total external energy supply (real-time energy balance) of the 18 solar houses as shown in Figure 71.

Figure 71: External energy supply (real-time energy balance) of the 18 solar houses in sub-scenario K1 in September 17th.

8.4.2.2.2 Sub-scenario K2

With the interaction of stakeholders from different buildings and their information exchange, the solar houses that have not achieved the energy balance can take advantage of the surplus energy of the other houses. For example, Solar House 1 and Solar House 2 can make use of the surplus energy of Solar House 4, and Solar House 5 and Solar House 10 can benefit the surplus energy of Solar House 7.

The information sharing facilitates the energy sharing among different solar houses, which help address the energy balance problem of Solar House 1, 2, 5, 10, 12 and 14. Therefore, the final external energy supply of the solar houses is shown in Figure 72. It implies that energy balance has been totally achieved through the use of energy batteries and, furthermore, the solar houses can export 93.77 kWh surplus energy to the external grid. The interaction among the building stakeholders minimizes the fluctuation of the external energy supply of the NetZEC, therefore improving the energy balance and energy self-consumption of the solar houses.

Figure 72: External energy supply (real-time energy balance) of the 18 solar houses under sub-scenario K2 on September 17th.

8.4.2.3 Scenario 3: Energy balance at a NetZEB level

As mentioned in Scenario 2, Solar House 1, 2, 5, 10, 12, 14 have not achieved their energy balance; and the energy balance of the NetZEC is realized through sharing the surplus energy among the solar houses. However, the building stakeholders are also desired to achieve energy balance in their own buildings in order to attain NetZEBs. In this scenario, the reason behind the energy imbalance of these solar houses will be analysed using the two different methodologies, in order to compare their practicality for improving single building energy balance.

8.4.2.3.1 Sub-scenario C3

In sub-scenario C3, since the performance information between different solar houses are not shared, building stakeholders can only take advantage of the collected data of their own buildings and analyse it in order to find the problem.

Taking Solar House 1 as an example, the value of 105 (single building energy balance) in September 17th is -3.7 kWh. To ascertain the reason behind it, the power generation and consumption data of this solar house is retrieved, which is visualized in Figure 73. It can be seen that the highest power generated is approximately 4 kW. A calculation shows that the total energy generation during the day is 22.72 kWh and the total energy consumption is 26.41 kWh. However, it is a common value for a single-family detached house. The installed capacity of the PV system is 9.2 kW. However, it is still not enough to infer whether the PV system has generation efficiency problem or not, since the energy generation depends on many other factors, such as the weather condition.

Figure 73: Power generated and consumed by Solar House 1 on September 17th.

8.4.2.3.2 Sub-scenario K3

With information sharing and performance comparison between different solar houses, the analysis will be much easier and intuitive. The building stakeholders can get access to the performance information of the other similar buildings and compare it. In order to infer whether the PV system in Solar House 1 has efficiency problem, the energy generation and the installed capacity of the PV system in each solar house are requested, respectively as shown in Figure 74 and Figure 75.

Figure 74: Total energy generation of each solar house in September 17th.

Figure 75: Installed power of the PV system in each solar house.

It can be seen that Solar House 1 has 22.7 kWh energy generation, the installed power of the PV system is 9.2 kW, which are both intermediate values among all of the solar houses. The comparison of the generation efficiency can be conducted from two aspects:

- 1) Considering the solar houses that have similar installed power of PV system with Solar House 1, the amount of energy generation is compared. As can be seen in Figure 74, Solar House 9 and Solar House 16 have almost the same installed power of PV system as Solar House 1, respectively, 9.24 kW and 9.3 kW. However, the comparison of their energy generation can be found that both Solar House 9 and Solar House 16 have considerable amount of energy generation more than that of Solar House 1, approximately 10 kWh and 7 kWh.
- 2) Considering the solar houses that have the similar amount of energy generation with that of Solar House 1, the installed power of PV system is compared. As can be seen in Figure 75, Solar House 6 has 24.7 kWh energy generation during the day, which is close to the energy generation of Solar House 1, however, its installed capacity is 6.75 kW, which is much lower than Solar House 1.

Therefore, it can be inferred that the PV system of Solar House 1 has a relatively low generation efficiency. With the comparison of the different solar houses, we can also find easily the reason of energy imbalance of the other solar houses. It can be seen apparently that Solar House 2 and Solar House 14 have failures in PV systems during the day, Solar House 10 has relatively low generation efficiency. However, the energy imbalance in Solar House 12 is due to the low installed capacity of PV system.

In addition to the performance comparison of different solar houses in a specific day, the comparison can be also carried out across different days. The following Figure 76 and

Figure 77, respectively, show the energy generation and energy consumption of each solar house from September 17th to September 28th. It can be seen clearly which solar house or which day has more energy generation or consumption. For example, Solar House 2 has least energy generation; Solar House 14 has few energy generation on September 17th and 18th, but began to have more generation in some other days. While, on September 27th and 28th, the generation of all of the solar houses is low due to the outdoor weather condition. Regarding the energy consumption, it can be seen that on September 22nd and 23rd, the solar houses have less consumption.

Figure 76: Energy generation of each solar house from September 17th to 28th.

Figure 77: Energy consumption of each solar house from September 17th to 28th.

The sharing of performance information among different buildings can help stakeholders understand better their concerned energy performance through the comparison with other buildings and facilitate the identification of performance problems.

8.4.2.4 Cost benefit analysis

In this section, an analysis of the cost benefit using the KPI-based linked data methodology is carried out. The analysis considers comprehensively the energy cost saving and the additional cost using the proposed methodology, thus calculating the final economic benefits. Figure 78 illustrates the equation for the calculation of final cost reduction.

Figure 78: Calculation of the economic benefit using the linked data methodology.

8.4.2.4.1 Energy cost saving

The energy cost saving considers the reduction of energy purchase, the gain from energy sale and the investment of the improvement measures, as shown in Figure 79.

Figure 79: Calculation of the energy cost saving using the linked data methodology.

To calculate the energy cost saving, firstly it is essential to know the external energy supply and the energy gain of the solar houses and the public services buildings. The external energy supply is the energy purchased from the external grid and the energy gain is the energy fed into the external grid. They are calculated and listed in Table 32. It can be seen that the solar houses have 4205 kWh energy gain during the monitored days, while the public services buildings only have external energy supply.

Table 32: Original external energy supply and energy gain of the buildings

	External energy supply (kWh)	Energy gain (kWh)
Solar houses	1645	4205
Public service buildings	7271	0

To calculate the energy cost, the related energy tariff for energy supply and energy gain should be known. Table 33 lists the used electricity tariff and feed-in tariff, considering

the location of the case. The feed-in tariff for energy gain is not available, since the Spanish government has suspended it in early 2012 based on the preamble of RDL 1/2012, which means that building owners cannot gain money from sending the renewable electricity to the external grid.

Table 33: Energy prices according to the used local energy tariffs

Electricity price for energy supply (€/kWh)	Feed-in electricity price (€/kWh)
0.227	0

Using the proposed methodology, the stakeholders of the solar houses and the public services buildings can exchange their energy information and interact with each other. The associated measures can be taken in order to benefit the surplus energy. The solar houses sell their energy gain to the public service buildings by half price of the external energy supply, therefore they can have some income from the energy gain, meanwhile the public service buildings can save their energy cost. If the solar houses only share their energy during the time of energy generation without energy storage measures, there are 3254 kWh energy gain from the solar houses exported to the public service buildings, and the other 951 kWh electricity was fed into external grid. The energy purchase and energy gain of the buildings are as listed in Table 34.

Table 34: Energy purchase and energy gain of the buildings using the proposed methodology

	Energy supply (kWh)		Energy gain (kWh)	
	External energy purchase	Internal energy purchase	Feed-in energy	Internal energy sale
Solar houses	1645	0	951	3254
Public service buildings	4017	3254	0	0

Furthermore, when the energy storage measures are used, the solar houses have no need to purchase energy; and the remaining surplus energy can be sold to the public service buildings at any time as opposed to only at the time of energy generation. Therefore, the energy purchase and energy gain of the buildings are shown in Table 35. However, in this case, investment is needed for energy batteries. The price of a home battery with capacity of 14 kW is 6300 € according to the manufacture Telsa. The total cost of the set of 13 home batteries is 83480 € including the installation and technical support fee. Since the calculation of the energy cost only considers the monitored days from September 17th to September 28th, the amortized cost of the home batteries during the monitored days is estimated by multiplying the daily average cost with 12 days. Considering the batteries have a life time of 15 years, the daily average cost is 15.5 €/day. Therefore, the cost for the 12 days is 186 €.

Table 35: Energy purchase and energy gain of the buildings using the proposed methodology and energy storage measures.

	Energy supply (kWh)		Energy gain (kWh)	
	External energy purchase	Internal energy purchase	Feed-in energy	Internal energy sale
Solar houses	0	0	0	2560
Public service buildings	4711	2560	0	0

As a result, the final energy cost in each case is calculated and listed Table 36.

Table 36: Energy cost for solar houses and public services buildings using fixed energy price.

	Original cost (€)	Energy cost 1 (€)	Energy cost 2 (€)
Solar houses	373.4	4.1	-104.6
Public service buildings	1650.5	1281.2	1360.0
Total	2023.9	1285.3	1255.4

Note: energy cost 1 is in the case of using the internal energy purchase and sale through stakeholders' interaction; energy cost 2 is in the case of using the internal energy purchase and sale combined with the energy storage measures.

In order to compare the energy cost when time of use (TOU) energy price is used, a further energy cost calculation using the hourly energy price is also conducted. Figure 80 shows the energy price. The lowest hourly energy price is in the early morning, the value is 0.106 €/kWh. While, the highest energy price is during the night, particularly from 20:00 to 22:00. The highest value is 0.276 €/kWh. The price already contains the tax and any other fees.

Using the hourly energy price, it is essential to know the hourly energy consumption during the day. Figure 81 shows the hourly energy consumption of the solar houses and the public service buildings during the monitored days. When the value is negative, it means that surplus energy is generated.

Figure 80: Hourly energy price compared to the fixed energy price in Spain⁷⁶.

Figure 81: Hourly energy consumption during the monitored days.

The calculation results of the final energy cost using the hourly energy price is listed in Table 37. The hourly energy price is applicable to external energy supply, while the internal purchase and sale of the surplus energy is still 0.1135 €/kWh, which is close to the valley price. It can be seen that the energy cost using hourly energy price is less than those of the fixed energy price, especially when the stakeholders' interaction and energy storage measures are used together. Because when only the internal energy purchase and sale among stakeholders are applied, the solar houses and public services buildings are limited to benefit the surplus energy only at the time of energy generation. However, the

⁷⁶ The electricity prices in this figure contains VAT / IGIC and tax on electricity and hydrocarbons. The data of the original electricity prices during the day is extracted from <http://www.tarifadeluz.com/>, based on September 17th, 2017. The final electricity prices including the other fees are calculated according to https://www.iberdrola.es/02sica/gc/prod/es_ES/comunes/docs/Destino_factura_caste.pdf. It is estimated that the energy supply cost accounts for 50% of the final price, the taxes, surcharges and other concepts also for 50%.

combined use of energy storage measures can store the surplus energy and use it during the night when there is the peak price. Therefore, more energy cost can be saved.

Table 37: Energy cost for solar houses and public services buildings using hourly energy price.

	Original cost (€)	Energy cost 1 (€)	Energy cost 2 (€)
Solar houses	316.7	-52.6	-104.6
Public service buildings	1403.6	1142.4	1026.7
total	1720.3	1089.8	922.1

Note: energy cost 1 is in the case of using the internal energy purchase and sale through stakeholders' interaction; energy cost 2 is in the case of using the internal energy purchase and sale combined with the energy storage measures.

Furthermore, in order to know the influence of feed-in tariff to the energy cost, another two analyses use the feed-in tariff together with the fixed energy price and hourly energy price. Since the feed-in tariff is not implemented currently in Spain. The related regulation in Germany is used as a reference. The feed-in tariff for specific building-mounted PV systems (e.g., roofs, facades, noise barriers, other building) is decided by 8.91 – 12.70 €ct per kWh minus 0.4 €ct per kWh⁷⁷; and it has no difference between the peak and valley. Therefore, in this case the feed-in tariff is taken as 0.1 €/kWh. The calculation result of the energy cost using the feed-in tariff and fixed energy price is shown in Table 38. Meanwhile, the result of the energy cost using the feed-in tariff and hourly energy price is listed in Table 39. It can infer that the energy storage measures are not economically efficient when the feed-in tariff is implemented, since it has more energy cost than the case of only using energy sharing during the time of generation.

Table 38: Energy cost for solar houses and public services buildings using fixed energy price and feed-in tariff (0.1 €/kWh).

	Original cost (€)	Energy cost 1 (€)	Energy cost 2 (€)
Solar houses	-47.1	-511.5	-104.6
Public service buildings	1650.5	1281.2	1360.0
total	1603.4	769.7	1255.4

Note: energy cost 1 is in the case of using the internal energy purchase and sale through stakeholders' interaction; energy cost 2 is in the case of using the internal energy purchase and sale combined with the energy storage measures.

⁷⁷ Data source: <http://www.res-legal.eu/search-by-country/germany/single/s/res-e/t/promotion/aid/feed-in-tariff-eeg-feed-in-tariff/lastp/135/>.

Table 39: Energy cost for solar houses and public services buildings using hourly energy price and feed-in tariff (0.1 €/kWh)

	Original cost (€)	Energy cost 1 (€)	Energy cost 2 (€)
Solar houses	-103.8	-568.2	-104.6
Public service buildings	1403.6	1142.4	1026.7
total	1299.8	574.2	922.1

Note: energy cost 1 is in the case of using the internal energy purchase and sale through stakeholders' interaction; energy cost 2 is in the case of using the internal energy purchase and sale combined with the energy storage measures.

8.4.2.4.2 Additional cost of the linked data methodology

To use the linked data methodology, additional cost for linked data tools or knowledge support may be needed. Figure 82 shows the calculation of the additional cost for the linked data methodology.

Figure 82: Calculation of the additional cost of the KPI-based linked data methodology.

Since many tools for generating and using linked data are free and open-source, the cost for linked data tools could be minimal. The current tools used for linked data generation include Protégé for ontology development, OpenRefine for RDF data transformation and RDF4J for triple storage and querying, which are all free. Furthermore, taking into account the life cycle of linked data in a project, the potential linked data tools may include those for RDF data extraction, storage/querying, authoring/creation, enrichment, interlinking, fusing and maintenance. As an example, a list of tools which supports the life cycle of linked data is shown in Table 40. The majority of the tools are free and open source. Only the tools PoolParty for authoring and exploration, Sig.ma EE for search and exploration and Virtuoso for storage and querying need to be charged. However, there are other alternatives free of charge. Therefore, no cost for linked data tools is considered in this case.

Table 40: Supported stages and cost of the tools for the whole life cycle of linked data [340]

Tool for linked data	Supported stages	Cost
Apache Stanbol ⁷⁸	Extraction	Free, open source
CubeViz ⁷⁹	Visualization	Free, open source
DBpedia Spotlight ⁸⁰	Extraction	Free, open source
D2RQ ⁸¹	Extraction	Free, open source
DL-Learner ⁸²	Schema Enrichment	Free, open source
OntoWiki ⁸³	Authoring, exploration	Free, open source
ORE ⁸⁴	Repair, enrichment	Free, open source
PoolParty ⁸⁵	Authoring, exploration	Charge
SemMap ⁸⁶	Browsing, exploration	Free
Sig.ma EE ⁸⁷	Search, exploration	Charge
Sieve ⁸⁸	Quality, repair	Free, open source
SILK ⁸⁹	Interlinking	Free, open source
LIMES ⁹⁰	Interlinking	Free, open source
Virtuoso ⁹¹	Storage/Querying	Charge
Valiant ⁹²	Extraction	Free, open source

Another important cost for implementing the linked data for energy management is the technical and knowledge support. Considering that the support may only be needed at the initial stage for staff training in the first year, a total cost of 25000 € is estimated to suffice this demand, based on the local income level. Therefore, the daily cost of the linked data methodology is 4.63 €/day during the lifetime of 15 years; and the total cost for the 12 days is 55.6 €.

⁷⁸ Apache Stanbol: <https://stanbol.apache.org/index.html>

⁷⁹ CubeViz <http://cubeviz.aksw.org/>

⁸⁰ DBpedia Spotlight <https://github.com/dbpedia-spotlight/>

⁸¹ D2RQ <http://d2rq.org/>

⁸² DL-Learner <http://dl-learner.org/>

⁸³ OntoWiki <http://ontowiki.net/>

⁸⁴ ORE <http://aksw.org/Projects/ORE.html>

⁸⁵ PoolParty <https://www.poolparty.biz/>

⁸⁶ SemMap <http://semmap.aksw.org/odp/v1/>

⁸⁷ Sig.ma <https://sig.ma/>

⁸⁸ Sieve <http://sieve.wbsg.de/>

⁸⁹ Silk <http://silkframework.org/>

⁹⁰ LIMES <http://aksw.org/Projects/LIMES.html>

⁹¹ Virtuoso <https://virtuoso.openlinksw.com/>

⁹² Valiant <https://github.com/bertvannuffelen/valiant>

Considering together the energy cost and the cost of linked data methodology, the final cost of the solar houses and the public service buildings can be calculated, as listed in Table 41.

Table 41: Final cost using different tariffs

	Original cost (€)	Final cost 1 (€)	Final cost 2 (€)
1) Fixed energy price, no feed-in tariff			
Solar houses	373.4	31.9	-76.8
Public service buildings	1650.5	1309.0	1387.8
total	2023.9	1340.9	1311.0
2) Hourly energy price, no feed-in tariff			
Solar houses	316.7	-24.8	-76.8
Public service buildings	1403.6	1170.2	1054.5
total	1720.3	1145.4	977.7
3) Fixed energy price, feed-in tariff (0.1 €/kWh)			
Solar houses	-47.1	-483.7	-76.8
Public service buildings	1650.5	1309.0	1387.8
total	1603.4	825.3	1311.0
4) Hourly energy price, feed-in tariff (0.1 €/kWh)			
Solar houses	-103.8	-540.4	-76.8
Public service buildings	1403.6	1170.2	1054.5
total	1299.8	629.8	977.7

The cost reduction is calculated by the following equation:

$$\text{Equation 9: Cost reduction} = \frac{\text{Original cost} - \text{Final cost}}{\text{Original cost}} \%$$

When fixed energy price and no feed-in tariff is applied, the result of the cost reduction using the proposed methodology is as shown in Table 42. It can be seen that both the solar houses and the public service buildings have considerable cost reduction using the proposed methodology. When taking the energy storage measures, the cost reduction in the solar houses is especially evident. Although the reduction for the public service buildings is less, since the solar houses have taken full advantage of their surplus energy and have supplied less to the public service buildings, the total cost reduction is still more than the case when no energy storage measures are taken.

Table 42: Cost reduction based on fixed energy price and no feed-in tariff.

	Cost reduction 1 (%)	Cost reduction 2 (%)
Solar houses	91.46%	120.56%
Public service buildings	20.69%	15.92%
Total	33.75%	35.23%

Note: cost reduction 1 is in the case of using the internal energy purchase and sale; cost reduction 2 is in the case of using the internal energy purchase and sale and the energy storage measures.

When hourly energy price and no feed-in tariff is applied, the cost reduction of the proposed methodology is shown in Table 43. It can be seen that the cost reduction in this case is more than that of fixed energy price for both the solar houses and the public service buildings when the energy storage measures are implemented. However, when the energy storage measures are not taken, the cost reduction of public service buildings is lower than that of fixed energy price. This is because the public service buildings have a considerable amount of energy consumption during the time of high energy price. However, the internal energy supply at the time of energy generation mainly occurred when the energy price is low. Therefore, the cost reduction is relatively lower than that of the fixed price. However, when the energy storage measures are used, the solar houses can store their surplus energy during the time of low energy price. The stored energy then can be discharged for the energy use of the solar houses during the night and for the energy supply to the public service buildings when the external energy price is high. Therefore, both the solar houses and the public service buildings can save more energy cost through consuming less high-price peak power.

Table 43: Cost reduction based on hourly energy price and no feed-in tariff.

	Cost reduction 1 (%)	Cost reduction 2 (%)
Solar houses	107.83%	124.24%
Public service buildings	16.62%	24.87%
Total	33.42%	43.16%

Note: cost reduction 1 is in the case of using the internal energy purchase and sale; cost reduction 2 is in the case of using the internal energy purchase and sale and the energy storage measures.

Furthermore, when the feed-in tariff is implemented, the cost reduction using the proposed methodology based on the fixed energy price and the hourly energy price is, respectively, presented in Table 44 and Table 45. It can be seen that the cost reduction when only implementing the internal energy purchase and sale is higher than those when no feed-in tariff is used. The total reduction for fixed energy price and hourly energy price are, respectively, 48.53% and 51.54%. The main reason is due the solar houses can not only benefit from the internal sale of surplus energy but also the external feed-in tariff. When the public service buildings need energy input, the solar houses can sell the surplus energy to them with a better price; and when the public service buildings do not need

energy input, the solar houses can sell the surplus energy to the external grid with the feed-in tariff. However, in this case, the energy storage measures are not an optimal solution in terms of economic benefit, due to the additional investment of the batteries. However, still 18.24% and 24.78% cost reduction can be obtained using, respectively, fixed energy price and hourly energy price, compared to the original cost without using the proposed methodology for information exchange and stakeholder interaction.

Table 44: Cost reduction of the KPI-based linked data methodology based on fixed energy price and feed-in tariff (0.1 €/kWh).

	Cost reduction 1 (%)	Cost reduction 2 (%)
Solar houses	-927.32%	-63.02%
Public service buildings	20.69%	15.92%
Total	48.53%	18.24%

Note: cost reduction 1 is in the case of using the internal energy purchase and sale; cost reduction 2 is in the case of using the internal energy purchase and sale and the energy storage measures.

Table 45: Cost reduction of the KPI-based linked data methodology based on hourly energy price and feed-in tariff (0.1 €/kWh).

	Cost reduction 1 (%)	Cost reduction 2 (%)
Solar houses	-420.76%	26.03%
Public service buildings	16.62%	24.87%
Total	51.54%	24.78%

Note: cost reduction 1 is in the case of using the internal energy purchase and sale; cost reduction 2 is in the case of using the internal energy purchase and sale and the energy storage measures.

Figure 83: Total cost reduction for the solar houses and the public service buildings considering different energy tariffs.

The total cost reduction for the solar houses and the public service buildings considering different tariffs is shown in Figure 83. Through the comparison of the results, it can be inferred that the linked data methodology for information exchange and stakeholder interaction can achieve a considerable energy cost saving, especially when hourly energy price is implemented. The combined use of hourly energy price and energy storage measures will bring big potential for energy cost saving when there is no feed-in tariff available. However, when feed-in tariff is implemented, a better choice that bring more economical benefit is to only use energy sharing at the time of energy generation.

8.5 SUMMARY

In this chapter, a case study was conducted to demonstrate the feasibility and benefits of the proposed KPI-based linked data methodology. The demonstration was performed in a small district called Villa Solar.

Firstly, the identification of the stakeholders using the three-task method is demonstrated. With the method, 5 main intervention points and 7 sub-intervention points for energy performance are used, in addition to 12 groups of stakeholders, among which 6 groups of key stakeholders, are identified. The use of intervention points facilitates the identification of stakeholders; and the calculation of stakeholder prioritization index (SPI) provides a quantitative way for their prioritization analysis.

Subsequently, the pre-list of PIs is proposed and the bi-index method is demonstrated for the selection of KPIs. The stakeholders participate in the selection of KPIs. They vote on energy PIs. Considering both the values of stakeholder vote index (SVI), obtained via stakeholders' votes, and the previously defined SPI, obtained using stakeholder prioritization analyses, the final comprehensive index (CI) for weighting the indicators is calculated. In total, a hierarchy of 35 PIs are defined, among which 23 indicators are selected as KPIs, including 4 strategic, 12 tactical and 7 operational ones. The selected KPIs not only support stakeholders' performance goals, but also balance their benefits.

Afterwards, the master data related to the selected KPIs were identified; the existing data sources were collected and the further data capture were determined. The main collected master data sources include energy production, supply, use, weather, building static information, indoor comfort, occupant, etc. An example linked dataset is generated by mapping KPIs and master data sources to the developed EM-KPI ontology, which demonstrates the feasibility of the ontology for exchanging key performance information and master data.

Taking the energy balance indicators (I03, I05 and I07) as example, their calculation and multi-level energy performance analysis are conducted using the generated linked data. The results reveal that the performance goal of I03 (district energy balance) was not

achieved, while most solar houses achieved their individual building energy balance (I05). Although I05 (individual building energy balance) had a desirable level of performance, the solar houses had an unsatisfactory value in relation to I07 (time correlation between generation and consumption). The results of these KPIs prove their multi-level relationship and the benefits of linked data in finding performance problems and helping improvement analysis.

Finally, the energy and cost benefits of the KPI-based linked data methodology is validated through its comparison with the current used methodology in the case. The proposed methodology facilitates the decision-making for improving multi-level energy performance through stakeholder interaction and information exchange. The analyses of three defined scenarios demonstrates the benefits of the proposed methodology for achieving energy balance at both the district and building levels. Moreover, the cost analysis shows that using the proposed methodology, there is a potential to save at least 18.24% of the total energy cost.

9 CONCLUSIONS AND FUTURE WORK

This chapter presents the conclusion of this thesis. Firstly, the efforts made by the author to achieve the research objectives is discussed in Section 9.1. Afterwards, the main contribution of this thesis is concluded in Section 9.2. The future research lines in order to overcome the current limitations of the thesis is illustrated in Section 9.3. Lastly, the dissemination of the results emanated from the thesis is presented in Section 9.4.

9.1 CONCLUSIONS IN RELATION TO RESEARCH OBJECTIVES

9.1.1 Conclusions in relation to Main Objective

This thesis develops a systematic KPI-based linked data methodology, in order to address the current challenge to improve multi-level energy efficiency at both the building and district scales, as well as to resolve the open research problem in the lack of a structured approach to ensure data-driven performance analysis address stakeholders' goals.

Energy management that helps to improve energy efficiency on both the district and building scales is a multi-stakeholder, cross-domain issue. There are many potential stakeholders and a vast amount of information involved. Therefore, a systematic approach for determining the key stakeholders and extracting and exchanging the key information is developed in this thesis for multi-level energy performance improvement.

The proposed KPI-based linked data methodology provides a means by which to extract, exchange and exploit the key performance information and cross-domain master data that underpin stakeholders' performance goals. This helps enhance multi-level energy management and improve multi-level energy performance through stakeholders' engagement. The feasibility and the benefits of the proposed methodology has been validated through the case study.

Stakeholders' engagement is of the utmost importance for enhanced energy management at district and building levels, since the distributed energy and information sources usually belong to different actors. The identification of stakeholders and the determination of their prioritization contribute to devise an appropriate, effective engagement mechanism among stakeholders for optimal decision-making in terms of energy performance improvement. The prioritization of stakeholders identifies the key stakeholders who take precedence in decision-making, which further determines the KPIs that underpin the key performance goals. The priority order in decision-making can effectively manage and obtain a trade-off between the needs of various stakeholders. This helps to rank the tasks for energy performance improvement according to their significance to the stakeholders. To support multi-level performance information and

represent stakeholders' goals in a way that can be measured and tracked, multi-level KPIs are selected. The sharing of multi-level key performance information and its related master data between the identified stakeholders using the linked data can enable a more thorough performance analysis, help to identify more profound energy performance problems and make more rational decisions for the improvement. In a context which contains various building prosumers as the case study, the involvement of stakeholders and their exchange of key performance information further facilitate energy sharing between various buildings in order to benefit from available surplus energy. Both energy and cost benefits can be obtained through using the proposed methodology.

9.1.2 Conclusions in relation to Sub-objective 1

The importance of stakeholders' involvement for the successful implementation of an energy management plan is widely recognized. However, studies on stakeholder identification and analysis in energy management are very limited (Section 2.3.3).

As the complexity of energy operations at the district and building scales involves numerous actors, stakeholder analysis and engagement are crucially important to the multi-level energy management. Therefore, a structured three-task method to identify and prioritize stakeholders for energy management at the district and building levels is proposed in this thesis. This fulfils the Sub-objective 1, which aims to decide who are the stakeholders and, moreover, who are the key stakeholders taking precedence in decision making.

Compared to current practices, which usually identifies stakeholders arbitrarily and presents them in a simple list, the proposed three-task method provides an explicit, evidence-based means by which to analyse stakeholders in accordance with different intervention points and various life cycle stages. Furthermore, the proposed method illustrates identified stakeholders in a two-dimensional stakeholders' map. Analysis of stakeholders confirms that the use of intervention points facilitates identification of stakeholders' roles. Moreover, the definition of the SPI offers a quantitative means for stakeholder prioritization. The calculation of the SPI is based on the levels of stakeholders' importance in relation to different intervention points as determined through analysing the impact/interest matrix.

The identification of stakeholders helps find who have an impact on, and/or interest in, the energy management, as well as who are influenced by the effect of energy management. This will support to make improved decisions when there are some energy performance problems. Furthermore, the prioritization analysis ranks the importance of various stakeholders, which provides priority orders for implementing the measures to achieve the performance goals concerned by different stakeholders when making the decisions. The identification and analysis of stakeholders is the first step to develop an engagement mechanism for collaborative multi-level energy management.

9.1.3 Conclusions in relation to Sub-objective 2

The use of KPIs offers a means by which to represent a few critical pieces of actionable information and to measure the progress towards an organization's goals. However, due to the complexity of energy management at the district and building levels, numerous performance indicators can be identified. It is a challenge to select appropriate KPIs. A study of current practices of KPI identification and selection found that there is a lack of a quantitative and objective means by which to weight, select and validate the KPIs that underpin stakeholders' performance goals in energy management (Section 2.4.3). Assigning a weighting to each indicator considering stakeholders' involvement is essential when aiming to identify the KPIs that underpin overarching stakeholders' goals.

Therefore, a bi-index method is defined in order to provide a quantitative and more objective method to weight and select the KPIs in energy management. This method targets to identify the KPIs that underpin stakeholders' performance goals, thus helping the decision-making achieve such goals concerned by stakeholders. The PIs are identified by energy review, which confirms that different energy performance information concerning the energy management context is represented by the indicators. A comprehensive index considering both the SVI and SPI decides the weighting of each indicator. The SVI for each indicator is weighted by the SPI of the associated stakeholder; this validates the advantage of the proposed method to balance the stakeholders' benefits in accordance with their importance. Instead, the current practices for KPI selection always involves only stakeholders' consensus or validation, without any consideration of stakeholders' prioritization. The comprehensive index provides a quantitative means by which to weight the indicators and select the KPIs. The KPIs are structured according to the three-level hierarchy and show their ability to underpin multi-level key performance information and support multi-level energy performance analysis. Furthermore, new KPIs were also defined, such as I02 (energy cost saving) and I07 (time correlation between energy generation and use).

KPIs help make decisions in energy management about whether there is a need to make improvement or not and where the improvement measures should be taken. Stakeholders in energy management using the KPIs can make their performance concerns measurable, thus taking measures to achieve their goals. The hierarchy of three-level KPIs ensures that the energy performance at each scale is tracked and measured. Therefore, energy managers and other stakeholders can have an overview of the multi-level energy performance; and when there is a need to conduct more profound performance analysis, they can examine the disaggregated indicators. Furthermore, the weighting of KPIs help determine the overall importance of indicators considering various stakeholders, thus to manage and obtain a trade-off between the needs of the stakeholders, and, furthermore, to decide the implementation order of the different performance tasks.

The KPIs also help to identify the core data that contain the valuable performance information for various stakeholders. The exploitation and analysis of such data combined with KPIs can facilitate the achievement of stakeholders' performance goals. This will help exclude the interference of irrelevant information. Using KPIs to determine successively the master data domains, objects and elements helps energy managers and other stakeholders obtain a clearer statistical view of the multi-level performance. In addition, the focus on the valuable information and insightful data can save time and cost.

9.1.4 Conclusions in relation to Sub-objective 3

The energy-related data from various domains usually have an explicit or implicit relationship with each other. However, since the cross-domain data often come from different sources and gathered from different stakeholders, they are heterogeneous and mutually islanded. Therefore, it is essential to define an effective mechanism to resolve the data interoperability problem in order to exchange the data among various stakeholders. Furthermore, in order to exploit the data for performance improvement, it is essential to assess the performance. Linked data is possible solution for cross-domain data sharing and exploitation, and a noticeable opportunity is the integration of the multi-level evaluation and performance problem identification. The study of the state of the art found that there is an absence of the ontology to integrate both the key performance information and the insightful core data (Section 2.5.2).

Therefore, an integrated EM-KPI ontology is developed in this thesis in order to facilitate the integration and interchange of the master data and key performance information among different stakeholders. The ontology enables to generate linked data, resolve the data interoperability problem and offer an engagement mechanism for various stakeholders.

The exchange, sharing and exploitation of multi-level performance information and data help identify energy performance problems and achieve stakeholders' performance goals. The conventional mechanism used for the exchange of heterogeneous data is usually ineffective and time-consuming. The use of linked data in this thesis provides an efficient means to facilitate the data interchange, using ontologies as the foundation. The most of existing ontologies related to energy management focus on enabling system control rather than generating linked data. Additionally, the ontologies, including those for performance assessment, are usually designed for individual buildings or power grids. Thus, the EM-KPI ontology aims to integrate performance information and data for both the demand and supply sides in a district in order to enhance multi-level energy management.

The developed ontology contains two components. The KPI component enables the interchange of multi-level key performance information, while the master data component facilitates cross-domain sharing of insightful data. The stakeholders who use

the ontology can not only obtain access to their relevant performance information, but can also identify meaningful insights for energy performance improvement.

The exploration and analysis of the generated linked data in the case study shows the feasibility of the EM-KPI ontology for exchanging multi-level key performance information and cross-domain master data. The ability to access the related information about I03, I05 and I07 proves that the stakeholders can retrieve their relevant performance information at different levels. Furthermore, the stakeholders can also access and exploit the master data from various domains, including the district energy supply data, the weather data, the multi-level KPI calculation data, the building energy production data and the building facility data. Such data span across different domains and scales, which are always heterogeneous and stored in isolation. Thus, it is quite difficult to exchange them if no linked data was applied. In addition, the effectiveness of the link between the KPIs and the related master data is also validated through the data querying. Such link facilitates performance tracking and analysis for performance problem identification. Since the queries can be predefined and saved in advance, stakeholders who need to access the specific information can simply enter the linked dataspace with their user authorisation and execute the predefined queries; this facilitates the use of the generated linked dataset for stakeholders who have little expertise in linked data.

The access to the key performance information and its related data sources, in addition to the information exchange in a structured, systematic and contextual manner, promote stakeholders' engagement and interaction in energy management and enhance the multi-level energy management through an improved energy performance analysis at the district and building levels.

9.2 CONTRIBUTIONS OF THE THESIS

The main contributions of the thesis are the following:

- 1) A systematic methodology of KPIs and linked data is proposed for multi-level energy performance analysis. KPIs are used to extract the multi-level key performance information and master data, and then the linked data to exchange and exploit them. The method comprises tasks such as identifying stakeholders, selecting KPIs, collecting master data, generating linked data and conducting improvement analysis.
- 2) A new three-task method for the identification and prioritization of stakeholders is suggested, which includes (task 1) identifying the energy management intervention points, (task 2) identifying the stakeholders' roles and (task 3) analysing the stakeholders' prioritization to identify the key stakeholders. The use of intervention points to identify the stakeholders and a stakeholder prioritization index (SPI) for prioritization analysis is proposed.

- 3) A specific bi-index method to weigh each PI and select the KPIs that support the stakeholders' performance goals is defined. The two indexes are, respectively, the stakeholder vote index (SVI), obtained via stakeholders' votes, and the previously defined SPI, obtained by stakeholder prioritization analysis. Thus, the selected KPIs not only support stakeholders' performance goals, but also balance their benefits.
- 4) A new EM-KPI ontology is developed to exchange the key performance information and master data in district and buildings among different stakeholders. The ontology contains two parts, the KPI part and the EM master data part, which represents the multi-level performance information for energy performance tracking and integrates the master data domains for data exploitation, respectively.

9.3 FUTURE WORK

Considering the current restrictions defined for this thesis, the future research lines include the following:

- 1) The research boundary of this thesis is limited in a district. A future work will extend the application of methodology at a city scale. This means to identify stakeholders, select KPIs and exchange data in a city for achieving energy sustainable cities;
- 2) Apart from the building sector, the other sectors such as transportation, especially the electric vehicles, will be included for the analysis;
- 3) The current ontology aims to enhance multi-level energy management only in terms of electricity; and only the electricity associated facilities, utilities, systems and equipment are considered. Other energy types such as gas and thermal energy are not included. Since the ontology, as well as the linked data, is scalable, a further study will focus on its extension for representing the other energy types and their related utilities and systems. Therefore, a more comprehensive energy management considering different energy types for data exchange at a massive scale can be proposed.
- 4) Currently, the calculation of the KPIs and the analysis and visualization of the performance data need to be carried out in separate tools. Therefore, another further research line involves the development of an integrated tool, which aims to automatically calculate and assess the KPIs, exploit and exchange the cross-domain performance information and data, in addition to visualize the data (Figure 84). This integrated tool aims to be applied in real energy management systems or control system for optimization of energy operations.

Figure 84: Future research line to develop an integrated tool for multi-level performance analysis.

9.4 DISSEMINATION OF RESULTS

The dissemination of the results derived from this thesis aims to convey the essence and main contributions of this thesis internationally.

- 1) A first version of the KPI-based linked data methodology has been presented in the *EuroFM's 16th Research Symposium EFMC (European Facility Management Conference) 2017*. A conference proceeding titled “*Linked data for district-scale energy management: an indicator-based method*” has been published and selected as one of the five best articles. This paper illustrates the general framework of the systematic KPI-based linked data methodology [341].
- 2) An original research paper titled “*Identifying stakeholders and key performance indicators for district and building energy performance analysis*” has been published by the journal of *Energy and Buildings* [342]. This paper focuses on the detailed three-task method for stakeholder identification and prioritization, as well as the bi-index method to KPI selection. The implementation of the proposed methods in the case study is also included. This paper demonstrates the feasibility of the three-task method and bi-index method, in addition to its benefit to support multi-level performance analysis.
- 3) Another original research paper titled “*Enhancing energy management at district and building levels via an EM-KPI ontology*” ***** by the journal of *Automation in Construction* *****. This paper depicts the development of the EM-KPI ontology, including the methodology used for the ontology development, the initial conceptual model of the ontology and the detailed models of the seven

ontology modules, as well as the generation of a linked dataset using the developed ontology for exploring the insights for performance improvement.

In addition, an oral presentation titled “*Development of an EM-KPI ontology for district and building energy performance analysis*” was presented in the workshop *LDCA (Linked Data for Construction and Architecture) 2016*. This presentation illustrates the first version of the EM-KPI ontology for enabling district and building energy performance analysis.

Another conference proceeding titled “*Life cycle thermal performance analysis of the VIP-insulated envelope based on the method of risk management*” has been published in the *I Congreso Internacional sobre Investigación en Construcción y Tecnología Arquitectónicas* [343]. This paper describes the life cycle performance analysis of the vacuum insulation panel (VIP) for building envelope, considering the technical risks during its lifetime. The VIP is one of the main types of insulation used in the solar houses. It has very high insulation efficiency, but the improper installation, inadvertent damage, material degradation and so on, will all lead to the decrease of its energy efficiency. Therefore, the risk theory is used to analyse the potential life cycle performance of VIP considering the possibilities of various unfavourable situations in long term.

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APPENDIX A EXISTING KPIS IN CURRENT LITERATURE

Table A.1 KPIS for facility performance assessment [241]

Category	Performance indicators
Financial indicators	Operating costs; Occupancy costs; Utility costs; Capital costs; Building maintenance cost; Grounds-keeping cost; Custodial and janitorial cost; Current replacement value; Deferred maintenance; Capital renewal; Maintenance efficiency indicators; Facility condition index; Churn rate and churn costs.
Physical indicators	Building physical condition – quantitative: building performance index; Building physical condition – qualitative: general building maintenance in (1) building physical condition, (2) sanitary, plumbing and storm water, (3) mechanical services and (4) lighting and electrical, property and real estate; Waste; Health and safety; Indoor environment quality; Accessibility for disabled; Resource consumption – energy: (1) energy use: total facility energy use or building energy use, (2) net energy consumption, (3) annual energy consumption, (4) total natural gas consumption, (5) building electrical consumption and (6) building electrical demand, demand intensity or peak electricity demand; Resource consumption – water; Resource consumption – material; Security; Site and location.
Functional indicators	Productivity; Parking; Space utilization; Employee or occupant's turnover rate; Mission and vision, and mission dependency index; adequacy of space.
Survey-based indicators	Customer/occupants' satisfaction; Community satisfaction and participation; Learning environment, educational suitability and appropriateness of facility for its function ((for educational building); Appearance.

Table A.2: KPIS for assessing environmental, social and economic performance in district retrofitting projects [242]

Category	Sub-category	Indicator
Environmental performance	Environmental impacts	Global warming (Greenhouse gas emissions); Ozone depletion, Acidification; Eutrophication; Photochemical ozone creation; Microclimate (Heat island, Air pollution)
	Material efficiency	Material efficiency
	Energy	Energy demand (Total primary energy demand, Operational energy use, Energy demand embodied); Energy technologies and use of synergies; Renewable energy production (Share of renewable energy on site)
	Biodiversity	Material sourcing
	Land use	Land use
	Environment risks	Environmental risks at the site (flooding, earthquake, etc.)
	Water	Water consumption; Intensity of water treatment
Social performance	Health	Risk from materials/hazardous materials; Indoor air quality
	User comfort	Thermal comfort (Operative temperature, Percentage predicted dissatisfied, Percentage of occupied hours outside comfort range, Outdoor temperature/Heat island effect); Indoor air quality (Occupancy-based ventilation rates, CO ₂ concentration above outdoor level, Occurrence of radon); Visual comfort

Category	Sub-category	Indicator
		(Availability of daylight throughout the building, Vertical sky component, Solar irradiance incident – insolation, Solar access); Sound insulation and noise level (Noise levels at building façade)
	Sociocultural quality	Social and commercial infrastructure; Safety and security
	Technical infrastructure	Water management; Waste management
	Functionality	Barrier-free accessibility; Open spaces offer; Conversion feasibility
	Mobility	Quality of traffic infrastructure
	Design quality	Design quality (aesthetic, influence on urban planning)
Economic performance	Costs	Life cycle cost; Investment costs; Savings in electricity and gas bills
	Economic performance	Fiscal effect on municipality; Environmental taxes; Unemployment rate; Job potential; Land value performance; Purchasing power index; Vacancy rate of district; Fuel poverty index; Value stability; Payback time; Change in value of property; Return on investment

Table A.3: KPIs for building renovation projects reviewed by [243]

Category	Sub-category	Indicators
Economic KPIs	Direct costs	Capital investment; Cost; Economic performance and affordability; Equipment at pre-budgeted rates; Initial Cost; Life cycle cost; Net Present Cost; Project profitability
	Indirect costs	Adverse effect on quality of groundwater level; Adverse impact on tourism values; Employment of labour; Flexibility and Adaptability; Minimum variations cost; No financial claims at completion; No increase materials cost; Rehabilitating cost of ecosystem; Resettling cost of people; Stable labour costs
Environmental KPIs	Generic	Environmental friendliness; Shadow cost; Utilised environmentally friendly technology
	Atmosphere	Annual carbon emission; Destruction of the stratospheric ozone layer; Embodied carbon; Emissions Payback Time; GHG emissions; Global warming potential; Project has led to air pollution, etc.
	Land use	Abiotic depletion potential; Acidification of land and water resources; Connectivity with hinterland; Extent of land acquisition
	Water resources	Acidification of land and water resources; Freshwater resources; Quality of water use in buildings; Water reuse
	Ecology	Eutrophication; Extent of loss of habitat or feeding grounds; Extent of tree felling; Mineral resource depletion, etc.
	Noise	Acoustic performance; Design flexibility towards noise reduction measures, etc.
	Visual impact	Glare; Harmony with surrounding; View from assessor on visual impact; Visual comfort, etc.

Category	Sub-category	Indicators
	Indoor quality	Air outlet design; Humidity; Indoor air quality; Indoor Environmental Quality-Health and Well-being; Overheating risk; Ventilation design—during construction; Ventilation design—service stage
	Energy	Annual electrical energy conservation; Energy consumption and resources saving; Energy management; Energy Payback Time; Energy policy and audit; Energy Return Ratio; Energy savings per annum; Exported energy; Materials for energy recovery; Peak Energy Demand Reduction for building operations; Renewable primary energy; Site orientation to maximise passive solar potential; Thermal performance; Total life cycle primary from renewable energy; Total life cycle primary non-renewable energy, emissions; Use of Daylight in the primary areas; Use of non-renewable primary energy
	Reuse/recycle	Components for reuse; Materials for recycling; Secondary fuels; Secondary materials
	Waste management	Hazardous waste to disposal; Increased solid waste; Materials used; Durability and Waste, etc.
	Public health	Public health; Public safety
Social KPIs	Cultural heritage	Complaints from local parties/villages; Extent of diversion; Footprint of project in archaeological site
	Public access	Accessibility for people with specific needs; Extent of blockage; Extent of congestion; View from local authorities
	Public perception	Extent of encroachment upon concerned areas; Stakeholder satisfaction
	Functionality	Functionality; Functionality, Usability, and aesthetic aspects; Office work performance
	Occupational safety	Accidents, injuries, fatalities; Accidents were reported; Fatalities did occur; Fire safety; Health and safety; Long-term health, etc.
Technological KPIs	Innovation	Innovation and design process; Innovation and improvement
	Intelligence	Intelligence and controllability
	maintenance	Maintenance requirement

Table A.4: KPIs for commercial building energy use based on New Buildings Institute's (NBI) investigation [244]

KPI	Description
Schedule visualized EUI	An indicator assesses the EUI (Energy Use Intensity) contribution of each system while also examining the number of hours per typical workday across a year that the system represents an “active” status implying a schedule of use.
Occupancy consistency indicator	A qualitative assessment of the occupancy in the building including its stability
Occupant usage indicator	Represented by Occupied Energy Use Rate Density, which is a measure of the average energy use rate during the occupied hours

KPI	Description
Design and operations vs. occupant indicator	A high-level comparison for design and operations as opposed to occupant behaviour with buildings of similar climate zones and from similar years
Daylight effectiveness indicator	The correlation between the monthly Occupied Energy Use Rate Density for lighting and night lengths in hours co-plotted versus time
Overall lighting performance indicator	Used to compare actual energy performance across different lighting systems
HVAC and Net electric baseload indicator	A numerical value based on the monthly energy signature of the building
Operational consistency indicator	A complement to the baseload indicator by looking at the HVAC and Net electric energy signature in monthly and weekly increments for an indication of whether the building HVAC system is well controlled

Table A.5: KPIs for energy management proposed by [245]

Category	Indicator	Description
Strategic KPIs	Energy cost index (ECI)	A measurement of the total energy costs (such as electricity, steam, gas and water) in a period
	Site energy use intensity	It focuses on the demand side of energy, calculating energy consumption by air-conditioned square footage.
	Source energy use (SEU)	It is also a demand metric, which not only captures the consumption specific to a site, but also quantifies the energy transmission, delivery and production losses.
	Productivity index	The rate at which energy is consumed per unit of input
	System performance	A measurement of the energy efficiency of mechanical systems per output unit
	Load factor	Calculated by average demand (kW) divided by peak demand (kW)
	Average minimum demand	The minimum power requirements of a site at its lowest point of utilization, which serves as a leading indicator to gain control over the specific load profile.
	Sustainability index	Including categories of environmental policy, staffing and auditing, ethical investments, renewable energy and waste recycling, etc.
	Greenhouse gas (GHG) emissions	Typically expressed as the equivalency of metric tons of CO ₂ or a percent reduction thereof
Site Controls-specific KPIs	Energy outliers	An aggregate of three individual metrics: consumption or site energy use intensity; load factor; and average minimum demand
	HVAC health	The efficiency (and thus cost effectiveness) of an HVAC unit and ultimately translated to expected lifespan of that unit
	Setpoint non-compliance	Deviations from the setpoint standards which cause overconsumption of energy
	Lighting exceptions	The lighting controls during times of troubleshooting, repair or remodelling
	Digital zone controller (DZC) connectivity	The connectivity of the controllers to the HVAC units
	Site connectivity	A measurement of the number and percentage of EMS-controlled sites that have connectivity to the cloud-based portal

Category	Indicator	Description
	Overrides	The excessive usage of push buttons onsite for a temporary adjustment to comfort issues or potential unscheduled cleanings

Table A.6: Indicators for assessing sustainable intelligent buildings [247]

Category	Indicator	Sub-indicators of energy and natural resource
Environmental indicators	Energy and natural resource	Total life cycle primary non-renewable energy; Site orientation to maximise passive solar potential; Total life cycle primary from renewable energy; Use of daylight in the primary areas; Peak energy demand reduction for building operations; Passive solar gain and cooling; Annual electrical energy conservation; Design features to maximise effectiveness of ventilation in naturally ventilated occupancies; Maximise the effectiveness of operable windows; Energy policy and audit.
	Water and water conservation	
	Material used, durability and waste	
	Land use and site selection	
	Transport and accessibility	
	Greenhouse gas emissions	
Social-cultural indicators	Functionality, usability and aesthetic aspects	Use of daylight in the primary areas; Peak energy demand reduction for building operations; Passive solar gain and cooling; Annual electrical energy conservation; Design features to maximise effectiveness of ventilation in naturally ventilated occupancies; Maximise the effectiveness of operable windows; Energy policy and audit.
	Indoor environmental quality – health and well being	
	Architectural considerations – cultural heritage integration	
	Innovation and design process	
Economic indicators	Flexibility and adaptability	Use of daylight in the primary areas; Peak energy demand reduction for building operations; Passive solar gain and cooling; Annual electrical energy conservation; Design features to maximise effectiveness of ventilation in naturally ventilated occupancies; Maximise the effectiveness of operable windows; Energy policy and audit.
	Economic performance and affordability	
	Building manageability	
	Whole life value	
Technological indicators	Intelligence and controllability	Use of daylight in the primary areas; Peak energy demand reduction for building operations; Passive solar gain and cooling; Annual electrical energy conservation; Design features to maximise effectiveness of ventilation in naturally ventilated occupancies; Maximise the effectiveness of operable windows; Energy policy and audit.
	Communications and mobility	

Table A.7 KPIs for assessing smart grid goals proposed by [248]

Macro-objective	Objective	Indicator
Improvement of energy efficiency	Efficiency of power delivery system	Reduction in overall demand
		Reduction in peak demand
		Reduction in technical losses
	Efficiency of power consumption	Reduction in street lighting
		Reduction in high power customers' consumption
		Reduction in domestic and SME consumption
		Influence in the Vehicle-to-Grid (V2G) technology
		Improvement in control system's efficiency
Increase of renewable energy use	Increase of renewable energy use	Percentage of total renewable generation
		Percentage of renewable mini-generation
		Percentage of micro-generation
Reduction of emissions	Reduction of emissions	Reduction in CO ₂ emission
		Improvement in zonal quality

Macro-objective	Objective	Indicator
Secondary objectives	Improvement of power quality	Improvement in waveform quality
		Improvement in early detection of LV (Low Voltage) occurrences
		Improvement in response to MV (Medium Voltage) occurrences
	Extension of service life of facilities	Extension in service life of transformers
		Extension in service life of switches
		Extension in service life cabling
	Reduction of breakdown and maintenance costs	Reduction in breakdown costs
		Reduction in maintenance costs

Table A.8: European green city index for CO₂ emissions, energy, buildings [344]

Category indicator		Description
CO ₂	CO ₂ emissions	Total CO ₂ emissions in tons per head
	CO ₂ intensity	Total CO ₂ emissions in grams per unit of real GDP (2000 base year)
	CO ₂ reduction strategy	An assessment of the ambitiousness of CO ₂ emissions reduction strategy
Energy	Energy consumption	Total final energy consumption, in gigajoules per head
	Energy intensity	Total final energy consumption, in mega joules per unit of real GDP (in euros, 2000 base year)
	Renewable energy consumption	The percentage of total energy derived from renewable sources, as a share of the city's total energy consumption, in tera joules
	Clean and efficient energy policies	An assessment of the extensiveness of policies promoting the use of clean and efficient energy
Buildings	Energy consumption of residential buildings	Total final energy consumption in the residential sector, per square meter of residential floor space
	Energy-efficient buildings standards	An assessment of the extensiveness of cities' energy efficiency standards for buildings
	Energy-efficient buildings initiatives	An assessment of the extensiveness of efforts to promote energy efficiency of buildings

APPENDIX B COMPETENCY QUESTIONS FOR DEFINING THE FUNCTIONAL REQUIREMENTS OF THE EM-KPI ONTOLOGY

Identifier	Category	Competency Question
CQ1	KPI	Who are the stakeholders in energy management at district and building levels?
CQ2	KPI	What energy performance goals do the stakeholders have?
CQ3	KPI	What key performance indicators can be used to measure the performance goals?
CQ4	KPI	How can KPIs be calculated?
CQ5	KPI	What is needed for KPI calculation?
CQ6	KPI	What object does each KPI evaluate?
CQ7	KPI	What is the interval at which each KPI evaluates?
CQ8	KPI	What are the results of the KPI calculation?
CQ9	Unit	What is the unit of each KPI value?
CQ10	Observation	What observation provides the datum sources for KPI calculation?
CQ11	Location	Where is the district located?
CQ12	Location	What is the geographic coordinate point of the district?
CQ13	Weather	What are the weather conditions in the district?
CQ14	Weather	How is the weather phenomenon in the district?
CQ15	Weather	What energy aspects are influenced by the weather?
CQ16	Weather	What are expected from the weather forecast in the district?
CQ17	Weather	What aspects are influenced the weather forecast?
CQ18	Observation	How can the weather be measured in the district?
CQ19	Date Time	When is the weather measured in the district?
CQ20	Unit	What is the unit of each weather measurement?
CQ21	Energy	Which is the energy type used in the district?
CQ22	Utility	What power systems are installed in the district?
CQ23	Location	Where are the district power systems located?
CQ24	Utility	What type of power equipment do the power systems contain?
CQ25	Observation	What are the status and parameters of each type of power equipment?
CQ26	Date Time	When are the equipment parameters measured?
CQ27	Unit	What is the unit of each equipment parameter?

Identifier	Category	Competency Question
CQ28	Utility	What kind of energy-generating units are installed in the district?
CQ29	Utility	What kind of energy storage units are installed in the district?
CQ30	Utility	What kind of power delivery units are installed in the district?
CQ31	Utility	What kind of energy consumers does the district have?
CQ32	Utility	How do the district power systems connect with the energy facilities in buildings?
CQ33	Building	What type of buildings does the district contain?
CQ34	Building	When were the buildings constructed?
CQ35	Building	What are the dimensions of the buildings?
CQ36	Building	What is the air conditioning volume of the buildings?
CQ37	Location	Where are the buildings located?
CQ38	Building	What building elements does each building contain?
CQ39	Building	How are the thermal properties of the building envelope?
CQ40	Building	What energy facilities are installed in the building?
CQ41	Building	What building equipment is contained in the building?
CQ42	Observation	What are the status and parameters of the building equipment?
CQ43	Date Time	When are the parameters of the building equipment measured?
CQ44	Unit	What is the unit of each measurement of the building equipment?
CQ45	Building	What is the use schedule of each zone in the building?
CQ46	Occupancy	How many occupants does each zone have?
CQ47	Occupancy	What events do the occupants attend?
CQ48	Occupancy	What behaviours do the occupants exhibit?
CQ49	Occupancy	What influences the occupants' behaviours in regard to energy use?
CQ50	Building	What factors affect the level of indoor comfort?
CQ51	Observation	What is the measurement value of these factors?
CQ52	Unit	What is the unit of measurement value?
CQ53	Date Time	When is the indoor comfort monitored?
CQ54	Energy	What systems or equipment produce energy?
CQ55	Energy	What energy type do the systems or equipment produce?
CQ56	Energy	What systems or equipment store energy?
CQ57	Energy	What energy type do the systems or equipment store?
CQ58	Energy	What systems or equipment deliver energy?
CQ59	Energy	What energy type do the systems or equipment deliver?

Identifier	Category	Competency Question
CQ60	Energy	What systems or equipment consume energy?
CQ61	Energy	What energy type do the systems or equipment consume?
CQ62	Energy	What energy parameters are important in the energy management?
CQ63	Energy	What is the relationship between these energy parameters?
CQ64	Observation	How much energy is produced in the district and the buildings?
CQ65	Date Time	When is the energy production monitored?
CQ66	Unit	What is the unit of measurement of energy production?
CQ67	Observation	How much energy is stored in the district and the buildings?
CQ68	Date Time	When is the energy storage monitored?
CQ69	Unit	What is the unit of measurement of energy storage?
CQ70	Observation	How much energy is supplied to the district and the buildings?
CQ71	Energy	From where does the energy supply come?
CQ72	Date Time	When is the energy supply monitored?
CQ73	Unit	What is the unit of measurement of the energy supply?
CQ74	Observation	How much energy is consumed in the district and the buildings?
CQ75	Date Time	When is the energy consumption monitored?
CQ76	Unit	What is the unit of measurement of energy consumption?
CQ77	Observation	What is the energy cost in the district and the buildings?
CQ78	Date Time	When is the energy cost observed?
CQ79	Unit	In what currency is the energy cost paid?
CQ80	Energy	What is the energy tariff for the purchase and sale of energy?
CQ81	Energy	What is the energy forecast in the district and buildings?
CQ82	Energy	What is the gap between the predicted energy production and the actual energy production?
CQ83	Energy	What is the gap between the predicted energy consumption and the actual energy consumption?

APPENDIX C EM-KPI ONTOLOGY REQUIREMENTS SPECIFICATION DOCUMENT (ORSD)

EM-KPI Ontology Requirements Specification Document (ORSD)	
1	Purpose
	The targeted EM-KPI ontology is aimed to exchange both the master data and key performance information between different stakeholders in district and buildings, in order to enhance energy management on both scales, and to enable the exploitation of knowledge and insights in linked data for performance tracking and improvement.
2	Scope
	The ontology should provide a consensual knowledge model that contains the key performance information at different levels, namely the district level, the building and system level, and the zone and equipment level. The multi-level KPIs should be represented, including their definitions, associated strategic goals and stakeholders, evaluated objects, calculations and needed datum sources. Furthermore, the related master data from different domains should be described. The master data domains include energy, utility, building, occupancy, location, weather, date and time, observation, and unit. The level of granularity is directly related to the competency questions defined and the terms identified.
3	Implementation Language
	The ontology should be implemented in OWL.
4	Intended End-Users
	User 1. District energy managers who perform district energy operations; User 2. Building energy managers who fulfil building energy optimization; and User 3. Stakeholders who are involved in the energy management.
5	Intended Use
	Use 1. To exchange the energy-related master data among different stakeholders; Use 2. To provide key performance information for various stakeholders; and Use 3. To support performance analysis through linked data for identifying key areas for improvement and achieving stakeholders' goals.
6	Ontology Requirements
	Non-Functional Requirements:

- a. The ontology will try to adopt concepts and design patterns in other existing ontologies where possible, combined with the newly developed ontology concept and patterns;
- b. The ontology should be developed by English language.

Functional Requirements: Competency Questions Groups (CQG)

CQG1: Energy 16 CQs

CQG2: Utility 7 CQs

CQG3: Building 10 CQs

CQG4: Occupancy 4 CQs

CQG5: Location 4 CQs

CQG6: Weather 5 CQs

CQG7: Date and time 9 CQs

CQG8: Observation 10 CQs

CQG9: Unit 10 CQs

CQG10: Key Performance Indicator 8 CQs

APPENDIX D AN RDF/XML SEGMENT OF THE EM-KPI ONTOLOGY

```

<!--
  http://energy.linkeddata.es/em-kpi/ontology#providesTo
-->
<owl:ObjectProperty rdf:about="http://energy.linkeddata.es/em-
kpi/ontology#providesTo">
  <rdfs:domain>
    <owl:Class>
      <owl:unionOf rdf:parseType="Collection">
        <rdf:Description rdf:about="http://energy.link
eddata.es/em-kpi/ontology#EnergyProduction"/>
        <rdf:Description rdf:about="http://energy.link
eddata.es/em-kpi/ontology#EnergyStorage"/>
        <rdf:Description rdf:about="http://purl.oclc.o
rg/NET/ssnx/ssn#Observation"/>
      </owl:unionOf>
    </owl:Class>
  </rdfs:domain>
  <rdfs:range>
    <owl:Class>
      <owl:unionOf rdf:parseType="Collection">
        <rdf:Description rdf:about="http://energy.link
eddata.es/em-kpi/ontology#DatumSource"/>
        <rdf:Description rdf:about="http://energy.link
eddata.es/em-kpi/ontology#EnergyStorage"/>
        <rdf:Description rdf:about="https://www.auto.tu
wien.ac.at/downloads/thinkhome/ontology/EnergyResour
ceOntology.owl#EnergyGain"/>
        <rdf:Description rdf:about="https://www.auto.tu
wien.ac.at/downloads/thinkhome/ontology/EnergyResour
ceOntology.owl#EnergySupply"/>
      </owl:unionOf>
    </owl:Class>
  </rdfs:range>
  <rdfs:label xml:lang="en">providesTo</rdfs:label>
</owl:ObjectProperty>
<!--
  http://energy.linkeddata.es/em-kpi/ontology#storesEnergy
-->
<owl:ObjectProperty rdf:about="http://energy.linkeddata.es/em-
kpi/ontology#storesEnergy">
  <rdfs:domain rdf:resource="http://energy.linkeddata.es/em-
kpi/ontology#PowerSystemResource"/>
  <rdfs:range rdf:resource="http://energy.linkeddata.es/em-
kpi/ontology#EnergyStorage"/>
  <rdfs:comment xml:lang="en">

```

Relation linking the energy storage system or equipemnt to the Energy Storage parameter

```

    </rdfs:comment>
    <rdfs:label xml:lang="en">storesEnergy</rdfs:label>
</owl:ObjectProperty>
<!--
  http://energy.linkeddata.es/em-kpi/ontology#storesEnergyType
-->
<owl:ObjectProperty rdf:about="http://energy.linkeddata.es/em-
kpi/ontology#storesEnergyType">
  <rdfs:domain rdf:resource="http://energy.linkeddata.es/em-
kpi/ontology#PowerSystemResource"/>
  <rdfs:rangerdf:resource="https://www.auto.tuwien.ac.at/downloads
/thinkhome/ontology/EnergyResourceOntology.owl#EnergyType"/>
  <rdfs:comment xml:lang="en">

```

Relation linking the energy storage system or equipment to Energy Type it stores

```

    </rdfs:comment>
    <rdfs:label xml:lang="en">storesEnergyType</rdfs:label>
</owl:ObjectProperty>

<!--
  http://energy.linkeddata.es/em-kpi/ontology#EnergyProduction
-->
<owl:Class rdf:about="http://energy.linkeddata.es/em-
kpi/ontology#EnergyProduction">
  <rdfs:subClassOfrdf:resource="https://www.auto.tuwien.ac.at/down
loads/thinkhome/ontology/EnergyResourceOntology.owl#EnergyParameter"/>
  <rdfs:subClassOf>
    <owl:Restriction>
      <owl:onProperty rdf:resource="http://energy.linkedda
ta.es/em-kpi/ontology#hasForecast"/>
      <owl:someValuesFrom rdf:resource="http://energy.link
eddata.es/em-kpi/ontology#EnergyProductionForecast"/>
    </owl:Restriction>
  </rdfs:subClassOf>
  <rdfs:subClassOf>
    <owl:Restriction>
      <owl:onProperty rdf:resource="http://energy.linkedda
ta.es/em-kpi/ontology#providesTo"/>
      <owl:someValuesFrom rdf:resource="http://energy.link
eddata.es/em-kpi/ontology#EnergyStorage"/>
    </owl:Restriction>
  </rdfs:subClassOf>
  <rdfs:subClassOf>
    <owl:Restriction>
      <owl:onProperty rdf:resource="http://energy.linkedda
ta.es/em-kpi/ontology#providesTo"/>

```

```

        <owl:someValuesFrom rdf:resource="http://energy.link
        eddata.es/em-
        kpi/ontology#EnergySupplyFromSiteProduction"/>
    </owl:Restriction>
</rdfs:subClassOf>
<rdfs:subClassOf>
    <owl:Restriction>
        <owl:onProperty rdf:resource="http://energy.linkedda
        ta.es/em-kpi/ontology#providesTo"/>
        <owl:someValuesFromrdf:resource="https://www.auto.tu
        wien.ac.at/downloads/thinkhome/ontology/EnergyResourceOnto
        logy.owl#EnergyGain"/>
    </owl:Restriction>
</rdfs:subClassOf>
    <rdfs:comment xml:lang="en">Energy producted by generation
    system</rdfs:comment>
    <rdfs:label xml:lang="en">EnergyProduction</rdfs:label>
</owl:Class>

```

APPENDIX E THE DEFINITION AND CALCULATION OF THE PROPOSED PIS

Tag	Performance Indicator (PI)	Description	Calculation	Unit
I01	CO ₂ emissions reduction	Reduction of CO ₂ emissions by energy savings and renewable energy use	$E_{Fossil\_fuel\_replaced\_by\_renewables} * Conversion\_factor_{CO_2}$	kg
I02	Energy cost saving	Total energy cost saving caused by reduced purchased energy and/or energy use at a lower energy price	$(E_{District\_energy\_supply\_from\_energy\_provider} \times Tariff_{Energy\_cost}) - (E_{District\_energy\_export\_to\_energy\_provider} \times Tariff_{Feed\_in})$	€
I03	District energy balance	District energy balance between generation and consumption during given time step (TS)	$E_{District\_generation} - E_{District\_consumption}$	kWh
I04	Overall energy use reduction	Total site energy use reduction due to global energy efficiency improvement	$E_{District\_consumption}$ (site energy use measurement)	kWh
I05	Individual building energy balance	Energy balance between building integrated energy generation and consumption in given TS	$E_{Building\_generation} - E_{Building\_consumption}$	kWh
I06	Inter-building energy balance	Energy balance between generation and consumption among several buildings	$\sum_1^n E_{Building\_generation} - \sum_1^n E_{Building\_consumption}$	kWh
I07	Time correlation between use and generation	Time correlation between energy generation and use for instantaneous energy balance	$\int_0^T P_{Demand\_uncovered\_by\_site\_generation}$	kWh
I08	Peak demand reduction	Curtailment of peak demand by adjusting energy demand	$\frac{P_{Average\_demand}}{P_{Peak\_demand}}$	kW/ kW
I09	Renewable energy share	The deployment level of renewable energy in district and buildings	$\frac{E_{Total\_renewable\_generation}}{E_{Total\_consumption}} * 100\%$	%
I10	System performance	A summary indicator measuring the global efficiency of the energy system	$\frac{E_{Desired\_output}}{E_{Input}} * 100\%$	%
I11	Energy loss reduction	Level of losses in the storage and distribution system in a given TS	$\frac{E_{Supply} - E_{Consumption}}{E_{Consumption}}$	kWh /kW h

Tag	Performance Indicator (PI)	Description	Calculation	Unit
I12	Generation system efficiency	Energy efficiency of energy generation system at a given time	$\frac{P_{Generation}}{P_{Solar\_radiation}} * 100\%$	%
I13	Storage system efficiency	System efficiency accounting for energy losses in the storage system in a given TS	$\frac{E_{Storage\_output}}{E_{Storage\_input}} * 100\%$	%
I14	Distribution system efficiency	System efficiency accounting for energy losses incurred in transporting energy at a given time	$\frac{P_{Distribution\_output}}{P_{Distribution\_input}} * 100\%$	%
I15	Consumption system efficiency	Energy efficiency of energy consumption systems at a given time	$\frac{P_{System\_output}}{P_{System\_input}} * 100\%$ (or COP)	%
I16	Single building energy use reduction	Energy use reduction in a building within a given TS. A lower value means more energy saving or efficiency	$\frac{E_{Building\_consumption}}{V_{Air\_conditioned\_volume}}$	kWh /m ³
I17	Significant energy use reduction	The reduction of significant energy use, such as HVAC, lighting system, etc.	$\frac{E_{Significant\_energy\_use}}{E_{Building\_consumption}}$	kWh /kW h
I18	Building functionality	A summary indicator assessing the overall function in a building	$Vote_{Building\_consumer/occupant}$	-
I19	Building comfort	A summary indicator assessing the overall comfort in a building	$Vote_{Building\_occupant}$	-
I20	Purchased energy use reduction	The amount of energy purchased from the external grid in a given TS	$\frac{E_{Purchased\_from\_main\_grid}}{E_{Total\_consumption}}$	kWh /kW h
I21	Purchased energy at lower price	The deployment level of TOU (time of use) energy prices for energy cost saving	$\frac{E_{Purchased\_at\_trough\_energy\_price}}{E_{Total\_consumption}}$	kWh /kW h
I22	Influence of energy storage on cutting peak demand	The effect of an energy storage system on curtailing peak demand at a given time	$\frac{P_{Covered\_by\_storage\_system}}{P_{Peak\_demand}}$	kW/ kW
I23	Influence of the TOU energy price on cutting peak demand	The effect of the TOU (time of use) energy price on curtailing peak demand within a given TS	$\frac{E_{valley\_energy\_price}}{E_{Peak\_energy\_price}}$	kWh /kW h

Tag	Performance Indicator (PI)	Description	Calculation	Unit
I24	Accuracy in energy supply and demand prediction	The gap between predicted and actual energy demand at a given time	$\frac{P_{Predicted\_supply/demand}}{P_{Actual\_supply/demand}}$	kW/ kW
I25	Capacity factor	The fraction of actual energy generated or delivered in the power system compared to the capacity that could be generated/delivered	$\frac{P_{Actual\_generated\_or\_deliered\_energy}}{P_{Generaton\_or\_distribution\_capacity}}$	kW/ kW
I26	Equipment energy efficiency	Energy efficiency of specific equipment	$\frac{P_{Equipmet\_output}}{P_{Equipment\_input}} * 100\%$	%
I27	Operational schedule and occupancy consistency	Evaluates whether the system's operational schedule is aligned with occupancy, in order to avoid energy wastage through off-occupancy consumption	$N_{Hours\_schedule\_inconsistent\_with\_occupancy}$	hour
I28	Occupancy stability indicator	The stability level of occupancy in a building or zone, which affects energy demand and its prediction	$N_{Occupant\_in\_zone\_or\_building}$	-
I29	Building thermal load reduction	Reduction of heating/cooling load caused by envelope insulation	$U_{value\_Envelope} \times Area_{Envelope} \times (Tp_{Indoor} - Tp_{Outdoor})$	W
I30	Thermal comfort	Provides comprehensive thermal comfort in a zone	$PMV = (0.303e^{-0.036M} + 0.028)L$	-
I31	Light comfort	Measures whether the illuminance intensity meets the specific requirements in a zone	$Measurement_{Illuminance\_intensity}$	lux
I32	Appropriate temperature	Assesses whether the temperature meets the specific requirements in a zone	$Measurement_{Temperature}$	°C
I33	Appropriate humidity	Gauges whether the humidity meets the specific requirements in a zone	$Measurement_{Humidity}$	%
I34	Appropriate amount of fresh air	Measures if the air quality meets the specific requirements in a zone	$Measurement_{CO_2\_concentration}$	ppm
I35	Consumers' participation	The amount of load participating in demand-side management at a given time	$\frac{P_{Interruptible\_tariffs\_and\_direct\_load}}{P_{Total\_demand}}$	kW/ kW

Note: In calculation equations, “E” means energy, with a unit of kWh; “P” means power, with a

unit of kW; “t” means time; “E” can also be presented as the integral of “P” based on time; “V” means volume, with a unit of “m³”; “N” means number; “Tp” means temperature; “PMV” means predicted mean vote index for thermal comfort; “M” means occupants’ metabolic rate; “L” means thermal load for a person at a comfortable skin temperature and evaporative heat loss by sweating at the actual activity level.