6

Virtual Power Plant

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Abstract

In the context of this chapter the virtual power plant (VPP) is considered as a high level design tool based upon load aggregation of near real-time metered energy demand and generation data at building/apartment levels.

Target users, city planners and utility companies, will be able to use the VPP to gain an understanding of energy demand/generation at user defined and selected levels of interest ranging from high level city planning to the selection of individual buildings or user defined energy networks and so on. 'What if' scenarios aid in future development and planning of cities.

This chapter outlines development and integration of the VPP within the iURBAN ICT architecture. Content is also provided on the VPP; graphical user interface, calculation engine and application via case studies taken from the iURBAN project.

Keywords: Virtual power plant, Central decision support system, iURBAN ICT architecture, City model, High level city planning, Distributed energy resources.

6.1 Introduction

This chapter outlines the development work required for the virtual power plant (VPP) as part of the iURBAN [1] project.

What is a VPP?

There are numerous definitions for a virtual power plant. Below are a few examples:

> *"a VPP is a system that relies upon software and a smart grid to remotely and automatically dispatch and optimize Distributed Energy Resources (DER)s via an aggregation and optimization platform linking retail to wholesale markets."* [2]

> *"a VPP as a system that integrates several types of power sources, (such as micro combined, heat and power (CHP), wind-turbines, small hydro, photovoltaics (PV), back-up generators, batteries etc.) so as to give a reliable overall power supply."* [3]

Further definitions can be found at [4, 5].

It is reported that due to increased activity in smart meter installations and other smart grid technologies, as well as challenges in balancing variable renewable generation on the grid, it is reported that total annual VPP vendor revenue will grow from $1.1 billion in 2014 to $5.3 billion in 2023 [6].

6.2 Virtual Power Plant in iURBAN

In the context of the iURBAN project, it was agreed that the VPP should not follow that of detailed network modeling software available on the current market, such as GridLAB-D$^{\mathrm{TM}}$ [7]. The VPP is developed as a high-level design tool. The modeling approach of the VPP is based upon load aggregation of near real-time metered energy demand and generation data and modeling of electricity and heat generation at building/apartment and district level. City planners and utility companies will be able to undertake VPP analysis to gain an understanding of energy demand and generation and the associated costs at selected levels of interest, ranging from high-level city planning to the selection of individual buildings or user-defined energy networks.

Figure 6.1 gives a simplified overview of the iURBAN information and communications technology (ICT) architecture. The broader overview of Figure 6.1 iURBAN ICT architecture includes components that combine to form the SMART urban decision support system (smartDSS) developed by the project.

6.2.1 smartDSS

The smartDSS consists of the following components (some of which have been described in other chapters):

- Local decision support system graphical user interface (LDSS GUI),
- LDSS part of the Smart City Database (SCDB-LDSS),

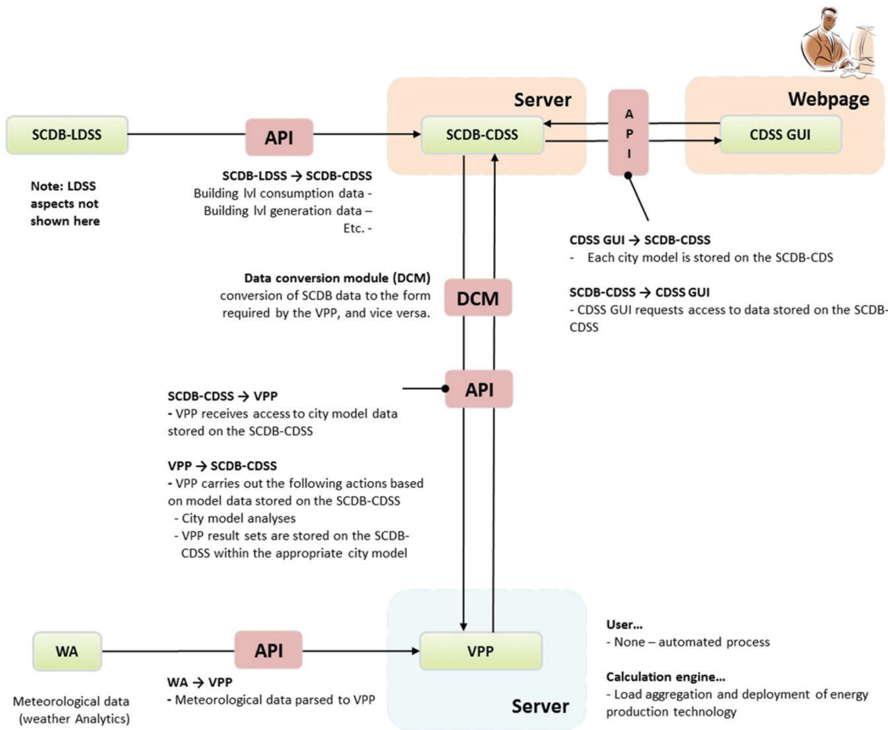

Figure 6.1 iURBAN ICT architecture—CDSS/VPP relationship diagram.

- Smart City Prediction Algorithms (SCPA),
- Meteorological data parsed from weather analytics (WA) [8].
- Central decision support system graphical user interface (CDSS GUI).
- CDSS part of the Smart City Database (SCDB-CDSS).
- VPP.

6.2.2 LDSS

A brief summary of the local decision support system (LDSS) is included for clarity. Within iURBAN, the LDSS GUI is a tool used by occupants of private buildings, apartments, and public municipality buildings such as kindergartens (schools), offices, and leisure centers.

Demand and generation metered data from buildings within the iURBAN demonstrations cities is parsed to the LDSS part of the SCDB-LDSS. These data along with meteorological data from WA are parsed to the SCPA. The SCPA component performs analysis on the data and generates forecast demand

and generation data up to 72 hours ahead, which is stored in the SCDB-LDSS. The LDSS GUI primary focus is to educate users on how and where energy is being consumed with a view to encouraging users to make savings, energy, and monetary, and reduce greenhouse gas emissions. The LDSS GUI also includes demand response (DR) actions.

6.2.3 CDSS

A brief summary of the central decision support system (CDSS) is included for clarity. The CDSS GUI is a tool used by utilities and municipalities. The CDSS GUI enables users to view metered data at a city scale and focused areas of interest such as district and neighborhood level, to make informed decisions on high-level planning.

There is an application program interface (API) layer that exists between the SCDB-LDSS and the SCDB-CDSS. This API parses stored metered and forecast data from the SCDB-LDSS to the SCDB-CDSS. The SCDB-CDSS and CDSS-GUI are both developed by the iURBAN partner Vitrociset [9].

6.2.4 VPP

The VPP, developed by IES [10], is a back end calculation engine to the CDSS GUI which acts as a front end to the VPP. The VPP is parsed, via an API layer, city model data stored on the CDSS part of the Smart City Database (SCDB-CDSS). The VPP writes the results of the calculations back to the SCDB-CDSS for access by the CDSS GUI.

6.3 User Interface

As discussed, the CDSS GUI acts as the front end to the VPP calculation engine. Figures 6.2–6.6 are screenshots of the CDSS GUI focusing on VPP functionality.

City models (explanation given within the following section) are created by CDSS GUI users. Figure 6.2 gives an example of saved city models stored on the SCDB-CDSS.

CDSS GUI users can create a new city model by clicking on the “New City Model” button, as shown in Figure 6.2. Upon clicking the button, a blank “City Model” screen appears, refer to Figure 6.3. Users can create city models for both Plovdiv and Rijeka. As explained within the below section, users define electricity and heating networks by creating network models consisting of site data, commodities, buildings, nodes, and installations.

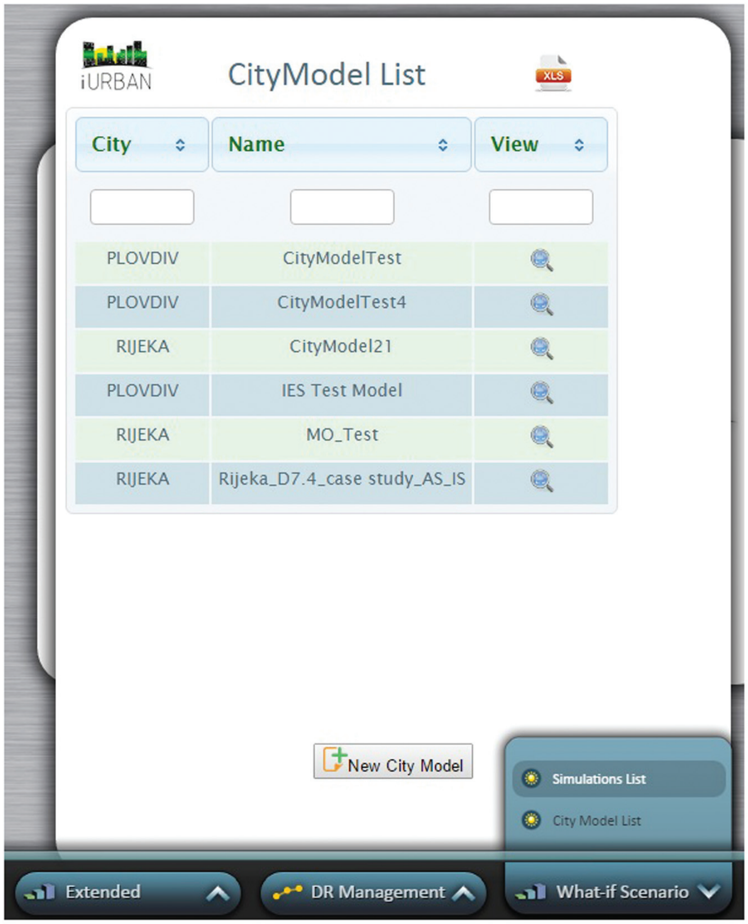

Figure 6.2 CDSS GUI—city model list.

An example of a simple city model is given within Figure 6.4 and consists of the following:

- Name: CityModel2
- City: Rijeka
- Site data: Lat. = 40, Long. = 13
- Commodities: Electricity commodity account
- Buildings: Buildings 1–4 (names removed)
- Nodes: Electricity root node (ELE1)
- Installations: None, baseline "as is" model.

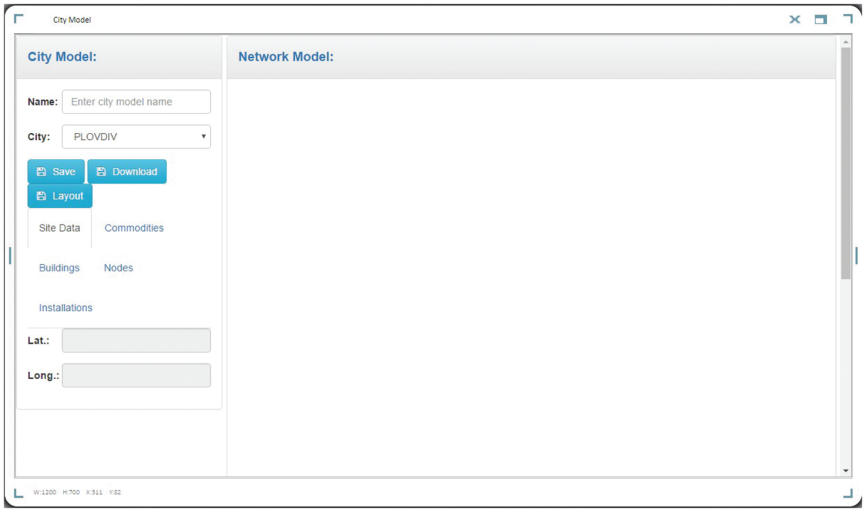

Figure 6.3 CDSS GUI—create city model.

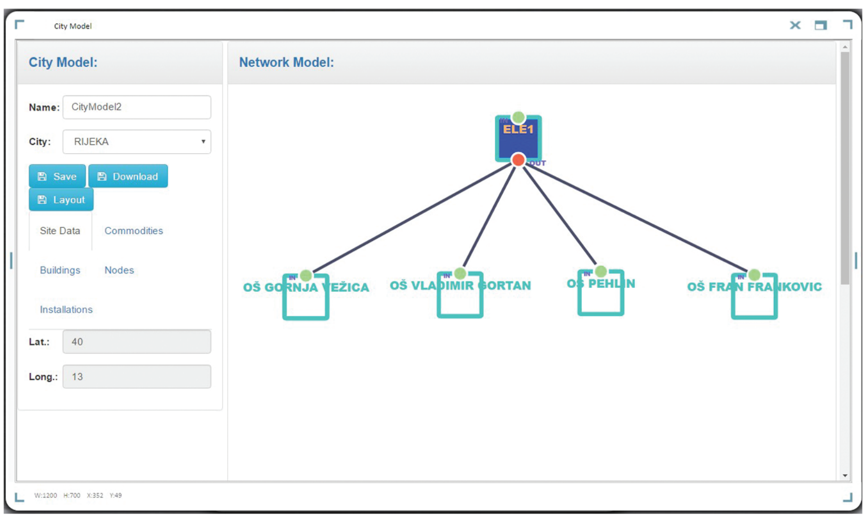

Figure 6.4 CDSS GUI—example city model.

Figure 6.4 represents an "as is" city model, refer to explanation given within the following section.

Figure 6.5 illustrates parameters required to enact a VPP simulation run. Users select the city model of interest, type of analysis, start/end dates, step,

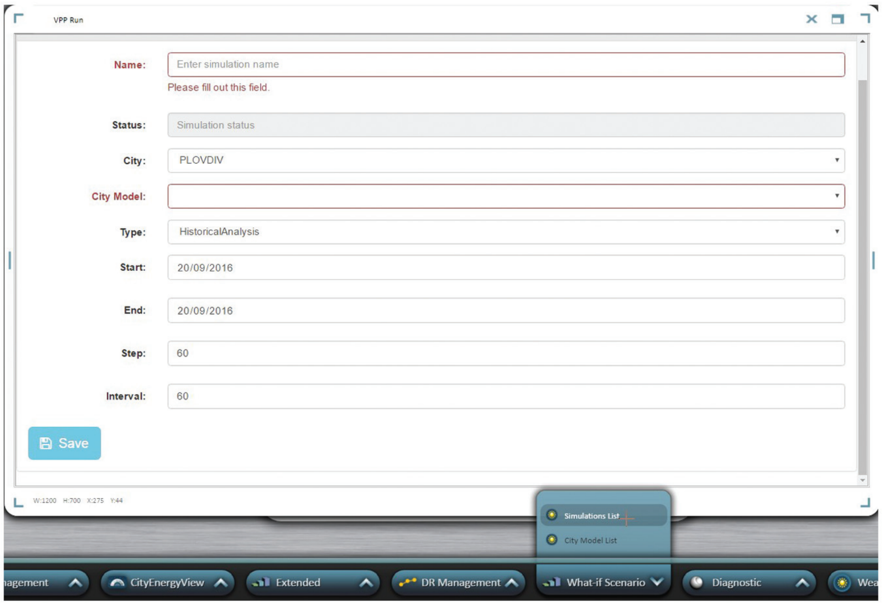

Figure 6.5 CDSS GUI—VPP run settings.

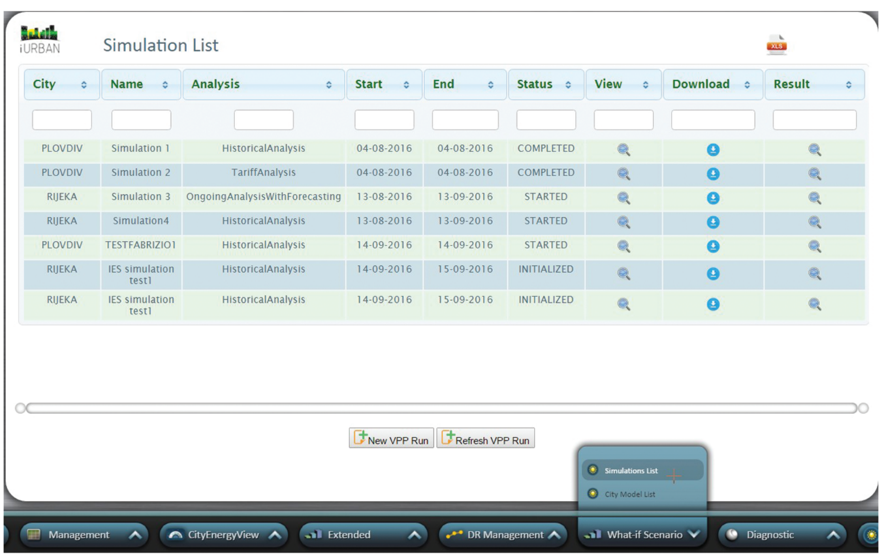

Figure 6.6 CDSS GUI—VPP simulation list.

and time interval. XML files, consisting of city model and VPP simulation run parameters, are parsed to the VPP engine. Metered data resides behind selected buildings of interest and are a driver for VPP calculations.

An example list of VPP simulation runs is shown in Figure 6.6. The CDSS GUI provides a status update. Results can be viewed or downloaded for further analysis.

The above process is repeated to create "what if" variants of the "as is" city model, refer explanation given within the following section.

6.4 City Models

The CDSS GUI enables users to create different models for different purposes such as modeling regions of a city, types of building, energy supply and management technologies, or degrees of modeling detail appropriate to particular tasks.

In addition, city models managed by the CDSS GUI user are conceptually divided into two categories:

- "as is"—city models representing the structures and consumption patterns currently in place (the status quo).
- "what if"—city models representing possible alternatives.

Examples of "what if" variant city model(s) include the addition of DER, electricity storage, modified demand from buildings, and electric vehicles. "What if" variant model(s) can answer questions such as the following:

- What is the likely effect of adding PV arrays to certain buildings?
- What is the likely effect of adding electricity storage at a certain point in the electricity distribution network?
- What is the likely effect of introducing a district CHP plant to serve a certain area?
- What is the likely effect of introducing a large-scale PV farm to serve a certain area?
- What is the likely effect of introducing tariffs in monetary and energy consumption terms?

The "as is" and "what if" city models allow for cross comparisons to be made between models.

6.5 Modeling Approach

City model data parsed to the VPP from the CDSS part of the SCDB-CDSS is referred to as the VPP city model. The VPP city model is formed around the following features: commodity, external supply, commodity account, fuel, carbon dioxide (CO_2) emissions, distribution network, network node, transmission channel, prosumer object, DER object, generator, storage device, and manager, which are illustrated in Figure 6.7. The figure illustrates an electricity distribution network defined for a city model. In this diagram, rectangles with dashed borders represent CDSS GUI objects, which serve as receptacles for VPP objects. VPP objects fall into three basic categories: nodes (colored discs), DER objects (color-filled rectangles), and managers (color-filled diamonds).

DER objects are further categorized according to type such as the following:

- Electricity network;
    - Power station,
    - CHP,
    - PV array,
    - Wind turbine,
    - Electrical storage.
- Heat network;
    - Heat generator,
    - Electric heat pump,
    - CHP,
    - Solar water heating,
    - Thermal storage.

The filled rectangles at the base of the diagram are prosumer units by means of which demands represented by input time series are connected to the system. Other VPP objects function algorithmically as a function of other variables in the model.

6.6 Case Study: Rijeka, Croatia

Figure 6.8 is a CDSS GUI demonstration of the iURBAN metered installations within Rijeka, Croatia, were 3 public kindergartens, 4 public schools, 12 residential, 4 sports centers, 2 culture centers, and 7 heating plant installations. CDSS GUI legend notation is shown in Figure 6.9.

6.6.1 "As is" Scenario

Due to the sparse nature of building locations, limited network topology information and metered installations within the framework of the iURBAN

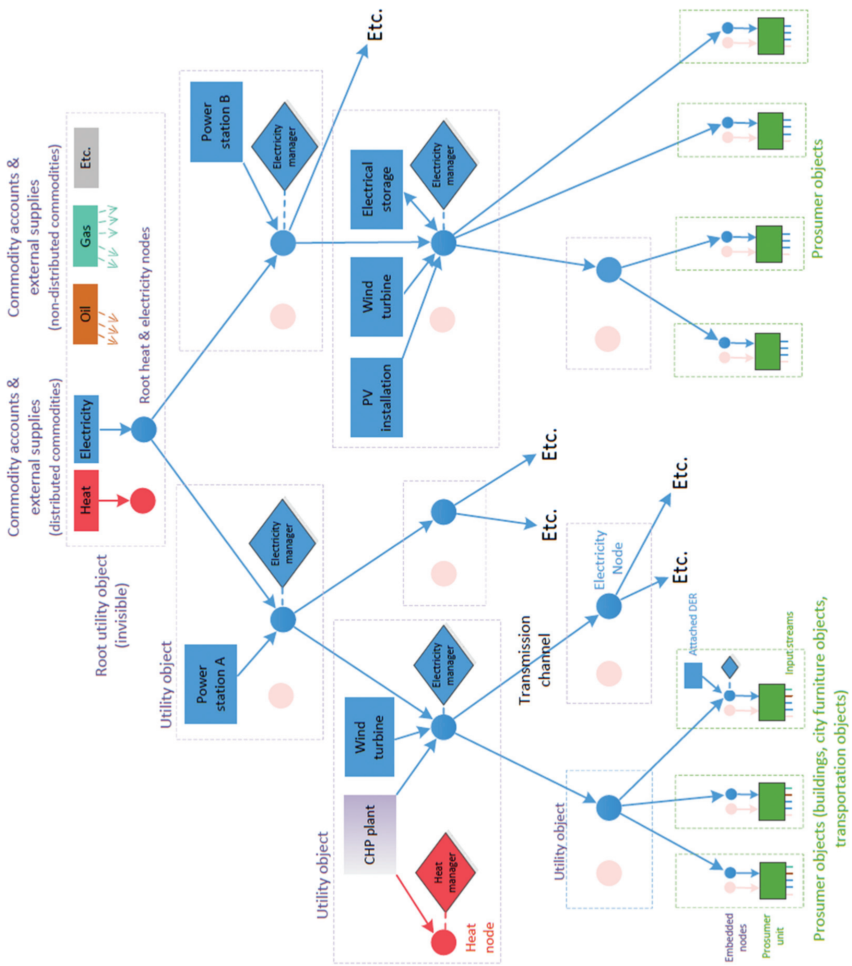

Figure 6.7 Part of an example city model focusing on the electricity distribution network.

Figure 6.8 CDSS GUI—Rijeka, Croatia. Red dashed circles denote defined building clusters.

Culture Center	Public Offices
Garden	Residential
Gas Station	School Public
Heating Plant	Shopping Center
Industrial	Sport Center
Kindergaten Public	Theater
Public Lighting	—

Figure 6.9 CDSS GUI legend.

project the Rijeka case study have been simplified. Figure 6.10 illustrates a simple VPP electricity network model for Rijeka.

In reference to the VPP modeling approach in Figure 6.7, five electricity sub-stations have been formed, representative of utility objects. Buildings within close proximity of a sub-station have been grouped together, refer to Figures 6.9 and 9.10. Buildings in this context are representative of prosumer objects in Figure 6.7.

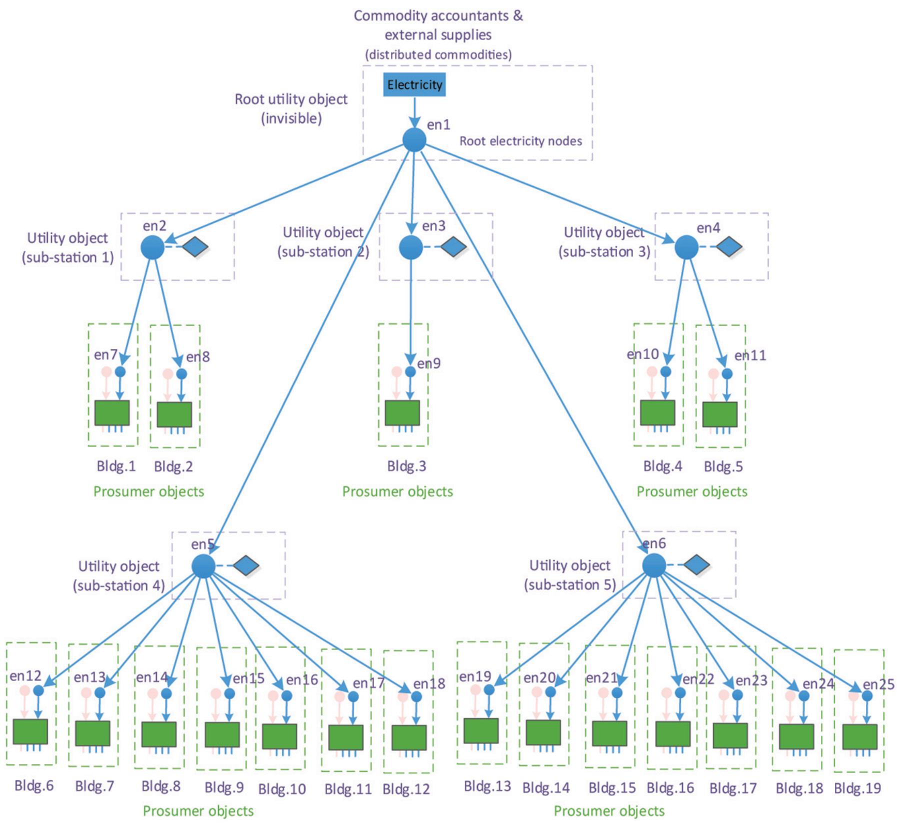

Figure 6.10 Simple VPP electricity network model—Rijeka, Croatia.

Further to sensitivity analysis carried out on the SCDB-CDSS data, the below period of analysis is considered for selected meter installations. The period of analysis was selected on the criteria of having the maximum number of meters with non-missing data for a whole week.

Data summary:

- Location: Rijeka (CityModelName calls weather analytics (WA) API for Rijeka weather data).
- Latitude: N/A (WA API).
- Altitude: N/A (WA API).
- Scenario: As is—electricity network.
- Start date/time: 2016-03-01 [00:00].
- End date/time: 2016-03-07 [23:00].

- Reporting period: Hourly (on the hour).
- Electricity installations devised into five hypothetical electricity sub-stations, refer to Figures 6.9 and 6.10.

The iURBAN project does not have access to all utilities, such as electricity, district heating, gas, and water, meter readings for each installation. Table 6.1 lists building types used within Rijeka case study and denotes available electricity consumption and production meters. Each building type is grouped to a hypothetical electricity sub-station.

Upon finalization of the “as is” city model within the CDSS GUI, the following extensible markup language (XML) files are created and parsed to the VPP engine via the CDSS part of the SCDB-CDSS:

- CityModel.xml—i.e., electricity network topology.
- Commodities.xml—i.e., commodity attributes such as CO_2 emission factors.
- Run.xml—i.e., VPP run specifier settings such as start/end date and time.
- Timeseries.xml—i.e., time series meter installation readings.

Table 6.1 Hypothetical electricity sub-stations 1–5

Hypothetical Sub-stations	Prosumer Object Name	Type	Meter (Consumption)	Meter (Production)
1	Building 1	Public kindergarten	Yes	Yes
“	Building 2	Sports center	Yes	Yes
2	Building 3	Public school	Yes	No
3	Building 4	Public school	Yes	Yes
“	Building 5	Public kindergarten	Yes	Yes
4	Building 6	Residential	Yes	No
“	Building 7	Sports center	Yes	No
“	Building 8	Residential	Yes	No
“	Building 9	Residential	Yes	No
“	Building 10	Residential	Yes	Yes
“	Building 11	Culture center	Yes	No
“	Building 12	Culture center	Yes	No
5	Building 13	Residential	Yes	No
“	Building 14	Sports center	Yes	No
“	Building 15	Public school	Yes	No
“	Building 16	Residential	Yes	No
“	Building 17	Residential	Yes	No
“	Building 18	Public kindergarten	Yes	No
“	Building 19	Public school	Yes	No

Source: Author.

6.6.2 "What if"—Scenarios

The below "what if" city models are an example of the application of creating variant models for comparison against the "as is" model.

Table 6.2 outlines selected DER installations for prosumer objects (buildings 1–19) and utility objects (sub-stations 1–5) across 8 scenarios. For example, scenario 1 includes a 1No. 1 kW (small domestic) photovoltaic (PV) panel assigned individually to all 19 buildings; sub-stations have not been assigned DER installations. Scenario 2 is the same as scenario 1 with the exception that the capacity rating of the PV panel installation is changed from 1 kW to 6 kW (large domestic). Wind turbines are modeled in scenarios 3 and 4. Scenarios 5–8 include energy storage device in addition to PV and wind turbines for selected scenarios. For example, scenario 5 includes 1No. 1 kW PV panel and 1No. 50 kWh energy storage device assigned individually to all 19 buildings and so on.

DER installation parameters are shown in Tables 6.3–6.5; installation types refer to the number shown in Table 6.2.

6.6.3 Results

Rijeka case study VPP results for "as is" and "what if" scenarios are shown in Table 6.6. Results are presented for the electricity commodity account, i.e., root node, not for each electricity node in the network.

For scenarios 1–4, no electrical energy storage devices, the results reflect the expected behavior of the electricity network when compared against the "as is" scenario, i.e., the baseline scenario. The introduction of renewables, PVs, and wind turbines reduces demand from external supply to the network. This is a result of renewables offsetting electricity demand from buildings 1 to 19. CO_2 emissions are also reduced within the model based on the reduction in fossil fuel-based external supply to the network. There is a noticeable difference between the PV and wind turbine scenario results. This difference is due to the variation in wind speed for Rijeka based on its coastal location; average, maximum, and minimum wind speed for the selected period of analysis is 3.44 m/s, 10.19 m/s, and 0.89 m/s. A wide range of wind turbine rated power, 1.5–15 kW per installation, is modeled. This may be considered unrealistic, but the model gives an indication of future potential if such solutions were considered feasible to install.

In scenarios 5–8, which include electrical energy storage in addition to selected renewable technology, external supply and carbon emission reduce when compared to scenarios 1–4 with no electricity storage installations.

Table 6.2 Scenario parameters

	Building 1	Building 2	Building 3, 4, …, 16, 17	Building 18	Building 19	Sub-station 1	Sub-station 2	Sub-station 3	Sub-station 4	Sub-station 5
Scenario 1										
PV (kW)	1	1	1	1	1	–	–	–	–	–
Scenario 2										
PV (kW)	6	6	6	6	6	–	–	–	–	–
Scenario 3										
Wind (kW)	1.5	1.5	1.5	1.5	1.5	–	–	–	–	–
Scenario 4										
Wind (kW)	15	15	15	15	15	–	–	–	–	–
Scenario 5										
PV (kW)	1	1	1	1	1	–	–	–	–	–
Energy storage (kWh)	50	50	50	50	50	–	–	–	–	–
Scenario 6										
PV (kW)	6	6	6	6	6	–	–	–	–	–
Energy storage (kWh)	50	50	50	50	50	–	–	–	–	–
Scenario 7										
Wind (kW)	1.5	1.5	1.5	1.5	1.5	–	–	–	–	–
Energy storage (kWh)	50	50	50	50	50	–	–	–	–	–
Scenario 8										
Wind (kW)	15	15	15	15	15	–	–	–	–	–
Energy storage (kWh)	50	50	50	50	50	–	–	–	–	–

Source: Author.

Table 6.3 PV array parameters

Installation Category	Area (m^2)	Azimuth (Clockwise from North)	Inclination (from Horizontal)	PV Module Nominal Efficiency	Nominal Cell Temperature (NOCT) (°C)	Reference Irradiance for NOCT (W/m2)	Temp. Coefficient for Module Efficiency (1/K)	Degradation Factor	Shading Factor	Electrical Conversion
PV 1 kW (small domestic)	7.2	180	35	0.1100	45.0	800	0.0040	0.99	1.0	0.85
PV 6 kW (large domestic)	43.2	180	35	0.1100	45.0	800	0.0040	0.99	1.0	0.85

Table 6.4 Wind turbine parameters

Installation Category	Rated Power (kW)	Hub Height (m)	Power Curve [wind speed (m/s), Power Output Fraction %]
Wind 1.5 kW (house)	1.5	5	0 0 4 0.1 7 0.5 12 0.8 25 1
Wind 15 kW (farm)	15	5	0 0 4 0.1 7 0.5 12 0.8 25 1

Table 6.5 Electrical energy storage parameters

Installation Category	Storage Capacity (kWh)	Initial Storage Energy (kWh)	Storage Method	Losses
lithium-ion Battery 50 kWh	50	2	lithium-ion Battery	0

Table 6.6 Rijeka VPP results, percentage difference against "as is" baseline model

Scenario	External Supply (% Diff)	External Indirect CO_2 Emission (% Diff)
As is (baseline model)	–	–
Scenario 1—1 kW PV	0.30	0.30
Scenario 2—6 kW PV	1.75	1.67
Scenario 3—1.5 kW wind turbine	0.78	0.77
Scenario 4—15 kW wind turbine	7.40	7.30
Scenario 5—1 kW PV and 50 kWh storage	0.31	0.31
Scenario 6—6 kW PV and 50 kWh storage	1.45	1.39
Scenario 7—1.5 kW wind turbine and 50 kWh storage	0.73	0.73
Scenario 8—15 kW wind turbine and 50 kWh storage	5.64	5.58

This is a result of model setup where electricity storage devices have been applied at building level. In some cases, on-site electricity generation from renewables at building level exceeds electricity building level demands. In this case, excess electricity generation charges on-site storage prior to being fed back to the electricity network upon electricity storage equaling storage capacity. In other instances, electricity demand at building level exceeds on-site electricity generation. This results in an electricity residual demand from the electricity network, sub-station, and then parent node, which in turn equates to an increase in external supply and CO_2 emissions to the model. This could be adverted with better electricity storage controls and storage at sub-station level. Future scenarios will look to address this.

6.7 Future Work

Future work consists of refining the Rijeka case study based on detailed electricity network topology. Other work includes the modeling of the second iURBAN case study in Plovdiv, Bulgaria.

Future VPP development includes the following:

- District cooling
- Water networks
- Optimized control strategies.

6.8 Conclusion

This chapter has provided information about the approach implemented within iURBAN with respect to virtual power plant development. This chapter also presents a use case example for Rijeka in Croatia, one of the iURBAN demonstration cities.

The VPP is developed as a high-level design tool. The modeling approach of the VPP is based upon load aggregation of near real-time metered energy demand and generation data and modeling of electricity and heat generation at building/apartment and district level.

Through use of the CDSS GUI, city planners and utility companies will be able to undertake VPP analysis to gain an understanding of energy demand and generation and the associated costs at selected levels of interest, ranging from high-level city planning to the selection of individual buildings or user-defined energy networks.

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