Preprint Cambridge Centre for Computational Chemical Engineering ISSN 1473 – 4273

Embedding Energy Storage Systems into a Dynamic Knowledge Graph

Laura Ong[1], Gourab Karmakar[1], Mei Qi Lim[1], Arkadiusz Chadzynski[1],
Lanyu Li[4], Xiaonan Wang[4], Markus Kraft[1,2,3]

released: 08 September 2021

[1] CARES
Cambridge Centre for Advanced
Research and Education in Singapore
1 Create Way
CREATE Tower, #05-05
Singapore, 138602

[2] Department of Chemical Engineering
and Biotechnology
University of Cambridge
Philippa Fawcett Drive
Cambridge, CB3 0AS
United Kingdom

[3] School of Chemical
and Biomedical Engineering
Nanyang Technological University
62 Nanyang Drive
Singapore, 637459

[4] Department of Chemical and
Biomolecular Engineering
National University of Singapore
Engineering Drive 4
Singapore, 117585

Preprint No. 280

UNIVERSITY OF CAMBRIDGE

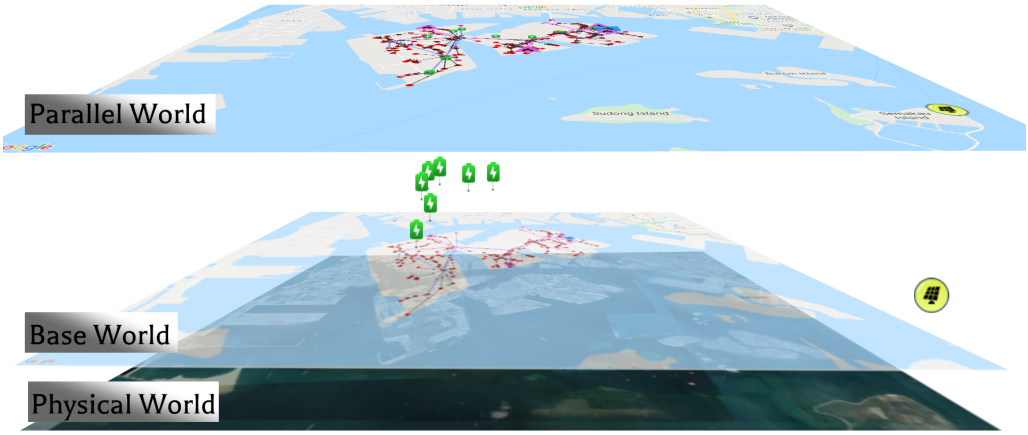
Keywords: Dynamic Knowledge Graph, Digital Twin, Interoperability, Energy Storage, Multi-criteria Decision Making

Edited by
Computational Modelling Group
Department of Chemical Engineering and Biotechnology
University of Cambridge
Philippa Fawcett Drive
Cambridge, CB3 0AS
United Kingdom

E-Mail: mk306@cam.ac.uk
World Wide Web: `https://como.ceb.cam.ac.uk/`

Abstract

This paper illustrates how a dynamic knowledge graph approach in the context of The World Avatar (TWA) project can support the decarbonisation of energy systems by leveraging the existing Energy Storage System (ESS) selection framework to assist in the selection and optimal placement of ESS. TWA is a dynamic knowledge graph based on the Semantic Web and its associated technologies, with intelligent agents operating on it. The agents act autonomously to update and extend TWA, and thus it evolves in time. TWA also provides the ability to consider different scenarios, referred to as parallel worlds, allowing for scenario analysis without mutual interference. A use case – the addition of a Battery Energy Storage System to the Singapore Jurong Island electrical network – is introduced to demonstrate the application of this approach. The domain ontology, OntoPowSys, was extended to describe and instantiate the relevant ESSs considered in the use case. This extension is described in the paper using the Description Logic syntax. The paper also outlines the details of how the various agents involved in the use case are being integrated into TWA. The use case also highlights how the parallel world framework can facilitate scenario analysis by considering different scenarios without affecting the real-world representation.



Highlights

- Integration of Energy Storage System (ESS) selection into The World Avatar.
- Extension of the power system domain ontology, OntoPowSys.
- Application of ESS selection and parallel world frameworks to facilitate scenario analysis.

Contents

1 Introduction **3**

2 Background **4**

2.1 Knowledge graph 4

2.2 Ontologies 5

2.3 Agents in the knowledge graph 5

2.4 Scenario management 5

2.5 Energy storage system selection framework 6

3 Extension of ontology **6**

4 Energy Storage System: a knowledge graph approach **8**

4.1 Parallel world framework in the knowledge graph 8

4.2 Application of parallel world framework for ESS 10

5 Conclusions **16**

6 Appendix **19**

References **22**

1 Introduction

Until the end of the twentieth century, fossil fuel dominated electricity generation, with electrical grids being highly centralized. Fossil fuel generators contribute to global warming and climate change via their carbon emissions. The effects of these emissions on the climate and health have hastened the movement towards clean energy [3], with renewable energy generators becoming more prevalent as an alternative to carbon-emitting fossil fuel generators [17, 34].

However, it is challenging to replace fossil fuel generators with renewable energy generators [5, 18]. The direct integration of renewable energy into a conventional energy grid would lead to deviations in frequency and voltage, thus contributing to grid blackouts [26]. Due to the intermittent nature of renewable energy sources [12, 23], power network administrators are hesitant to move away from fossil fuel generators as they fear losing the conventional electrical grid's assurance of grid reliability.

One approach to integrating renewable energy sources into an established, fossil fuel-based electrical grid without losing grid reliability is through the use of energy storage systems (ESSs) [1, 33]. ESSs help to regulate energy supply and demand by storing excess energy produced by renewable energy sources and discharging the stored energy when required *e.g.* when renewable energy sources are unavailable [36]. In addition, adopting ESSs into an electrical grid improves time-shift and demand-side management price savings [28], helps power quality, and minimizes the total loss in the power distribution system [15]. By storing excess energy, the adoption of renewable energy sources can be accelerated without affecting the reliability of the electrical grid [20, 28].

Singapore wants to adopt more renewable energy sources into its electrical grid [9]. However, Singapore faces limited options because of its unique geographic location and topology [28]. Currently, solar photovoltaic generates less than 1% of Singapore's electricity [11] and Singapore aims to deploy at least 2 gigawatt-peak (GWp) of solar energy by 2030 [10]. Considering the intermittent nature of renewable energy sources, ESSs are imperative to Singapore's power network [32]. Unfortunately, not all forms of energy storage technology can be used in Singapore. The selection of appropriate ESSs for a system is a complex, multi-domain and multi-objective problem. With the increasing types of ESS available in the market, it is necessary to develop a systematic framework that facilitates its selection.

Several ontology-based frameworks for energy management have been proposed [4, 21, 22], but they lack the capability to store relevant information in modelling an electrical grid. In particular, [22] presents work similar to this paper – it employs a receding horizon Optimal Power Flow (OPF) to solve an optimization problem for a specified period. The paper considers multiple energy sources and ESSs for stabilising the fluctuations arising from multiple sources and demands. In addition, the work provides an interface between lower-level devices and the application in real-time, which serves as a communication infrastructure that enables grid-wide control. However, this paper does not take into consideration the associated environmental and economic impact. While [22] considered the use of renewable energy as a generation source, similar to [19], it fails to account for the optimal placement of ESSs. Poor placements of ESSs can increase system losses and required battery capacity, leading to higher costs [14].

One approach to utilise real-time and multi-domain data for energy management is The World Avatar (TWA) project. TWA is a dynamic knowledge graph based on the Semantic Web and its associated technologies, with intelligent agents operating on it [16, 37]. The agents act autonomously to update and extend TWA, and thus it evolves in time [37]. TWA also provides the ability to consider different scenarios, referred to as parallel worlds [8], allowing for scenario analysis without mutual interference. Therefore, integrating the ESS selection framework introduced by [19] into TWA will leverage the benefits of Semantic Web technologies, real-time data and automation in the context of a decision support tool that facilitates the selection and placement of ESSs. To achieve this, an extension of the ontology introduced in [6], and transformation of the ESS selection framework into agents are needed.

The **purpose of this paper** is to illustrate how a dynamic knowledge graph approach in the context of TWA can support and augment the ESS selection framework introduced by [19] to facilitate the selection and placement of ESSs.

The paper is structured as follows. Section 2 summarizes the main ideas of TWA and the ESS selection framework. Section 3 presents the proposed extension of the domain ontology OntoPowSys [6]. Section 4 describes the implementation details of integrating the ESS selection framework into TWA. A use case is introduced to demonstrate the application of this approach. Conclusions are discussed in Section 5.

2 Background

TWA is a dynamic knowledge graph that aims to represent every aspect of the real world in a digital "avatar" world. Besides data representation, TWA also contains agents that act autonomously and operate on the knowledge graph [37]. The following sub-sections will describe the various technologies, concepts and features employed in TWA.

2.1 Knowledge graph

A knowledge graph is a directed graph, with relationships expressed as edges, and concepts as nodes. By making use of the principles of Linked Data, knowledge graphs allow information to be hosted across multiple pieces of hardware, hence addressing potential scalability issues. As knowledge graphs store the relationships between entities, the nodes are inherently indexed and the traversal of a knowledge graph is highly efficient. Consequently, knowledge graphs are best suited for multi-scale and multi-domain systems, such as energy systems. By describing information semantically in a knowledge graph, the information silos that typically exist across different domains and scales can be broken down *i.e.* increasing their interoperability. Search algorithms can also be applied to the knowledge graph to facilitate question answering [30, 31]. Moreover, inference engines such as HermiT [29] can operate on data expressed using ontologies to reason about existing knowledge and infer new knowledge.

2.2 Ontologies

Semantic data heterogeneity has been identified as one of the major bottlenecks for data integration. Semantic Web technologies can support the integration, especially when complex mappings between data sources are required. Ontologies form the core of Semantic Web technologies; they describe and incorporate data as instances of concepts. Instances can be linked to each other by reusing the relations defined on the concept level. The ability of concepts and instances from different ontologies to be linked enables cross-domain applications. Numerous ontology languages have been developed and most of them are based on Extensible Markup Language (XML) which enables them to be machine-interpretable. Notable examples are the Resource Description Framework (RDF) and RDF Schema, the DARPA Agent Markup Language (DAML), the Ontology Inference Layer (OIL), the Web Ontology Language (OWL) and OWL2 [24].

2.3 Agents in the knowledge graph

Besides data representation, TWA also contains software agents that act autonomously and operate on the knowledge graph. TWA refers to "agents" as applications and services that utilise Semantic Web technologies to operate on the knowledge graph to fulfil certain objectives. TWA connects data and agents to create a living digital "avatar" of the real world in the sense that some agents will incorporate real-time data such that the digital world remains up to date.

TWA contains different types of agents. An *ad-hoc* classification distinguishes them between I/O agents and Type 1 to Type 4 agents. I/O agents operate on the real-world boundary of the knowledge graph and facilitate information exchange via input (from users or sensors) or output actions (*e.g.* visualisation or controlling actuators). Type 1 agents modify elements at the instance-level of the knowledge graph (*e.g.* through simulation) and/or query the knowledge graph, while Type 2 agents add and/or remove elements at the same level. Type 3 agents facilitate the integration of vocabularies and knowledge into the knowledge graph. Type 4 agents provide services for agent discovery and composition to create new composite agents. Agents themselves are part of the knowledge graph and are described by an agent ontology [37]. More details on the various types of agents can be found in references [8] and [7].

2.4 Scenario management

Beyond representing the real world in a digital "avatar" world, TWA also contains a "parallel world" framework that provides the ability to consider different scenarios, referred to as parallel worlds. In TWA, the portions of the knowledge graph that describe real-world entities, such as sensors or buildings, are defined as the "Base World" layer. This layer reflects the current state of our world and is connected to various real-time data sources. Parallel worlds are constructed based on the base world and remain connected to it. The parallel world framework keeps agents involved in the same scenario together and delegates their operations to scenario-specific portions of the knowledge graph. The unique feature of this framework is that the scenario-specific portions only overshadow the portions of the base world where modifications are necessary. Unchanged entities remain connected to the base world. This design allows agents involved in the same scenario to share the same view on data as other agents operating on the knowledge graph, and operate on the knowledge graph without interfering with other agents or affecting the base world. More details on the parallel world framework can be found in reference [8].

2.5 Energy storage system selection framework

The ESS selection framework introduced in [19] has been adapted for integration into TWA. The objective of the framework is to recommend optimal energy storage technology based on a variety of factors, such as technical constraints posed by the energy storage technology, technical maturity, capital and operating costs, environmental performance *etc*. From a technical aspect, the rated power and discharge duration are considered as the dominant criteria for selecting ESS, acting as constraints for the assessment of technical suitability. In addition, other technical factors such as the maturity and popularity of choice of the ESS are also considered in defining the objective function. From an economic aspect, the levelized cost of electricity is used to evaluate the economic performance of ESSs. The main cost components of this analysis include total capital expenditure (*e.g.* cost of purchase, installation, and delivery of the ESSs), operational and maintenance costs, and disposal and recycling costs for the ESSs, as well as replacement costs for replaceable ESSs. Environmental criteria based on the Life Cycle Analysis study conducted by [25] are used to evaluate the environmental impact of the ESSs.

By considering these objectives and constraints, a model is implemented in General Algebraic Modeling System (GAMS) as a multi-objective mixed integer programming (MOMIP) problem. More details on the optimisation model and ESS selection framework can be found in reference [19]. As the selection of optimal ESS is a multi-domain problem, automation of the work in [19] can benefit from the cross-domain interoperability offered by TWA.

3 Extension of ontology

To describe and instantiate the relevant ESSs considered in [19] in TWA, the OntoPowSys ontology [6] has to be extended. This section describes the extension using Description Logic (DL) syntax.

ESS is modelled as a type of electrical equipment as represented in Axiom 1 of Table 1. Energy storage technologies can generally be classified under five categories based on the form in which energy is stored: mechanical, thermal, chemical, electrical and electrochemical. Pumped hydroelectricity storage and compressed air energy storage, as represented by Axioms 16 – 17, are mature technologies that have dominated the large-scale energy storage market [35]. They are examples of mechanical storage technologies with the former storing energy in the form of water at high gravitational potential and the latter in compressed air held under pressure. However, pumped hydroelectricity storage is limited to geographic areas with height variations and large water bodies, whereas compressed air energy storage requires underground caverns or specifically built pressure vessels [13, 36]. Flywheel energy storage, as represented by Axiom 18, is also a type of mechanical energy storage which stores energy in the form of rotating discs or cylinders and is mostly used for short-duration applications. Thermal energy storage (Axiom 15) stores energy as heat and produces steam or gas for a conventional thermal power plant. Hydrogen and synthetic natural gas (Axioms 13 – 14) are examples of chemical storage. Superconducting magnetic energy storage (Axiom 12) stores energy in the magnetic field of a coil.

Battery Energy Storage System (BESS) has become increasingly viable [28] as energy storage for a conventional electrical grid. Batteries are an electrochemical form of energy storage (Axiom 2). The OntoPowSys ontology [6] is extended to include new types of batteries described in [19] (Axioms 3 – 9). BESSs are more scalable and flexible than other storage technologies [2], and hence have become more common in standard electrical grids that are adopting renewable energy generators.

Table 1: *Selected concept inclusion axioms related to ESSs in the OntoPowSys knowledge base.*

S.No	DLs concept inclusion axioms
1	EnergyStorageSystem $\sqsubseteq$ ElectricalEquipment
2	Battery $\sqsubseteq$ EnergyStorageSystem
3	BlueBattery $\sqsubseteq$ Battery
4	PolySulphideBromideBattery $\sqsubseteq$ Battery
5	Powerwall2Battery $\sqsubseteq$ Battery
6	SodiumNickelChlorideBattery $\sqsubseteq$ Battery
7	SodiumSulphurBattery $\sqsubseteq$ Battery
8	VanadiumRedoxBattery $\sqsubseteq$ Battery
9	ZincBromideBattery $\sqsubseteq$ Battery
10	LeadAcidBattery $\sqsubseteq$ Battery
11	NickelCadmiumBattery $\sqsubseteq$ Battery
12	SuperconductingMagneticEnergy $\sqsubseteq$ EnergyStorageSystem
13	HydrogenStorage $\sqsubseteq$ EnergyStorageSystem
14	SyntheticNaturalGas $\sqsubseteq$ EnergyStorageSystem
15	ThermalEnergyStorage $\sqsubseteq$ EnergyStorageSystem
16	PumpHydro $\sqsubseteq$ EnergyStorageSystem
17	CompressedAir $\sqsubseteq$ EnergyStorageSystem

18	$\mathrm{FlyWheel} \sqsubseteq \mathrm{EnergyStorageSystem}$

Table 2 lists selected Role Inclusion (RI) axioms that depict the properties added to the OntoPowSys ontology for ESSs. Axioms $1-7$ describe the technical aspects of ESSs while Axioms $8-9$ describe the economic aspects of ESSs.

Table 2: *Selected role inclusion axioms related to ESSs in the OntoPowSys knowledge base.*

S.No	DLs role inclusion axioms
1	$EnergyStorageSystem \sqsubseteq \forall hasRatedDischargePower.RatedDischargePower$
2	$EnergyStorageSystem \sqsubseteq \forall hasRatedEnergyCapacity.RatedEnergyCapacity$
3	$EnergyStorageSystem \sqsubseteq \forall hasRatedFrequency.RatedFrequency$
4	$EnergyStorageSystem \sqsubseteq \forall hasRatedVoltage.RatedVoltage$
5	$EnergyStorageSystem \sqsubseteq \forall hasReactivePowerGenerated.GeneratedReactivePower$
6	$EnergyStorageSystem \sqsubseteq \forall hasRoundTripEfficiency.RoundTripEfficiency$
7	$EnergyStorageSystem \sqsubseteq \forall hasStateOfCharge.StateOfCharge$
8	$EnergyStorageSystem \sqsubseteq \neg \exists hasShutdownCost.ShutdownCosts$
9	$EnergyStorageSystem \sqsubseteq \neg \exists hasStartupCost.StartupCosts$
10	$EnergyStorageSystem \sqsubseteq \forall realizes.(PowerConsumption \sqcup PowerGeneration)$

4 Energy Storage System: a knowledge graph approach

This section describes the implementation details of integrating the ESS selection framework [19] and optimal placement of the selected ESS in TWA. A use case is introduced using the parallel world framework [8] to demonstrate the application of this approach.

4.1 Parallel world framework in the knowledge graph

Figure 1 illustrates the key concepts employed in TWA. The "Physical World" layer represents our world and is the basis upon which the other layers are generated. As mentioned in Section 2, TWA represents and models various aspects and behaviours of the real world in a digital "avatar" world, referred to as the "Base World" layer in Figure 1. The "Parallel World" layers are constructed based on the "Base World" layer and remain connected to it. Each parallel world in TWA is identified by a unique scenario identifier that agents can utilise when interacting with the scenario-specific portions of the knowledge graph. As the parallel worlds are connected to the base world – for entities that are

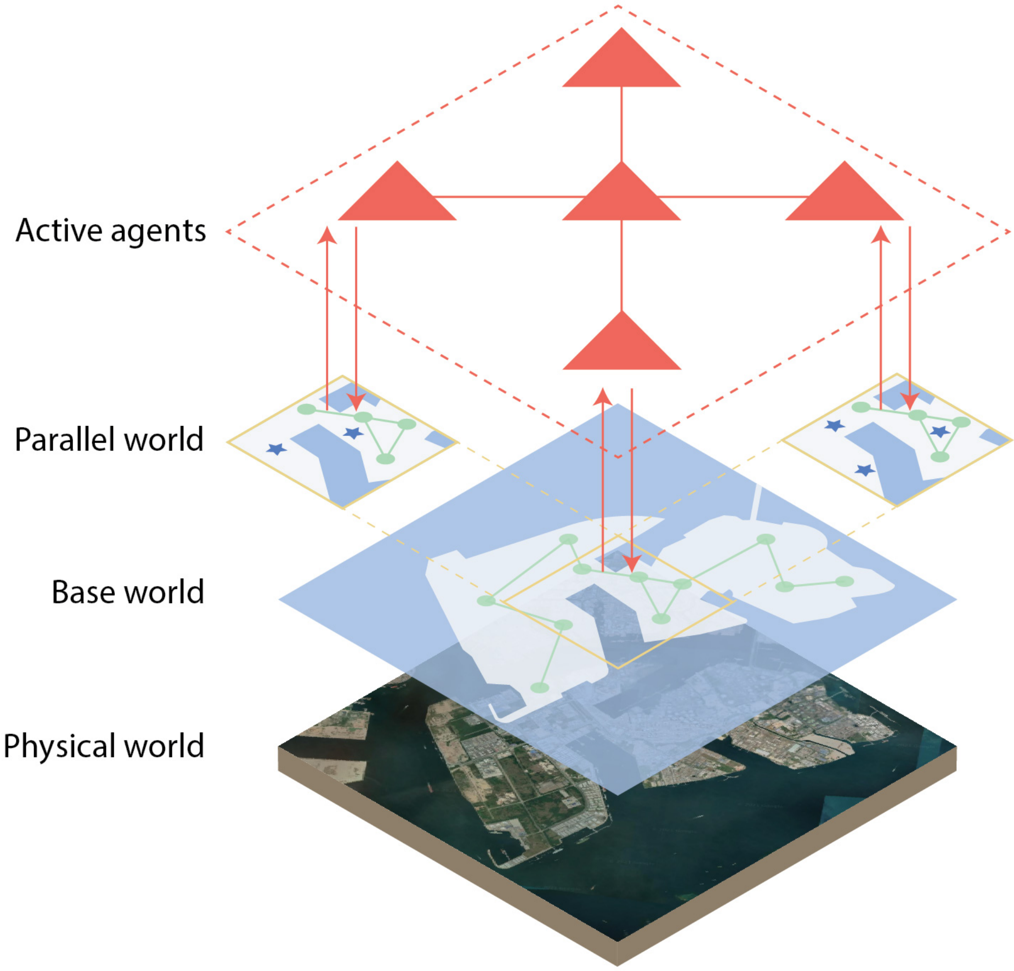


Figure 1: *The main concepts employed in TWA. The base world, a digital "avatar" of the physical world, is represented by the blue layer. The parallel worlds are constructed from sections of the base world and remain connected to it. The active agents (represented by red triangles) can operate on the base world or the parallel worlds. Agents can operate in a unique parallel world without interfering with other parallel worlds or affecting the base world. As the parallel worlds are connected to the base world – for entities that are unchanged by the parallel world, modifications in the base world will be reflected in the parallel worlds for these portions.*

unchanged by the parallel world, modifications in the base world will be reflected in the parallel worlds for these portions. The parallel world framework keeps agents involved in the same scenario together and delegates their operations to scenario-specific portions of the knowledge graph (via the unique scenario identifier), allowing agents to operate on the knowledge graph without interfering with other agents or affecting the base world. Agents in TWA toggle between operating on the base world and the parallel worlds by using the unique scenario identifier within the *JPSContext*. *JPSContext*, scenario-specific metadata, is propagated amongst the agents involved in the same scenario.

4.2 Application of parallel world framework for ESS

This sub-section introduces a use case to demonstrate the application of the parallel world framework (outlined in Section 4.1) to facilitate scenario analysis in TWA. The ESS selection framework and optimal placement of the selected ESS (outlined in Section 2.5) are employed for this purpose.

Table 3 lists some of the Abox assertions that depict this use case – the addition of BESS to the Singapore Jurong Island electrical network. Axiom 1 in Table 3 instantiates the BESS $VRB - 004$. Axioms $2 - 11$ describe how the BESS's active power is represented in TWA. Axioms $12 - 16$ describe how the state of charge is linked to the BESS. Axioms $17 - 20$ describe the number of cells within the BESS. Axioms $21 - 24$ represent the negative environmental impact of placing the BESS, while Axioms $25 - 28$ represent its economic costs.

Table 3: *Abox assertions for the use case example.*

S.No	Individual assertions
1	VanadiumRedoxBattery(VRB-004)
2	MaxActivePower(MAPVRB-004)
3	hasMaximumActivePowerGenerated(VRB-004, MAPVRB-004)
4	hasValue(MAPVRB-004, V-MAPVRB-004)
5	numericalValue(V-MAPVRB-004, 3)
6	hasUnitOfMeasure(V-MAPVRB-004, MW)
7	MinActivePower(MnAPVRB-004)
8	hasMinimumActivePowerGenerated(VRB-004, MnAPVRB-004)
9	hasValue(MnAPVRB-004, V-MnAPVRB-004)
10	numericalValue(V-MnAPVRB-004, 0.03)
11	hasUnitOfMeasure(V-MnAPVRB-004, MW)
12	StateOfCharge(DTVRB-004)

Continued on next page

Table 3 – continued from previous page

S.No	Individual assertions
13	hasStateOfCharge(VRB-004, DTVRB-004)
14	hasValue(DTVRB-004, V-DTVRB-004)
15	upperLimit(V-DTVRB-004, 10)
16	lowerLimit(V-DTVRB-004, 0.00028)
17	NumberOfCells(NVRB-004)
18	hasNumberOfCells(VRB-004, NVRB-004)
19	hasValue(NVRB-004, V-NVRB-004)
20	numericalValue(V-NVRB-004, 61)
21	EnvironmentalFactor(MC-VRB-004)
22	hasProperty(VRB-004, MC-VRB-004)
23	hasValue(MC-VRB-004, V-MC-VRB-004)
24	numericalValue(V-MC-VRB-004, 0.01)
25	CostsForSystemsRealization(EC-VRB-004)
26	hasCost(VRB-004, EC-VRB-004)
27	hasValue(EC-VRB-004, V-EC-VRB-004)
28	numericalValue(V-EC-VRB-004, 0.849387149)
29	ActivePowerBalance(API-VRB-004)
30	hasActivePowerInjection(VRB-004, API-VRB-004)
31	hasValue(API-VRB-004, V-API-VRB-004)
32	numericalValue(V-API-VRB-004, 1.0753182590822234)
33	hasUnitOfMeasure(V-API-VRB-004, MW)

Figure 2 illustrates in a UML sequence diagram how the various agents involved in the use case are integrated into TWA, *i.e.* how they communicate with each other and interact with the knowledge graph. The use case is initiated by calling the coordination agent via a scenario modifier agent (not shown in Figure 2). The scenario modifier agent generates a unique scenario identifier based on the agent that is being called. This unique scenario identifier, as described in Section 4.1, is one of the input parameters being sent to the scenario agent. The scenario agent will then call the coordination agent. By calling agents in TWA with a unique scenario identifier, the *JPSContext* (described in Section 4.1) toggles from the default base world to the scenario-specific parallel world named after the unique scenario identifier. The *JPSContext* is propagated amongst all the agents throughout the parallel world framework to keep agents involved in the same scenario together and delegate their operations to scenario-specific portions of the knowledge graph.

The coordination agent handles the overall service composition and ensures relevant agents are called in the correct sequential order. The coordination agent first calls the renewable generator retrofit agent whose task is to connect selected renewable energy generator(s) to a specified conventional electrical network. To achieve this, the agent receives its inputs – the specified conventional electrical network and selected renewable energy generator(s) in the form of Internationalized Resource Identifiers (IRIs). The agent determines the nearest electric bus to the selected renewable energy generator by querying and retrieving information from the knowledge graph using the given IRIs. The agent then connects the generator to the nearest electric bus. The connectivity between the renewable energy generator and the electrical network is established by adding relationships between the electric bus, renewable energy generator, and electrical network in the scenario-specific portions of the knowledge graph. The agent does not return any output and terminates upon modifying the knowledge graph. In this use case, we have chosen the photovoltaic generator located in Singapore Semakau Island and the electrical network in Singapore Jurong Island [27].

The coordination agent then calls the energy storage selection agent. The energy storage selection agent is created by packaging the ESS selection framework proposed by [19] (described in Section 2.5) as an agent that can apply the Semantic Web stack to interact with the knowledge graph. The energy storage selection agent determines the optimal energy storage technology based on the properties of the specified electrical network and energy storage technology catalogue. Similarly, the agent queries and retrieves relevant information from the knowledge graph using the given IRIs (electrical network and energy storage technology catalogue). Such information includes electrical network topology, environmental cost, technical cost, and economic cost associated with each type of ESS. The agent returns the IRI of the selected type of ESS. For this use case, the energy storage selection agent chose vanadium redox battery, a form of electrochemical energy storage, as the optimal energy storage technology for Jurong Island's electrical network.

The coordination agent then calls the energy storage placement agent to recommend a suitable agent for creating and placing the chosen type of ESS. For this use case, as the recommended ESS is a type of BESS, the battery creation coordination agent is selected and its IRI is returned by the energy storage placement agent to the coordination agent.

The coordination agent then calls the battery creation coordination agent, whose task is to coordinate the creation and placement of BESS. The inputs to the battery creation coordination agent are the IRIs of the specified electrical network, and the selected type of BESS *i.e.* vanadium redox battery in this use case.

The battery creation coordination agent first calls the EN agent with the IRI of the specified electrical network to execute an optimal power flow (OPF) model to optimise the power flow throughout the given electrical network. Initially, the EN agent queries and retrieves information about the specified electrical network *e.g.* power generation and consumption, from the knowledge graph using the given IRI. Subsequently, the EN agent runs the OPF model and then updates the scenario-specific portions of the knowledge graph with the converged simulation results. More details on the EN agent can be found in reference [8].

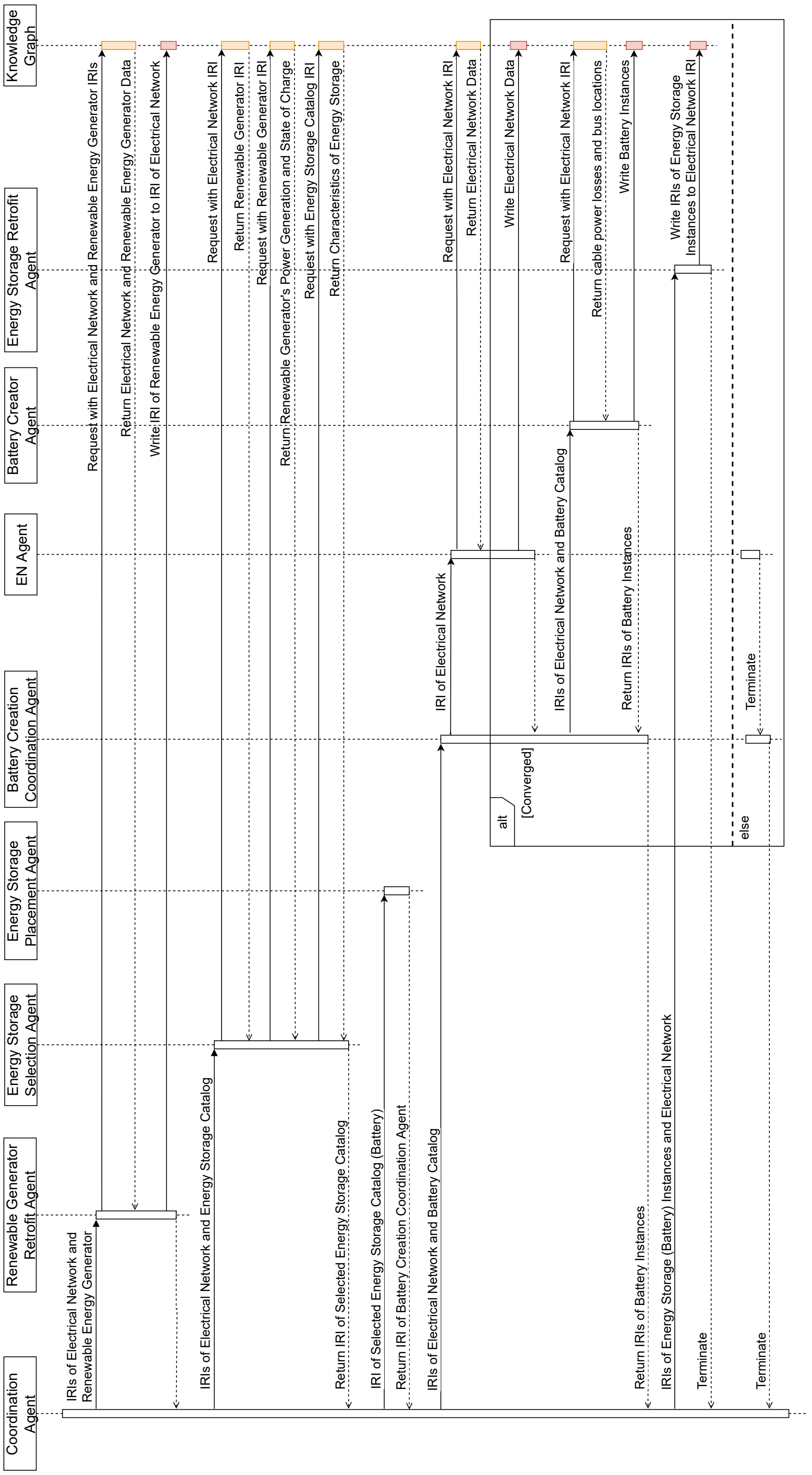


Figure 2: *UML sequence diagram of the use case depicting the interactions between the different agents and the knowledge graph. Actions where the agent retrieves data from the knowledge graph are shaded in yellow and those where the agent populates the knowledge graph are shaded in magenta.*

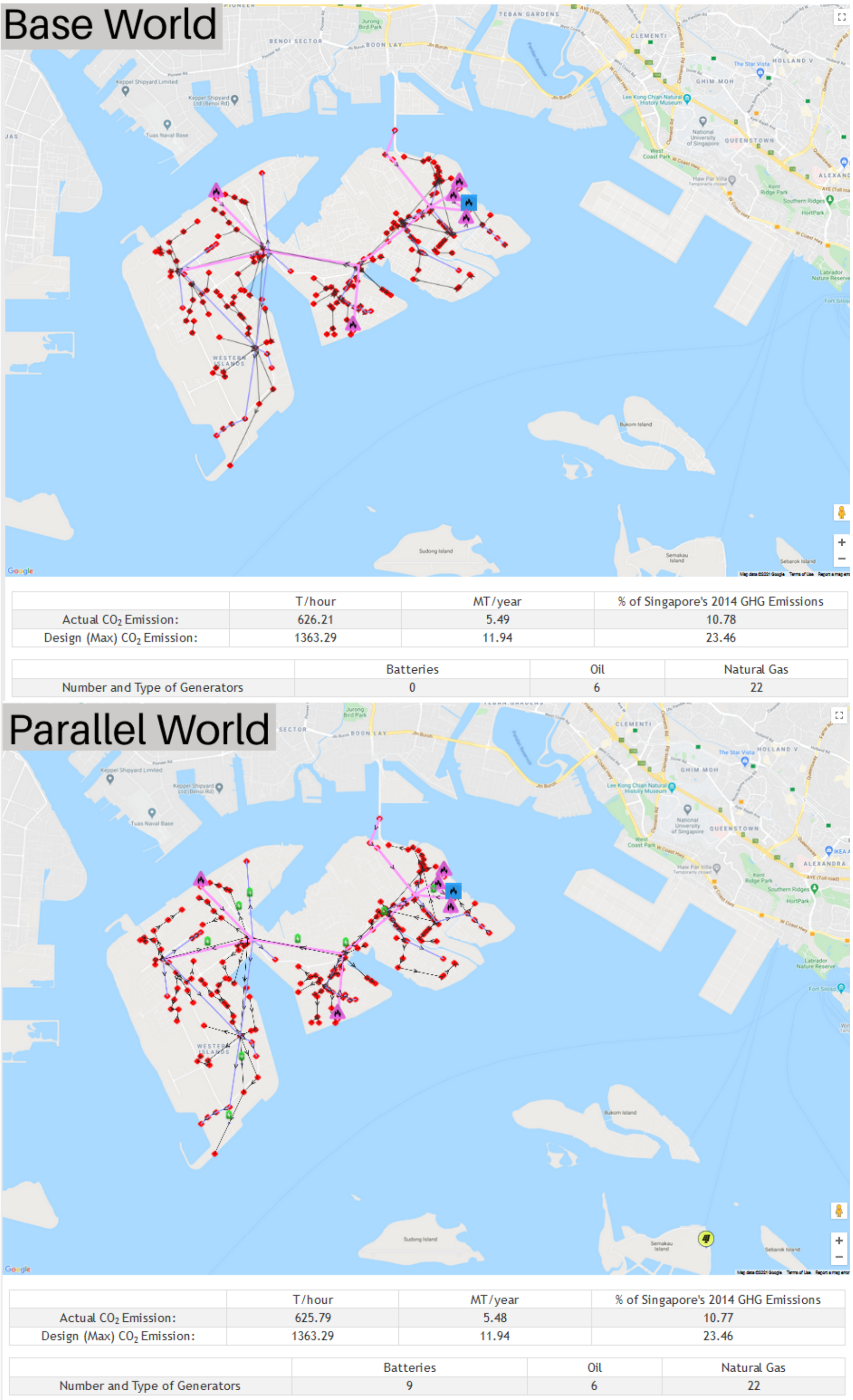
The battery creation coordination agent then calls the battery creator agent, which creates the BESS instances in the knowledge graph. Similarly, the battery creator agent queries and retrieves information about the specified electrical network *e.g.* power losses and energy storage technology from the knowledge graph using the given IRIs (electrical network and energy storage technology catalogue). Subsequently, the battery creator agent utilises the loss sensitivity index of each electric bus to determine the placement of the BESS. Voltage limit violation at each electric bus is also utilised by the battery creator agent to determine the capacity of each BESS. The battery creator agent then creates the BESS instances accordingly in the scenario-specific portions of the knowledge graph and returns a list of IRIs of the BESS instances to the battery creation coordination agent. For our use case, the number of BESS instances can vary between 7 to 9. The battery creation coordination agent passes this list of IRIs to the main coordination agent.

The main coordination agent calls the energy storage retrofit agent whose task is to connect the BESS to the specified electrical network. To achieve this, the energy storage retrofit agent receives its inputs – the specified electrical network and a list of the BESS instances in the form of IRIs. The agent then connects the BESS instances to the electrical network by adding relationships between them in the scenario-specific portions of the knowledge graph. The agent does not return any output and terminates upon modifying the knowledge graph.

A front-end visualisation agent, ENVisualization agent (not shown in Figure 2) utilises the unique scenario identifier to query and retrieve information about the scenario-specific portions of the knowledge graph to generate visualisation for the parallel world *i.e.* retrofitted electrical network.

Figure 3 illustrates both the base world (above) and parallel world (below) of the Singapore Jurong Island electrical network model. The coloured lines represent the transmission lines in the electrical network that connect electric buses which are represented by the red points. Different coloured transmission lines represent different voltage levels: pink represents 230 kV, purple represents 66 kV and black represents 22 kV. The blue square denotes an oil-based power plant while the pink triangles denote gas-based power plants. BESSs are represented as green batteries in the visualisation. The corresponding types and number of generators, as well as BESSs and estimated CO_2 emissions (tonnes per hour and mega-tonnes per year), are indicated in the tables. Note that the estimated values for the design or maximum CO_2 emissions are the same for both worlds as the types and number of carbon-emitting fossil fuel generators (oil and gas) remain the same. The addition of 9 BESSs in the parallel world enables the integration of renewable energy generated by solar photovoltaic, hence leading to a reduction in the estimated actual or operating CO_2 emissions. The CO_2 emissions reduction is small as the line losses are small in the Singapore Jurong Island electrical network. By exploring different algorithms for selecting and placing ESS, different CO_2 emissions reduction potential can be investigated.

Upon clicking on the entities in the electrical network *e.g.* electric bus, transmission line *etc.*, a pop-up window (as shown in Figure 4) containing information about the selected component will appear. As the parallel world has real-time connections to the base world, modifications in the base world will be reflected in the parallel world for these portions. Due to the application of the parallel world framework, the agents described in this use



Base World

	T/hour	MT/year	% of Singapore's 2014 GHG Emissions
Actual CO_2 Emission:	626.21	5.49	10.78
Design (Max) CO_2 Emission:	1363.29	11.94	23.46

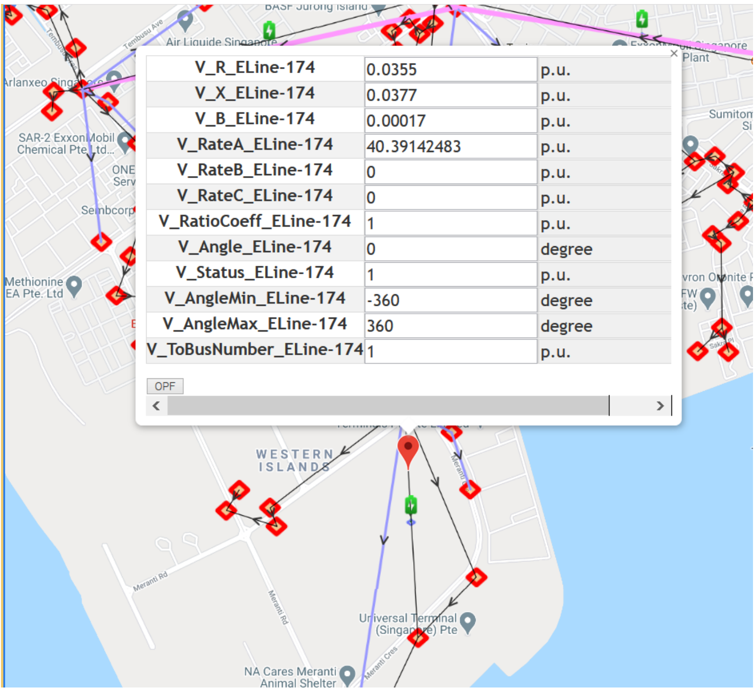
	Batteries	Oil	Natural Gas
Number and Type of Generators	0	6	22

Parallel World

	T/hour	MT/year	% of Singapore's 2014 GHG Emissions
Actual CO_2 Emission:	625.79	5.48	10.77
Design (Max) CO_2 Emission:	1363.29	11.94	23.46

	Batteries	Oil	Natural Gas
Number and Type of Generators	9	6	22

Figure 3: *Visualisation of the base world (above) and parallel world (below) of the Singapore Jurong Island electrical network model. The coloured lines represent the transmission lines that connect electric buses which are represented by the red points. The blue square denotes oil-based power plants while the pink triangles denote gas-based power plants. BESSs are represented as green batteries in the visualisation. The corresponding types and number of generators, as well as BESSs and estimated CO_2 emissions, are stated in the tables.*



V_R_ELine-174	0.0355	p.u.
V_X_ELine-174	0.0377	p.u.
V_B_ELine-174	0.00017	p.u.
V_RateA_ELine-174	40.39142483	p.u.
V_RateB_ELine-174	0	p.u.
V_RateC_ELine-174	0	p.u.
V_RatioCoeff_ELine-174	1	p.u.
V_Angle_ELine-174	0	degree
V_Status_ELine-174	1	p.u.
V_AngleMin_ELine-174	-360	degree
V_AngleMax_ELine-174	360	degree
V_ToBusNumber_ELine-174	1	p.u.

Figure 4: *A pop-up window within the visualisation containing information about the selected component (transmission line).*

case only modify the parallel world. Therefore, a comparison can be made between the base world and the parallel world to facilitate scenario analysis.

5 Conclusions

This paper illustrates how a dynamic knowledge graph approach in the context of TWA can support the decarbonisation of energy systems by leveraging the ESS selection framework introduced by [19] to assist in the selection and optimal placement of ESS. In particular, the paper presents the proposed extension of the domain ontology, OntoPowSys, for describing and instantiating the relevant entities considered in the use case – the addition of BESSs to the Singapore Jurong Island electrical network. TWA increases the interoperability between data (static and real-time) from different domains, allowing for knowledge sharing and to cope with heterogeneity encountered in this use case. It is also highlighted in the use case how the parallel world framework [8] can consider different scenarios and hence facilitate scenario analysis.

There is still more work and improvements to be made in order to advance and further leverage the potential of TWA concepts. For example, extending the knowledge graph to model and describe different domains in more detail, *e.g.* economic performance and environmental costs. Increasing the knowledge graph's connectivity to physical energy systems (via sensors and actuators) in the future will allow feedback to the framework. Nevertheless, TWA has the potential to address and overcome the challenge of low interoperability between multiple domains involved in decarbonisation processes, contributing to CO_2 abatement.

Acknowledgements

This research is supported by the National Research Foundation (NRF), Prime Minister's Office, Singapore under its Campus for Research Excellence and Technological Enterprise (CREATE) programme. Markus Kraft gratefully acknowledges the support of the Alexander von Humboldt foundation.

List of abbreviations

BESS	**B**attery **E**nergy **S**torage **S**ystem
CI	**C**oncept **I**nclusion
DAML	**D**ARPA **A**gent **M**arkup **L**anguage
DL	**D**escription **L**ogic
ESS	**E**nergy **S**torage **S**ystem
GAMS	**G**eneral **A**lgebraic **M**odeling **S**ystem
HTTP	**H**yper**t**ext **T**ransfer **P**rotocol
IRI	**I**nternationalized **R**esource **I**dentifier
JPS	**J**-**P**ark **S**imulator
KB	**K**nowledge **B**ase
MOMIP	**M**ulti-**O**bjective **M**ixed **I**nteger **P**rogramming
OIL	**O**ntology **I**nference **L**ayer
OPF	**O**ptimal **P**ower **F**low
OWL	**W**eb **O**ntology **L**anguage
RDF	**R**esource **D**escription **F**ramework
RI	**R**ole **I**nclusion
TWA	**T**he **W**orld **A**vatar
XML	E**x**tensible **M**arkup **L**anguage

6 Appendix

List of Agents

Coordination Agent

- Inputs:
  - ‘Electrical Network’ (e.g. "http://www.jparksimulator.com/kb/sgp/jurongisland/jurongislandpowernetwork/JurongIslandPowerNetwork.owl#JurongIsland _PowerNetwork")
  - ‘Renewable Energy Generator’ (e.g. "http://www.theworldavatar.com/kb/sgp /semakauisland/semakauelectricalnetwork/PV-001.owl #PV-001")
  - ‘Energy Storage Technology Catalogue’ (e.g. "http://www.theworldavatar.com/kb/batterycatalog/BatteryCatalog.owl#BatteryCatalog")
- Outputs:
  - void

Renewable Generator Retrofit Agent

- Inputs:
  - ‘Electrical Network’
  - ‘Renewable Energy Generator’
- Outputs:
  - void

Energy Storage Selection Agent

- Inputs:
  - ‘Electrical Network’
  - ‘Energy Storage Technology Catalogue’
- Outputs:
  - ‘Energy Storage Technology’ (e.g. http://www.jparksimulator.com/kb/batterycatalog/VRB.owl)

Energy Storage Placement Agent

- Inputs:

  - ‘Energy Storage Technology’
- Outputs:
  - ‘Battery Creation Coordination Agent’

Battery Creation Coordination Agent

- Inputs:
  - ‘Electrical Network’
  - ‘Battery Catalogue’
- Outputs:
  - ‘Battery Instances’ (e.g. http://www.jparksimulator.com/jps/kb/<unique scenario identifier>/sgp/jurongisland/jurongislandpowernetwork/VRB-004.owl,...)

EN Agent

- Inputs:
  - ‘Electrical Network’
- Outputs:
  - void

Battery Creator Agent

- Inputs:
  - ‘Electrical Network’
  - ‘Battery Catalogue’
- Outputs:
  - ‘Battery Instances’

Energy Storage Retrofit Agent

- Inputs:
  - ‘Electrical Network’
  - ‘Battery Instances’
- Outputs:
  - void

EN Visualization Agent

- Inputs:
  - ‘Electrical Network’
- Outputs:
  - void

References

[1] W. A. Braff, J. M. Mueller, and J. E. Trancik. Value of storage technologies for wind and solar energy. *Nature Climate Change*, 6:964–969, 2016. doi:10.1038/nclimate3045.

[2] M. Bulut and E. Ozcan. A novel approach towards evaluation of joint technology performances of battery energy storage system in a fuzzy environment. *Journal of Energy Storage*, 36:102361, 2021. doi:10.1016/j.est.2021.102361.

[3] J. J. Buonocore, E. J. Hughes, D. R. Michanowicz, J. Heo, J. G. Allen, and A. Williams. Climate and health benefits of increasing renewable energy deployment in the United States. *Environmental Research Letters*, 14:114010, 2019. doi:10.1088/1748-9326/ab49bc.

[4] A. Daouadji, K. Nguyen, M. Lemay, and M. Cheriet. Ontology-Based Resource Description and Discovery Framework for Low Carbon Grid Networks. In *2010 First IEEE International Conference on Smart Grid Communications*, page 477–482, 2010. doi:10.1109/SMARTGRID.2010.5622090.

[5] M. Davis, A. Moronkeji, M. Ahiduzzaman, and A. Kumar. Assessment of renewable energy transition pathways for a fossil fuel-dependent electricity-producing jurisdiction. *Energy for Sustainable Development*, 59:243–261, 2020. doi:10.1016/j.esd.2020.10.011.

[6] A. Devanand, G. Karmakar, N. Krdzavac, R. Rigo-Mariani, Y. Foo Eddy, I. A. Karimi, and M. Kraft. OntoPowSys: A power system ontology for cross domain interactions in an eco industrial park. *Energy and AI*, 1:100008, 2020. doi:10.1016/j.egyai.2020.100008.

[7] A. Eibeck, M. Q. Lim, and M. Kraft. J-Park Simulator: An ontology-based platform for cross-domain scenarios in process industry. *Computers & Chemical Engineering*, 131:106586, 2019. doi:10.1016/j.compchemeng.2019.106586.

[8] A. Eibeck, A. Chadzynski, M. Q. Lim, K. Aditya, L. Ong, A. Devanand, G. Karmakar, S. Mosbach, R. Lau, I. A. Karimi, E. Y. S. Foo, and M. Kraft. A Parallel World Framework for scenario analysis in knowledge graphs. *Data-Centric Engineering*, 1:e6, 2020. doi:10.1017/dce.2020.6.

[9] Energy Market Authority. The Future of Singapore's Energy Story | EMA Singapore, 2021. URL `https://www.ema.gov.sg/ourenergystory?utm_source=facebook&utm_medium=post&utm_campaign=Life247&utm_term=ABCs&utm_content=C`. Accessed on 2021-06-15.

[10] Energy Market Authority (EMA). Solar Photovoltaic Systems, 2020. URL `https://www.ema.gov.sg/Solar_Photovoltaic_Systems.aspx`. Accessed on 2021-06-15.

[11] Energy Market Authority (EMA). Plant Mix for Generation, 2021. URL https://www.ema.gov.sg/cmsmedia/Publications_and_Statistics/Statistics/Monthly%20data/Plant-mix.pdf. Accessed on 2021-06-15.

[12] R. Fares. Renewable Energy Intermittency Explained: Challenges, Solutions, and Opportunities - Scientific American Blog Network, 2015. URL https://blogs.scientificamerican.com/plugged-in/renewable-energy-intermittency-explained-challenges-solutions-and-opportunities/. Accessed on 2021-06-15.

[13] C. Guo, C. Li, K. Zhang, Z. Cai, T. Ma, F. Maggi, Y. Gan, A. El-Zein, Z. Pan, and L. Shen. The promise and challenges of utility-scale compressed air energy storage in aquifers. *Applied Energy*, 286:116513, 2021. doi:10.1016/j.apenergy.2021.116513.

[14] S. B. Karanki and D. Xu. Optimal capacity and placement of battery energy storage systems for integrating renewable energy sources in distribution system. In *2016 National Power Systems Conference (NPSC)*, page 1–6, 2016. doi:10.1109/NPSC.2016.7858983.

[15] B. Khaki. Joint sizing and placement of battery energy storage systems and wind turbines considering reactive power support of the system. *Journal of Energy Storage*, 35:102264, 2021. doi:10.1016/j.est.2021.102264.

[16] M. J. Kleinelanghorst, L. Zhou, J. Sikorski, E. F. Y. Shyh, K. Aditya, S. Mosbach, I. Karimi, R. Lau, and M. Kraft. J-Park Simulator: Roadmap to Smart Eco-Industrial Parks. In *Proceedings of the Second International Conference on Internet of Things, Data and Cloud Computing*, page 10, 2017. doi:10.1145/3018896.3025155.

[17] T. Kåberger. Progress of renewable electricity replacing fossil fuels. *Global Energy Interconnection*, 1:48–52, 2018. doi:10.14171/j.2096-5117.gei.2018.01.006.

[18] M. D. Leonard, E. E. Michaelides, and D. N. Michaelides. Energy storage needs for the substitution of fossil fuel power plants with renewables. *Renewable Energy*, 145:951–962, 2020. doi:10.1016/j.renene.2019.06.066.

[19] L. Li, P. Liu, Z. Li, and X. Wang. A multi-objective optimization approach for selection of energy storage systems. *Computers and Chemical Engineering*, 115: 213–225, 2018. doi:10.1016/j.compchemeng.2018.04.014.

[20] J. Liu, C. Hu, A. Kimber, and Z. Wang. Uses, Cost-Benefit Analysis, and Markets of Energy Storage Systems for Electric Grid Applications. *Journal of Energy Storage*, 32:101731, 2020. doi:10.1016/j.est.2020.101731.

[21] C. Lork, V. Choudhary, N. UL Hassan, W. Tushar, C. Yuen, B. Ng, X. Wang, and X. Liu. An Ontology-Based Framework for Building Energy Management with IoT. *Electronics*, 8:485, 2019. doi:10.3390/electronics8050485.

[22] A. Maffei, S. Srinivasan, P. Castillejo, J. F. Martínez, L. Iannelli, E. Bjerkan, and L. Glielmo. A Semantic-Middleware-Supported Receding Horizon Optimal Power Flow in Energy Grids. *IEEE Transactions on Industrial Informatics*, 14:35–46, 2018. doi:10.1109/TII.2017.2655047.

[23] J. Mikkola and P. D. Lund. Modeling flexibility and optimal use of existing power plants with large-scale variable renewable power schemes. *Energy*, 112:364–375, 2016. doi:10.1016/j.energy.2016.06.082.

[24] K. Munir and M. S. Anjum. The Use of Ontologies for Effective Knowledge Modelling and Information Retrieval. *Applied Computing and Informatics*, 14:116–126, 2018. doi:10.1016/j.aci.2017.07.003.

[25] L. Oliveira, M. Messagie, J. Mertens, H. Laget, T. Coosemans, and J. Van Mierlo. Environmental performance of electricity storage systems for grid applications, a life cycle approach. *Energy Conversion and Management*, 101:326–335, 2015. doi:10.1016/j.enconman.2015.05.063.

[26] J. Pelley. Climate change will force boost in electrical grid capacity, mostly from renewables, 2021. URL `https://cen.acs.org/environment/climate-change/Climate-change-force-boost-electrical/99/web/2021/02`. Accessed on 2021-06-15.

[27] R. Rigo-Mariani, K. V. Ling, and J. Maciejowski. A clusterized energy management with linearized losses in the presence of multiple types of distributed generation. *International Journal of Electrical Power & Energy Systems*, 113:9–22, 2019. doi:10.1016/j.ijepes.2019.04.049.

[28] S. Somasundram, S. Y. Chiam, and M. C. Lin. Energy Storage Systems Technology Roadmap for Singapore, 2020. URL `https://www.ntu.edu.sg/docs/librariesprovider60/publications/ess-technology-roadmap-singapore.pdf?sfvrsn=c91c9ae8_2`. Accessed on 2021-06-15.

[29] The Knowledge Representation and Reasoning Group. HermiT OWL Reasoner, 2007. URL `http://www.hermit-reasoner.com/index.html`. Accessed on 2021-06-15.

[30] P. Trivedi, G. Maheshwari, M. Dubey, and J. Lehmann. LC-QuAD: A Corpus for Complex Question Answering over Knowledge Graphs. In *The Semantic Web - ISWC 2017*, pages 210–218, 2017.

[31] C. Unger, A. Freitas, and P. Cimiano. *An Introduction to Question Answering over Linked Data*. Springer International Publishing, 2014.

[32] J. Wang, L. Kang, X. Huang, and Y. Liu. An analysis framework for quantitative evaluation of parametric uncertainty in a cooperated energy storage system with multiple energy carriers. *Energy*, 226:120395, 2021. doi:10.1016/j.energy.2021.120395.

[33] Y. Yang, H. Li, A. Aichhorn, J. Zheng, and M. Greenleaf. Sizing Strategy of Distributed Battery Storage System With High Penetration of Photovoltaic for Voltage Regulation and Peak Load Shaving. *IEEE Transactions on Smart Grid*, 5:982–991, 2014. doi:10.1109/TSG.2013.2282504.

[34] R. York and S. E. Bell. Energy transitions or additions?: Why a transition from fossil fuels requires more than the growth of renewable energy. *Energy Research and Social Science*, 51:40–43, 2019. doi:10.1016/j.erss.2019.01.008.

[35] S. Zhang, P. Andrews-Speed, and P. Perera. The evolving policy regime for pumped storage hydroelectricity in China: A key support for low-carbon energy. *Applied Energy*, 150:15–24, 2015. doi:10.1016/j.apenergy.2015.03.103.

[36] X. Zhang, C. C. Qin, Y. Xu, W. Li, X. Zhou, R. Li, Y. Huang, and H. Chen. Integration of small-scale compressed air energy storage with wind generation for flexible household power supply. *Journal of Energy Storage*, 37:102430, 2021. doi:10.1016/j.est.2021.102430.

[37] X. Zhou, A. Eibeck, M. Q. Lim, N. B. Krdzavac, and M. Kraft. An agent composition framework for the J-Park Simulator - A knowledge graph for the process industry. *Computers & Chemical Engineering*, 130:106577, 2019. doi:10.1016/j.compchemeng.2019.106577.