and the house archetypes listed in Table 1 are selected. The ownership and the specifications of home appliances are then given randomly based on database. Regarding the specifications, database contains information on the duration of operation and power consumption during operation that were developed based on actual electricity consumption collected from 586 households (Higashino et al., 2014).

Table 1. *The family compositions, the house types, and the floor area*

Family compositions	One member	Single male, Single female, Single aged man, Single aged female
	Two members	Working couple, Couple, Aged couple, Working mother and child, Mother and child
	Three members	Working parents and child, Parents and child, Working mother and two children, Mother and two children
	Four members	Working parents and two children, Parents and two children
	Five members	Working parents and three children, Parents and three children
	Six members	Working parents, grandparents and two children, Parents, grandparents and two children
Detached house		40 m^2, 50 m^2, 70 m^2, 90 m^2, 113 m^2 , 146 m^2
Apartment house		20 m^2, 30 m^2, 52 m^2, 73 m^2, 91 m^2 , 119 m^2

The time resolution of the model is 5-minutes. The family composition defines attributes of household members defined by age, gender, and occupation. For each attribute, different time use data is prepared. The time use data contains statistical information on time allocation for about 50 kinds of behavior on weekdays and holidays. The data is used to generate behaviors of household members stochastically on simulation days (Yamaguchi et al. 2014a). Based on the behavior, the room in which occupants spend time is determined based on an input file defining the relationship between behavior and room. This room information is used to determine the operation of space lighting, heating and cooling. The behavior is then converted to the operation of home appliances and equipment such as TV. Then, the information is converted to the energy consumption while taking into account specifications of home appliances and equipment. The specifications are given for each room respectively. Finally, the electricity demand of a house is quantified as the sum of consumption by all the appliances and equipment (Yamaguchi et al. 2014b).

For space heating and cooling, a dynamic thermal load simulation based on the thermal circuit network method is conducted by utilizing building data, internal heat gain and meteorological data. The building data is defined by the given house archetype. Internal heat gain is calculated by using the energy consumption of home appliances and lighting.

The energy demand for water heating such as bath, face washing, and cooking is estimated by considering the amount of hot water, hot water temperature, and city water temperature. This paper assumes two type of water heating equipment, that are a heat pump water heater and a condensing gas water heater which recovers latent heat in exhaust gas. Heat pump water heaters usually use night time electricity after 11 pm to 6 am to storage hot water in its storage tank, since electricity price is low.

Electricity generation by PV is calculated for each household based on PV specifications and meteorological data.

ENERGY MANAGEMENT SIMULATION MODEL

(1) Optimization of DSEMR

Figure 2 shows the energy flow considered in the energy management simulation model. This model solves a mixed-integer linear programming that optimizes the operation of home appliances, and equipment to minimize the energy cost defined by the equation (1). The equation (1) considers electricity purchase cost from electric grid and revenue gained by selling electricity surplus generated by PV. Figure 3 shows the electricity purchase price, V_{BUYt}, assumed in this paper (KEPCO, 2014). The selling price, V_{SELLt}, was assumed to be 37 yen/kWh under the current FIT program. V_{SELLt} can be changed to negative value to assume penalty for electricity surplus in Equation (1).

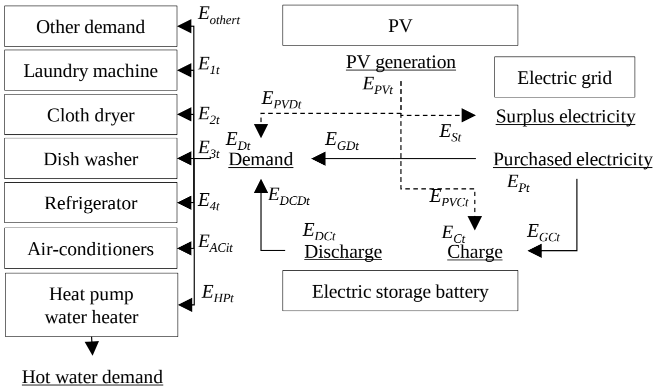

__Figure 2.__ The energy flow

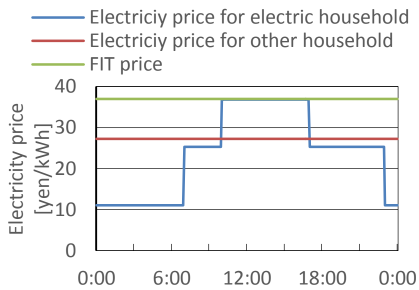

__Figure 3.__ The electricity price

$$\sum_{t=1}^{MAX\ STEP} V_{Buy_t} \times E_{P_t} - V_{SELL} \times E_{S_t} \rightarrow minimize \quad (1)$$

We considered three energy management cases. Base case assumes a situation in which no energy management is conducted. CostMin case assumes a situation in which the energy management system model optimizes the operation of DSEMR by using the equation (1) to minimize energy cost, while SurplusMin case do it by using the equation (1) with negative selling value to minimize electricity surplus.

(2) Setting of DSEMR

As energy storage device, we considered heat pump water heater and electric battery are considered. Heat pump water heaters generate hot water by using electricity to satisfy the hot water demand quantified by the energy demand simulation model. Electric batteries can charge electricity supply from the electric grid and discharge the storage electricity to satisfy

__Table 2.__ The specifications of the heat pump water heater and the electric battery

Heat pump water heater	Tank capacity	370L
	Thermal capability	4.2kw
	Self heat release rate	16%/day
Electric battery	Storage capacity	5,000W
	Maximum charge/discharge power	3,000W
	Inverter efficiency (on charging and discharging)	85%
	Charge-discharge efficiency	95%
	Self-discharge rate	0.01%/5min

the electricity demand in house. In this paper, we do not consider discharge to the electric grid. The specifications of the heat pump water heater and the electric battery are listed in Table 2. The variables and the constraint equations used in this model can be found on Appendix.

As the DSEMR in the second category, we assumed that the operation time at which laundry and dish washer are operated can be shifted to anytime in a day. For refrigerator, we assumed that the operation time at which defrosting is conducted can be shifted within the defrosting interval that is given for each refrigerator.

As the third category, we assumed that air-conditioners have two service levels in set point room air temperature. The first service level, Mode 1, is 26 °C for cooling and 22 °C for heating; and the second, Mode 2, is 28 °C for cooling and 20 °C for heating. We assumed that either of the service levels, Mode 1 or Mode 2, is decided every day to be applied to all air-conditioners in house. The electricity consumption at each service level is estimated by the energy demand simulation model.

ELECTRIC DISTRIBUTOIN SYSTEM MODEL

Finally, the electric distribution system model calculates the medium voltage (MV) and the low voltage (LV) at each node of the distribution network. Figure 4 shows the system configuration of the electric distribution network. The figure on top shows MV line, also called feeder line. Each node of the MV line equips a voltage transformer. Voltage transformers convert electric voltage from MV to LV. Each LV line delivers electricity to 10–20 houses. In the model, distribution network voltages at each node of MV and LV lines are calculated by so called Distflow model developed by Baran and Wu. (1989). The nominal voltage on MV and LV distribution networks are 6,600 V and 100 V, respectively. Details of the model can be found elsewhere (Kusakiyo et al., 2013). As LV has the legal limit (107 V) defined in the Electricity Business Act, when the electric voltage exceeds the limit, a power conditioner attached to PV disconnects PV from the electric grid.

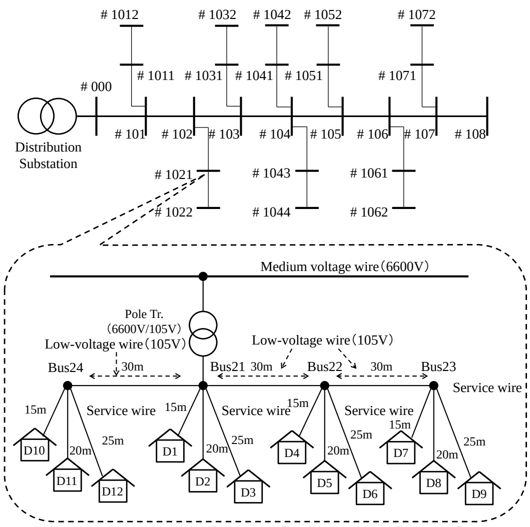

Figure 4. *The electric distribution network*

CASE SETTING

In this case study, 512 households, consisting of 240 detached houses and 272 apartment houses, were assumed to be connected to the abovementioned feeder line. The family composition and the house archetype (see Table 1) of each house were randomly selected. We assumed that detached houses equip either a heat pump water heater or a condensing gas water heater, while all apartment houses equip a condensing gas water heater. We also assumed that all detached houses equip PV and an electric battery. The capacity of PV was randomly selected based on the normal probability distribution with 4 kW of average and 1 kW of standard deviation. The house archetypes define a concrete roof area for each compass direction. This roof area limitation was considered in setting PV capacity for each compass direction.

SIMULATION RESULTS

Figure 5 shows the simulation result of the electricity demand, the PV generation and the grid load on 8th July calculated for a four member family consisting of a working male, a housewife, and two children. The grid load is the purchased and the sold electricity after charging and discharging of the electric battery. The positive grid load shows that the electricity demand of the house was larger than the electricity generated by PV. In CostMin case, the electricity consumption of laundry, cloth dryer, dish washer, and refrigerator occurred during night time. It was shifted from morning in Base case to decrease the electricity purchase and increase the electricity surplus since the surplus electricity can be sold for higher price than the electricity price. Additionally, the electric battery was charged for 1.5 hours in the morning and discharged during day-time to further increase the electricity surplus. On the contrary, in SurplusMin case, the appliances were operated during daytime to decrease the electricity surplus and remaining surplus was charged by the electric battery.

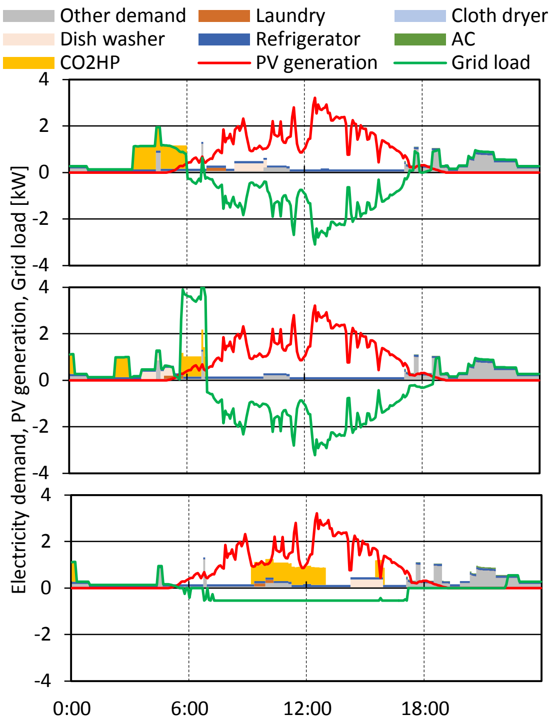

Figure 5. *The household simulation results (top: Base, Middle: CostMin Bottom: SurplusMin)*

Figure 6 shows the total balance of electricity in the community on 8th July. The negative values in grid load means that PV generated a larger amount of electricity than the demand in the community. The electricity surplus differs among the energy management cases. Base case has 3,250kWh/day of the electricity surplus, while it was 3,460kWh/day in CostMin case and 1,780kWh/day in SurplusMin case.

Figure 7 shows the simulation result of electric voltage on the LV at terminal node (#1072) on 8th July. The red dotted line indicates the legal limit of the LV, 107V. As shown in the figure, the electric voltage exceeded the legal limit during daytime in Base case and CostMin case. This caused that a part of PV was disconnected. On the contrary, in SurplusMin case, the electric voltage was lower than the legal limit as DSEMR was used to reduce surplus.

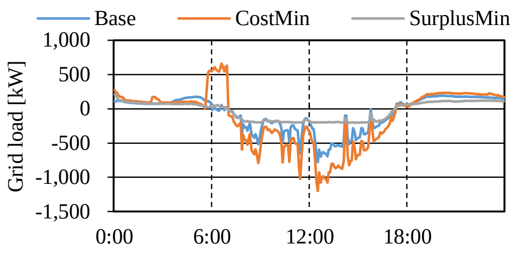

Figure 6. The grid load simulation results

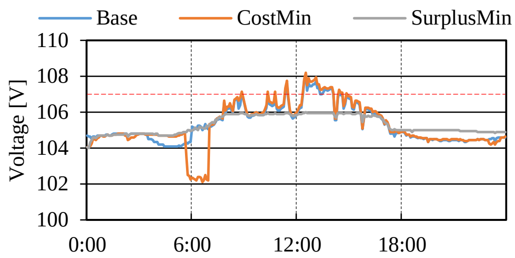

Figure 7. The electric voltage simulation results

CONCLUSION AND IMPLICATIONS

This paper demonstrated an integrated model for residential communities in which energy demand, operation of demand side energy management resources (DSEMR), and performance of electric distribution system are simulated. A case study showed that DSEMR is useful to maintain the stability of an electric distribution system. Results revealed that the distribution system becomes unstable as the current operation of appliances and equipment with large scale PV diffusions. When each household give priority to one's economy like CostMin case, this trend is promoted. However, DSEMR have the possibility to maintain the stability of the distribution system like SurplusMin case. These results highlight the importance to consider DSEMR of home appliances such as laundry, dish washer, and air-conditioner, in addition to the heat pump water heater and the electric battery.

APPENDIX

The equations (2) – (30) show the constraint equations and table 3 shows the variables used in the energy management simulation model.

$$\mathrm{E}_{S_t} + E_{PVC_t} + E_{PVD_t} = E_{PV_t} \quad (2)$$

$$\mathrm{E}_{P_t} = \mathrm{E}_{GD_t} + \mathrm{E}_{GDC_t} \quad (3)$$

$$\mathrm{E}_{D_t} = E_{PVD_t} + E_{GD_t} + E_{DCD_t} \quad (4)$$

$$\mathrm{E}_{D_t} = \sum_{a=1}^{5} E_{a_t} + \sum_{i=1}^{4} E_{ACi_t} + E_{other_t} \quad (5)$$

$$\mathrm{E}_{C_t} = E_{PVC_t} + E_{GC_t} \quad (6)$$

$$\mathrm{E}_{DC_t} = E_{DCD_t} + E_{DCG_t} \quad (7)$$

$$\mathrm{E}_{a_t} = P_{a_t} \times OPI_{a_t} \quad (8)$$

$$\mathrm{E}_{4_t} = P_R \times \left(1 - OPI_{4_t}\right) \quad (9)$$

$$OPI_{a_t} - OPI_{a_{t-1}} = OPS_{a_t} + OPF_{a_t} \quad (10)$$

$$OPS_{a_t} \leq OPI_{a_t} \quad (11)$$

$$OPF_{a_t} \leq 1 - OPI_{a_t} \quad (12)$$

$$\sum_{t=1}^{MAX\_STEP} OPS_{a_t} = \mathrm{N}_{day} \quad (13)$$

$$T_{a_{day}} \times OPS_{a_t} = \sum_{T=t}^{T_{a_{day}}} OPI_{a_T} \quad (14)$$

$$OPS_{3_t} = OPS_{1_{t-T_{1day}}} \quad (15)$$

$$E_{ACi_t} = \mathrm{ACi}_{M1_t} \times \mathrm{OPM1}_{day} + \mathrm{ACi}_{M2_t} \times \mathrm{OPM2}_{day} \quad (16)$$

$$\mathrm{OPM1}_{day} + \mathrm{OPM2}_{day} = 1 \quad (17)$$

$$P_{H_t} = HP/COP_t \quad (18)$$

$$COP_t = 0.137 \times T_t + 2.25 \quad (19)$$

$$\mathrm{STH}_t = (1 - loss_H) \times STH_{t-1} + HP \times OPI_{H_t} - H_{D_t} \quad (20)$$

$$\mathrm{STH}_t \leq MAX\ STH \quad (21)$$

$$\mathrm{STH}_t \geq MIN\ STH \quad (22)$$

$$\mathrm{STE}_t \leq MAX\ STE \quad (23)$$

$$\mathrm{STE}_t \geq MIN\ STE \quad (24)$$

$$E_{C_t} \leq MAX_C \times OPC_t \quad (25)$$

$$E_{DC_t} \leq MAX_{DC} \times OPD_t \quad (26)$$

$$E_{C_t} \geq MIN_C \times OPC_t \quad (27)$$

$$E_{DC_t} \geq MIN_{DC} \times OPD_t \quad (28)$$

$$OPC_t + OPD_t + OPN_t = 1 \quad (29)$$

$$\mathrm{STE}_t = (1 - loss_E) \times STE_{t-1} + \frac{r_C \times E_{C_t}}{24 \times 60 / MAX\ STEP} - \frac{E_{DC_t} / r_{DC}}{\left(24 \times 60 / MAX\ STEP\right)} \quad (30)$$

Table 3. *The variables used in the demand side energy management model*

Indices			Endogenous variable		
Variable	Definition	Unit	Variable	Definition	Unit
t	Index of time interval (= 1〜288)	step	r_{self}	Self-sufficiency ratio	%
day	Index of days (= 1〜366)	day	Es	Annual electricity surplus	kWh/year
a	Index of appliances 1:Laundry machines, 2:Cloth dryer, 3:Dish washer, 4:Refrigerator	-	E_D	Annual electricity demand	kWh/year
			E_C	Annual electricity charge	kWh/year
i	Index of air-conditoners 1:LDK, 2:Bed room1, 3:Bed room2, 4:Bed room3, 5:Bed room4	-	E_{DC}	Annual electricity discharge	kWh/year
			E_{St}	Electricity surplus at time t	W
Exogenous variable			E_{Dt}	Electricity demand at time t	W
Variable	Definition	Unit	E_{Pt}	Purchased electricity at time t	W
E_{PVt}	PV generation at time t	W	E_{Ct}	Electricity charge at time t	W
E_{Othert}	Other electricity demand at time t	W	E_{DCt}	Electricity discharge at time t	W
ACi_{M1t}	Electricity demand for mode1 of air-conditioner i at time t	W	E_{PVDt}	Electricity demand provided by PV at time t	W
ACi_{M2t}	Electricity demand for mode2 of air-conditioner i at time t	W	E_{GDt}	Electricity demand provided by grid at time t	W
P_{at}	Consumed power for appliance a at time t	W	E_{DCDt}	Electricity demand provided by battery at time t	W
P_{Rt}	Consumed stanby power for refrigerator at time t	W	E_{at}	Electicity demand for appliance a at time t	W
H_{Dt}	Hot water demand at time t	W	E_{ACit}	Electricity demand for air-conditioner i at time t	W
H_P	Thermal capability for heat pump water heater (=4.2kW)	W	E_{ht}	Electicity demand for Heatpump water heater at time t	W
COP_t	Coefficient of performance for heat pump water heater at time t	-	E_{PVCt}	Electricity charge provided by PV at time t	W
T_t	Outside temperature at time t	degree Celsius	E_{GCt}	Electricity charge provided by grid at time t	W
$MAX\ STH$	Maximum storage heat quantity (=25.8kWh)	Wh	E_{DCGt}	Electricity discharge for grid at time t (= 0)	W
$MIN\ STH$	Minimum keeping storege heat quantity	Wh	STH_t	Storege heat quantity of water heater tank at time t	Wh
$loss_H$	Self heat release (16%/day)	-	STE_t	Storege electricity of battery at time t	Wh
MAX_c	Maximum charge power (3kW)	W	OPI_{at}	State of appliance a at time t, binary; ON/OFF	-
MAX_d	Maximum discharge power (3kW)	W	OPS_{at}	Varialbe denoting start up of appliance a at time t	-
$MAX\ STE$	Maximum storage electricity (=5kWh)	Wh	OPF_{at}	Varialbe denoting shut down of appliance a at time t	-
$MIN\ STE$	Minimum keeping storege electricity	Wh	$OPM1_{day}$	Variable denoting mode1 of air-conditioners at day	-
N_{aday}	Number of operation time of appliance a at day	times	$OPM2_{day}$	Variable denoting mode2 of air-conditioners at day	-
T_{aday}	Operation hours by an operation of appliance a at day	step/times	OPI_{Ht}	State of heat pump water heater at time t, binary; ON/OFF	-
r_C	Inverter efficiency for charging (=90%)	-	OPC_t	Binary varialbe denoting charge of battery at time t	-
r_{DC}	Charge-discharge efficiency (=70%)	-	OPD_t	Binary varialbe denoting discharge of battery at time t	-
$loss_E$	Self-discharge rate (=1%/day)	-	OPN_t	Varialbe denoting stop of battery at time t	-
$MAX\ STEP$	Maximum succesive time (=288)	-			

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