

MODELING OF CONNECTED COMMUNITY INFRASTRUCTURES ACCOUNTING FOR THE INTERDEPENDENCIES AMONG ENERGY, TRANSPORTATION, AND COMMUNICATION NETWORKS

Xing Lu¹, Yangyang Fu¹, and Wangda Zuo¹
¹University of Colorado Boulder, Boulder, CO

ABSTRACT

A future connected community is rendered as an aggregate of sophisticated public infrastructure not only the energy system but also the transportation and communication networks, intertwined with each other. The issues multiply when researchers start juggling how, when, and where to allocate heterogeneous infrastructures, such as renewable energy sources, electric vehicles, and advanced wireless communication and sensor systems. In order to achieve a globally optimum operation and cost reductions, energy, transportation and communication networks should be modeled and optimized collectively. In this paper, a preliminary connected community package implemented in Modelica is proposed considering the interdependency between these three networks. In this package, a connected community is divided into multiple regional blocks. Each block has three system agents including an agent for energy consumption and renewable generation, an agent for transportation which includes an electric vehicle station, and an agent for communication. The three different system agents in energy, transportation, and communication are interconnected through different interfaces. For the energy system agent, the cable model links the interaction of different energy agents. For the transportation system agent, the road model is built to simulate the commuting between the different blocks. For the communication system agent, the transmission model is built to mimic reduction or delay in transmitting the information flow. Finally, a case study is presented to demonstrate how the transportation and communication networks influence on the operation of the energy systems between various blocks.

INTRODUCTION

The concept of a smart and connected community is always evolving and going far beyond one single definition to cover (Albino, Berardi, and Dangelico 2015). However, it is well acknowledged as an aggregate of infrastructure systems where various stakeholders make active efforts, such as smart grid networks, intelligent transportation systems (ITS) and

information and communications technology (ICT). These infrastructure systems are not only complex in themselves, but also highly intertwined. Issues will multiply when integrating these emergent technologies in a whole due to the intricacy arising from the interdependency. For example, the charging behavior of electric vehicles (EV) would have a huge impact of the power distribution network. In turn, the battery energy in EVs will also determine the traffic routing (Amini and Karabasoglu 2017). The communication system will also affect the charging coordination and the transportation network dynamics through the rational dispatching. Therefore, it is crucial to consider three key infrastructure systems in a whole.

This presence of interdependency exacerbates the need for new modeling approaches for these interconnected infrastructures both during the early system design phase, as well as the late periods of operation and maintenance. The combined modeling approach can be divided into three types in general. The first approach is to extend the existing specialized monolithic modeling tool. For instance, some power system simulation tools also support the telecommunication simulations (Mets, Ojea, and Develder 2014). However, modeling communication systems in these simulators often lead to simplifications and inaccurate translation of the foreign model. Also, the tools often cannot fulfil the specific modeling objective of the user. Another approach is to use the co-simulation techniques to couple specialized software packages that use validated model libraries and tailor-made solvers by a certain orchestration mechanism (Palensky et al. 2017). Coupling the energy system and communication system, Chatzivasileiadis et al. built a coupled platform implemented the Ptolemy II framework to integrate the building models, power system software, and the communication network software. The platform can be used to investigate the demand-response strategies and the volt/var control strategies (Chatzivasileiadis et al. 2016). To investigate the integration of the electromobility, Federico et al. coupled the traffic simulator SUMO and the power network simulator EMTP (Montori, Borghetti, and Napolitano 2016). Although co-simulation is a power tool that can handle

multi-domain systems with reasonable details and speed, its coupling mechanism is complex due to the heterogeneity arising from different domains. Apart from these two approaches, general purpose multidomain simulation tools have the capability to simulate heterogeneous components and systems. In general, these languages have a rich of validated models and libraries to use and could incorporate different versions of the component behavior (Wetter et al. 2014; Franke and Wiesmann 2014; Liyana, Lacroux, and Barbe 2015).

In this paper, a preliminary Modelica package for interdependent infrastructures of energy, transportation, and communication networks is proposed for future connected communities. According to the authors, it is the first library that considers the three systems within one platform. The interdependency of different domains is also reflected in the framework. In addition, the models have the function of plug-and-play feature which facilitates its reuse when upgrading the infrastructure systems in connected communities.

The rest of the paper is organized as follows. Sections 2, 3 and 4 detail the packages of the individual system. Section 5 illustrates how to utilize the above individual system models into the coupled system package. The principle and the built-in interfaces are also discussed in this section. Section 6 presents two examples to demonstrate the application scenarios of the package and the necessity of the integration of three systems. Finally, salient concluding remarks are presented.

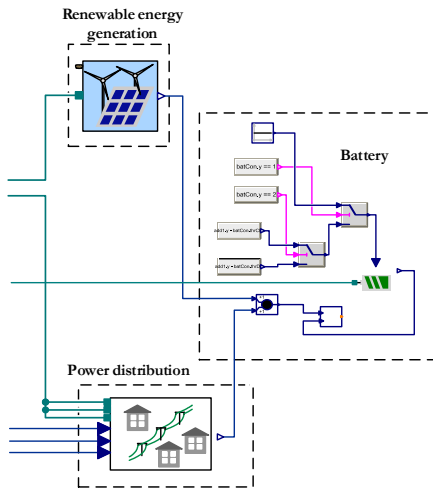


Figure 1 Schematic of energy system model

ENERGY SYSTEM PACKAGE

This section details the energy subsystems in the package. The energy demand side models consist of the load from buildings, EVs, communication towers, and general loads in the power grid. The detailed distribution network model is also introduced in this

section. The energy supply side models are composed of renewable generations (Photovoltaic (PV) panels and wind turbines), grid power and energy storage.

Demand side model

The demand side of the energy system in future connected communities is comprised of the loads from buildings, charging EVs, communication towers and general loads. The loads from buildings can be calculated using grey-box models such as RC models or imported by data-driven models. The EV charging power is calculated as the product of the number of the charging EVs and the charging power, with the assumption that the charging power is constant. The load from the communication towers is calculated using Eq. (1), considering the power for sending, receiving and processing packets (Chen et al. 2009).

$$P_{com} = 2s \cdot E_{elec} + s \cdot \epsilon_{elec} \cdot d^{\alpha}, \quad (1)$$

where E_{elec} is the equipment power for sending and receiving packets, s is the packet amount, d is the distance of the transmission, α and ϵ_{elec} are transmission coefficients.

Different configurations of power distribution networks can be built in this package including the IEEE 16-node test feeder (Civanlar et al. 1988). These networks can be used to investigate the performance of power distribution systems. The models in package Electrical are reused to build the distribution network models, including the load model and line model.

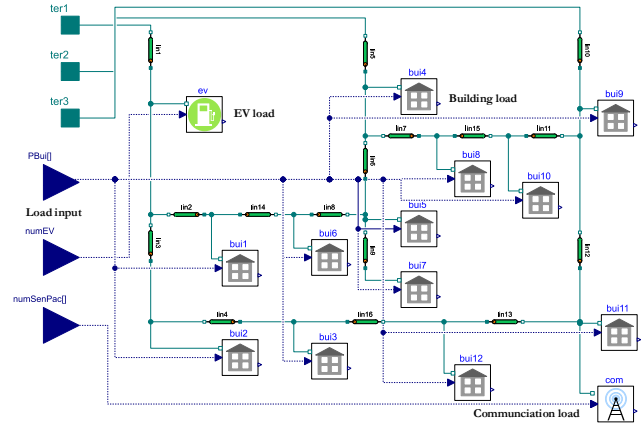


Figure 2 Distribution network model built in Modelica (IEEE16)

Renewable generation model

The models for asynchronous renewable generators are used. For the PV model, we used the PVSImpleOriented model in the Modelica Buildings library (MBL) (Wetter et al. 2014). It calculates the electrical power, P , generated by the PV using the following equation:

$$P = A f_{act} \eta G \eta_{DCAC}, \quad (2)$$

where A is the area of each PV panel, f_{act} is the fraction of the aperture area, η is the PV panel efficiency, G is the total solar irradiation, and η_{DCAC} is the efficiency of the conversion between direct current (DC) and alternating current (AC). In this model, G is the sum of direct and diffuse irradiation, which is calculated by:

$$G = G_{Dif} + G_{Dir}, \quad (3)$$

where G_{Dif} and G_{Dir} are the sum of diffuse and direct irradiation on tilted surface respectively. They are calculated by the following equations:

$$G_{Dir} = \text{Max}(0, \cos(\text{incAng})H_{DirNor}), \quad (4)$$

where incAng is the solar incidence angle on the surface and H_{DirNor} is the direct normal radiation.

$$G_{Dif} = G_{SkyDif} + G_{GroDif}, \quad (5)$$

where G_{SkyDif} and G_{GroDif} are the hemispherical diffuse solar irradiation on a tilted surface from the sky and hemispherical diffuse solar irradiation on a tilted surface from the water, respectively.

For the wind turbine model, we used the WindTurbine model in the library. The model is computed as a function of the wind speed defined by a table, which maps the wind speed in meters per second to generated power P_t in Watts. The model has a parameter called scale that can be used to scale the power generated by the wind turbine. The generated active electrical power is calculated as Eq. (6).

$$P = P_t \cdot \text{scale} \cdot \eta_{DCAC_Win} \quad (6)$$

Energy storage model

A revised energy storage model is built based on the Electrical.AC.OnePhase.Sources.Grid model in the MBL (Wetter et al. 2014) since the base model does not enforce that the state of charge is between zero and one and the user should provide a control so that only a reasonable amount of power is exchanged. Hence, the control logic adopted here is that the power generated by the renewable system covers the demand load in the first place. When there is excessive power, the battery bank starts to charge. When the power demand exceeds certain amount, the battery bank starts to discharge. In other cases, the battery bank remains stand-by.

Grid power model

In this paper, we used the Electrical.AC.OnePhase.Sources.Grid model in MBL to build the physics-based model for the utility supplied power. The input for this model is a fixed voltage signal while the output will be the power supplied by the utility at a Point of Common Coupling (PCC) to the power distribution system. The convention is that the power is positive if real power is consumed from the grid, and negative if power flows out of the PCC and back into the grid.

Examples

This example demonstrates the energy interconnection between the two blocks using the component models in this section. One is the residential block and the other is the commercial block. The peak load of the residential buildings often occurs in the nocturnal period while that of the commercial buildings happens at the working time during the daytime. Therefore, the power could ideally flow from the residential block to the commercial block due to the oversupply through the transmission. If the amount is insufficient, the grid would compensate the rest of the power demand.

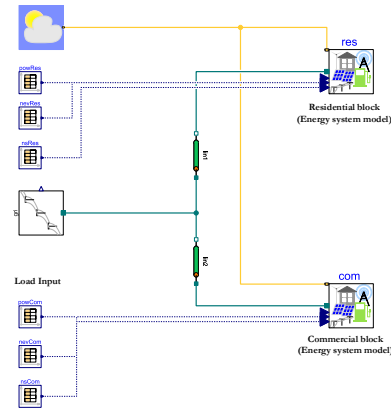


Figure 3 Example of energy system network

TRANSPORTATION SYSTEM PACKAGE

Traffic flow has such intrinsic irreproducibility that it is impossible to predict precise vehicle trajectories via models. However, it is recognized that the prediction of large-scale field quantities could be possible. The traffic simulation models can be micro, meso and macroscopic with different granularity. For example, macroscopic models describe the traffic as flows, velocity and density of vehicles while microscopic models simulate individual vehicles down to basic physical and kinematic properties such as speed, locations, and fuel. In this package, we simulate the transportation infrastructures from a macroscopic perspective. The road model and charging station model are detailed in this section.

Road model

The road model described here is able to calculate the travel time of a road, which utilizes the empirical model of the flow-velocity correlation in (Wei 2003), as shown in Eq. (7). Figure 4 demonstrates the relationship between the velocity and the traffic load ($\frac{V}{C}$) of different road design velocity under a certain road type. It can be found that the velocity descends faster when traffic flow exceeds the road capacity ($\frac{V}{C}$ is larger than 1). Eq. (8) represents the relationship between the velocity,

density and traffic flow. Combining these equations, the traffic condition on the road can be jointly obtained.

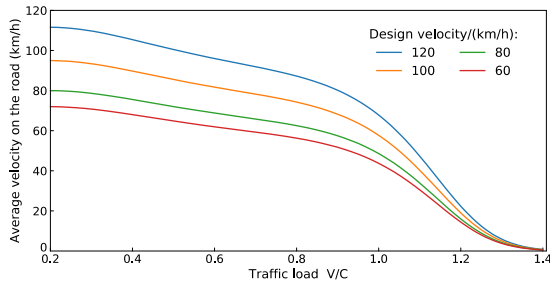


Figure 4 Relationship between the velocity and the traffic load of different road design velocity

$$\begin{cases} U = \frac{\alpha_1 U_s}{1 + (\frac{V}{C})^\beta} \\ \beta = \alpha_2 + \alpha_3 (\frac{V}{C})^3 \end{cases} \quad (9)$$

where U is the speed, V is the number of arrived vehicles, which means average vehicle flow, α_1 , α_2 , α_3 are regression parameters and U_s is the speed designed for the highways, C is the capacity of road. It is noted that different road type has a distinct α_1 , α_2 , α_3 , U_s and C based on its design traffic velocity.

$$V = \frac{U \cdot \int (q_{out} - q_{in}) dt}{L} \quad (10)$$

where q_{out} and q_{in} are the traffic outflow and traffic inflow respectively and L is the length of the road.

The road model consists of the traTim model and the signal delay model. The schematics of the road model implementation is depicted in Figure 5 and the pseudo-code of traTim model using the aforementioned principle is shown in Figure 6.

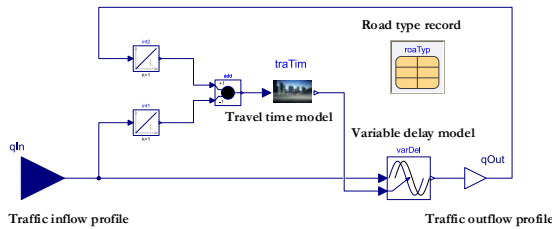


Figure 5 Schematics of road model

```
...
equation
num=qIn; //Traffic inflow
qAve=num/l*u; //Average traffic flow on the road
b=roaTyp.a2 + roaTyp.a3*
(qAve/(roaTyp.q_nominal/3600))^3; //Beta
u=roaTyp.a1*roaTyp.uf/(1+
(qAve/(roaTyp.q_nominal/3600))^b); //Average velocity
t= if noEvent(u>0.1) then l/u else l/0.1;
delTim=t; //Travel time
```

Figure 6 Pseudo-code of traTim model in Modelica

Validation

We validate the road model using comparative testing the data in (Ang* and Neo 2005), as depicted in Figure 7. It can be concluded that the model fits well with real data from the literature and could represent the traffic condition for the integrated model.

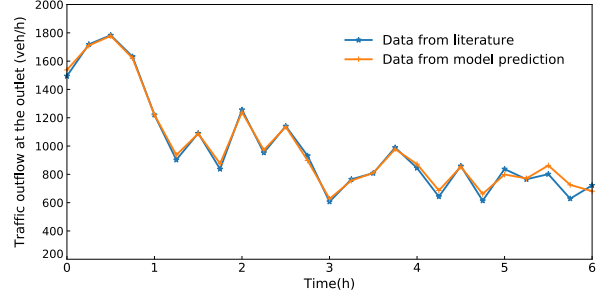


Figure 7 Comparative testing of the road model

Charging station model

The charging station model calculates the number of EVs in the station using traffic flow balance, as shown in Eq. (9).

$$\dot{N} = \sum_{i=1}^{k_{in}} q_{in} - \sum_{i=1}^{k_{out}} q_{out} \quad (11)$$

where \dot{N} represents the number difference of EVs in the station, and k_{in} and k_{out} denote the number of inlets and outlets of the station respectively. q_{in} and q_{out} represent the traffic inflow and the traffic outflow.

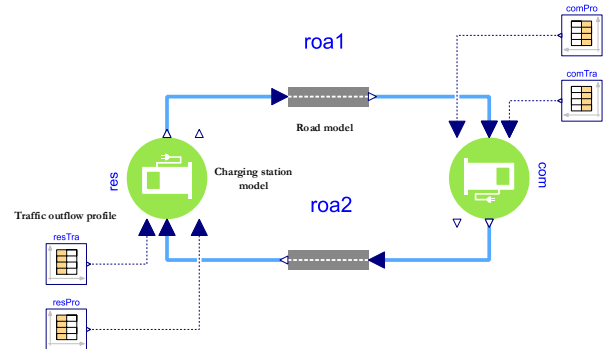


Figure 8 Example of transportation system network

Examples

This example demonstrates the transportation network between the two blocks using the component models described in this section. One is the residential block and the other is the commercial block. Traffic condition on the road and charging condition in the block can be calculated based on the input of the traffic outflow.

COMMUNICATION SYSTEM PACKAGE

In this package, a simplified packet loss model is used to describe the transmission process in a wireless communication network. Eq. (12) shows the empirical

relationship between the packet loss rate and the normalized throughput. It is assumed that the packet loss rate is direct proportional to the throughput under certain bandwidth in the communication system (Liu, Hou, and Li 2009). Also, the simplified model does not account for a transmitting latency and the retransmission mechanism if a message is lost.

$$\gamma = \kappa \sqrt{Q - C}, \quad (13)$$

where γ is the packet loss rate, Q is the normalized throughput, κ is a proportional coefficient and C is the threshold of the transmission.

Examples

This example demonstrates the transmission between two communication towers using the component models in this section. The results show that there exists some packets losses when the number of the packet to be sent rises more than a certain threshold.

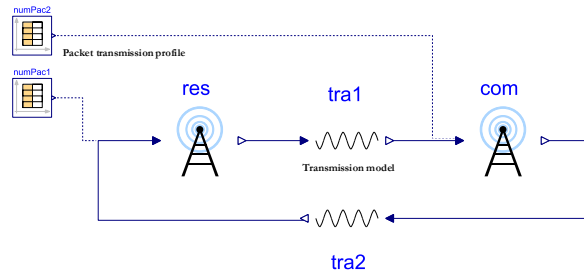


Figure 9 Example of communication system network

COUPLED SYSTEM PACKAGE

Having discussed the component models in the single domains, in this section, we illustrate how the aforementioned models are integrated and interconnected. The coupled system can be a pairwise combination of the energy, transportation and communication systems, while it could also be a combination of three systems. In this section, we use the three-coupled system to illustrate the modeling approach.

Principle and interfaces

A multi-level, multi-layer, multi-agent (3M) approach is proposed for modeling coupled systems. As depicted in Figure 10, the community layer consists of multiple block agents, representing different functional areas. Each block agent has three system agents including an agent for energy consumption, storage, and generation, an agent for charging stations, and an agent for communication towers. Within each system agent, there will be individual subagents for infrastructure nodes. For instance, an energy system agent will have

subagents for renewable generation, power distribution network and battery banks for storage.

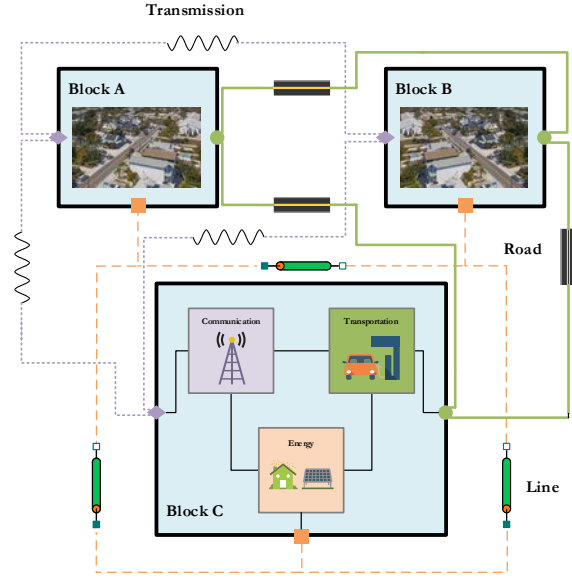


Figure 10 Principle of 3M approach

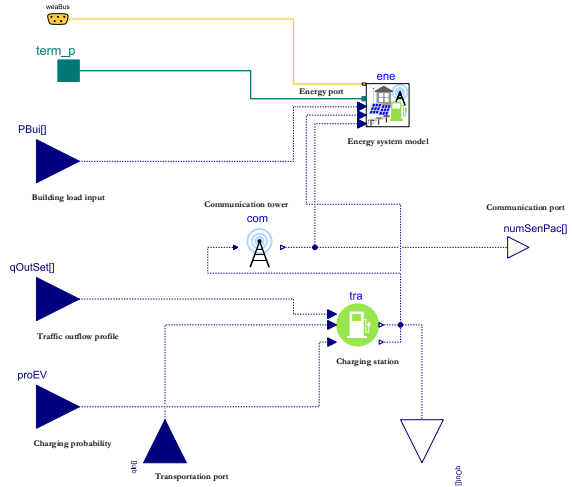


Figure 11 Schematics of three coupled system model

In one block, the three distinct system agents in energy, transportation and communication are interconnected through built-in interfaces, as shown in Figure 11. For example, the charging station agent sends the number of charging vehicles to the energy system agent. Likewise, the communication tower agent sends the throughput information to the energy system agent. On one layer, different blocks are connected through the power transmission model of the energy system, the road model of the transportation system and the wireless transmission model as discussed in the previous section. The agents can have up to three kinds of ports to connect flows of traffic, power, and communication packets for the multi-level systems.

Moreover, the agents can only be connected via the ports while one port can take multiple connections.

APPLICATIONS

To demonstrate the capacity of the package, we propose to evaluate the performance of infrastructures of energy, transportation, and communication networks in connected communities where large renewable energy generation and full electrified transportation are adopted. The communication system here serves as the enabler of the traffic routing.

The community layer is composed of two residential blocks and a commercial block. The residential blocks mainly consist of residential buildings while the commercial block is composed of commercial buildings, such as offices, restaurants and schools. Each block has its own renewable generation farm, energy storage (battery bank), charging stations, and communication towers, as outlined in Section 2. Six roads of the same road type link the commuting between different blocks. The communication system in these two cases are dedicated to the traffic routing of the vehicles on the road. The communication tower in each block exchanges traffic information with the vehicles on the road, and thus the performance of the communication system has a direct effect on the transportation system. The first example presents the case only using the models in energy system package while the second example utilizes the coupled system package which considers the traffic dynamic and the communication process between the communication tower and the vehicles on the road. Detailed parameter settings and Modelica implementation are shown in Table 1 and Figure 12 for the two examples.

Table 1 Detailed parameter settings of two examples

Parameter	Residential Block1	Residential Block2	Commercial Block
Weather profile	USA_CA_San.Francisco.Intl.AP		
Solar power farm area (m ²)	20000	30000	50000
Nominal wind turbine power (MW)	1	1	1
Battery maximum charge (kWh)	4000	5000	6000
Distribution system type	IEEE 16 test feeder		
Initial EV number	800	800	200
Building type	Residential houses, Midrise apartments		Offices, Retail, Hotels, Schools, Restaurants

Example 1: Energy system

The building load profiles for this case are input from the Department of Energy (DOE) dataset which contains hourly load profile data for 16 commercial building types (based on the DOE commercial reference building models) and residential buildings (based on the Building America House Simulation Protocols) (Department of Energy 2017). The inputs for transportation system and communication system are prescribed for this case. For instance, the EV charging profile in one block is prescribed according to the travel demand analysis, and the travel time between the blocks is neglected in this example.

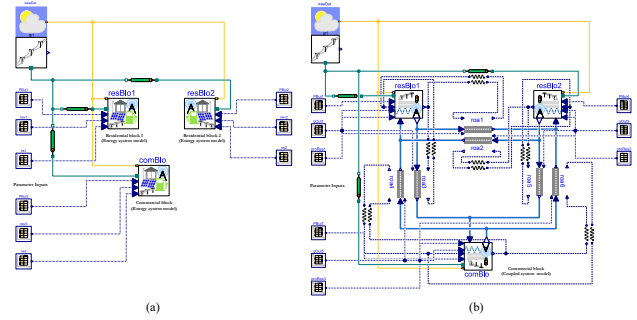


Figure 12 Schematics of the two examples in Modelica

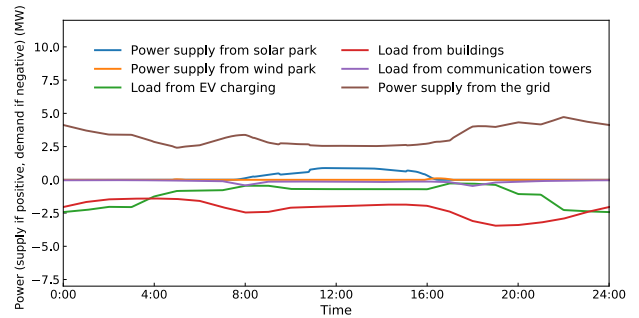


Figure 13 Energy supply and demand profile

The simulation results for the energy system are depicted in Figure 13. From the supply side, the power generated from the solar park peaks at noon. However, the wind power contributes little during that time period. From the demand side, the load from the EV charging has a higher demand in the nocturnal period rather than in the daytime due to the EV charging in the residential blocks. The load from the building blocks is quite stable compared to the EV charging load pattern. It is noted that the load from the communication towers is negligible to the load from EV charging and the buildings.

It can also be seen that the power grid curve looks like a duck curve and the peak-valley ration is relatively high value caused by the high EV charging demand at night and renewable energy generation in the daytime. However, it is compromised by the adoption of the

battery bank and the modest renewable energy generation during that time period.

Example 2: Three coupled system

In this case, the parameter inputs for the energy system and transportation system are the same as the one in example 1. However, instead of specifying the EV charging profile, the traffic dynamic is considered in this case based on the traffic outflow profile. The data from the National Cooperative Highway Research Program (NCHRP187) is used (Martin and McGuckin 1998). Instead of specifying the packets transmission profile, the packet exchange processes between the road and the corresponding communication tower are modeled. The assumption is made that the traffic travel time would be increased due to the data loss and incomplete transmission of the traffic information.

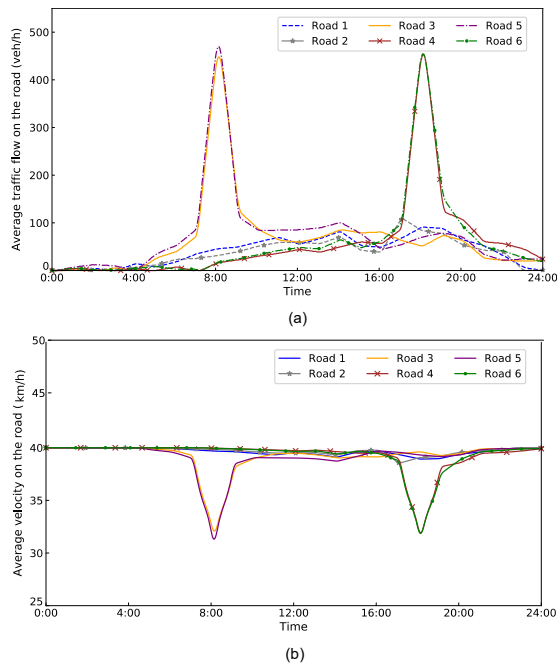


Figure 14 Result of transportation system (a) Average traffic flow profile (b) Average velocity on the road

The quantitative results for the transportation system is illustrated in Figure 14, which shows the average traffic flow profile and the average velocity on different roads. The results demonstrate that there are traffic peaks at the roads 1, 3, 4 and 6, which link the residential blocks and commercial blocks. At the peak commuting time (around 8:00 and 18:00), the average traffic flow has a peak value while the average velocity on the road descends to a valley. The energy results are not displayed in this example to avoid the repetition however the comparison of the energy results in these two examples will be analyzed later.

The simulation results for the communication system are depicted in Figure 15. In contrast to Figure 14(a), the packet loss surges when the average traffic flow peaks at the highest commuting time because the communication throughput far exceeds the capacity threshold.

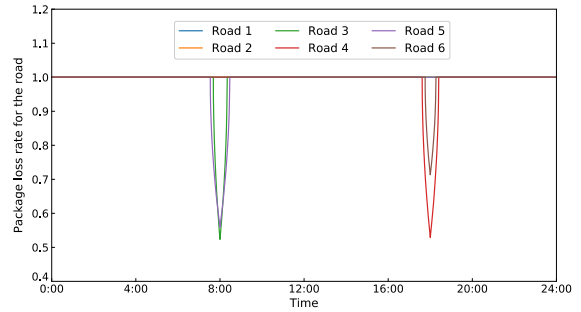


Figure 15 Result of communication system

Other interesting results are obtained through the comparison of simulation results in two examples. We can analyze the impact of the other two systems on the energy system from the comparison of the three cases. Figure 16 shows the comparison of the power from the grid calculated from two examples. It can be seen that although there is little difference on the power demand from the grid in most of the time, large deviation exists during the peak commuting time (as circled in red), which is mainly caused by the collective impacts of the transportation and communication system. This will have a direct influence on the dispatching of the spinning reserves for ensuring a good operation of the power grid, which also indicates the necessity of coupling three systems in modeling future connected communities.

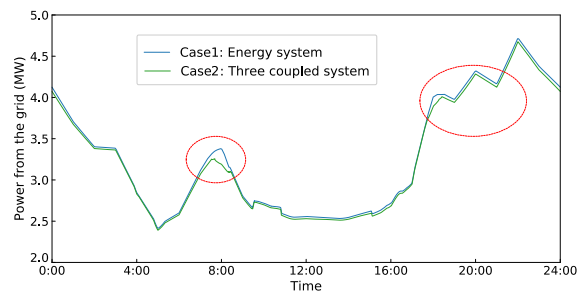


Figure 16 Comparison of grid power in two cases

CONCLUSION

This paper describes a preliminary package implemented in Modelica considering the interdependency between these three networks. First, the individual system packages of different domains are illustrated. On top of that, the three systems of energy, transportation, and communication are interconnected through a multi-level, multi-layer, multi-agent (3M) approach. Finally, case studies are presented to

demonstrate the application of the modeling framework in the operation of connected communities. The quantitative analyses show how the transportation and communication networks influence on the operation of the energy systems between various blocks. We should note that although the modeling framework incorporates three critical infrastructure systems and their interdependency in a multi-domain language, it still faces several challenges to be addressed. Since the system complexity rises dramatically, assumptions and simplifications in this paper are made that will lead to the inaccurate and incomplete translation for some component models. Future work is to extend the framework through interfaces (e.g. FMI) according to the modeling requirements.

ACKNOWLEDGMENT

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