論文の内容の要旨

論文題目　A study on the effect of demand response to energy resilience of communities (デマンド・レスポンスがコミュニティのエネルギー・レジリエンスに与える影響に関する研究)

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1. Introduction

The proposal of this study was to contribute ideas and solutions to ensure stable interaction among these three elements: human, architecture and energy. The critical problems of interest in this study are about: exploring the underutilized potential of demand response (DR) program of a smart grid system, exhibiting the importance of considering the interests of both supply and demand sides when making any studies or practices related to energy system performance, and examining the concept of resilience and its applicability in the area of human, architecture and energy. Three research questions were formulated: What constitutes resilience? What in a community system are considered? How to assess energy resilience of a community system?

2. Research aim

This study aimed to propose an assessment methodology to study the effect of DR capacity on energy resilience of communities based on bottom-up approach. The scope of this study was to demonstrate the usefulness of the proposed methodology to support decision-making process especially for energy suppliers, town planners and policymakers.

3. Resilience definition and scoping

A series of intensive reviews of literature related to resilience and smart grid systems were made to assist in defining resilience and determining proper scope of assessment for this study context. Many existing literature describes resilience either as an ability to withstand disturbance, an ability to recover rapidly or an ability to adapt to changes but the definition of resilience in this study has a different view. After reviewing more than 50 existing resilience definitions from various fields of study, analyzing them by identifying the fundamental structure of a resilience definition and the elements within the structure, and interpreting the meaning and representation of the identified elements, this study proposed that resilience is defined as the ability of a system depending on its own responsiveness and vulnerability to maintain its system functionality throughout any disturbances.

Literature reviews of resilience and smart grid systems supported the scoping of assessment target to be town-level community system including its power generation, network and consumption components. Town-level community was selected because it has the optimum size to function as a microgrid which is an essential factor in the study of resilience of power grid systems. The assessment data was decided to be based on daily power operation of community systems. Based on the proposed resilience definition, energy resilience of a community system is defined as the ability of a community system depending on its own responsiveness and vulnerability to maintain its energy-dependent functionality throughout any disturbances. Disturbances in this study was defined as any destabilizing factors that can cause small-scale and short-term difficulties to daily power operation of a community system to achieve power balance. In addition, this study assessed a system based on its performance to stay resilient and did not look into the system performance in unresilient state. Therefore, the recovery rapidity of a system was not considered in the assessment.

4. Proposal of methodology to assess energy resilience of community systems

Then, two categories of indicators: functionality and attribute indicators were assigned to assess energy resilience (Figure 1). Functionality indicators were used to represent resilience performance of a community system and were assessed based on overall system functionalities. System functionalities significant from the perspective of both supply and demand sides were selected as functionality indicators that power balance of daily power operation was selected to represent the functionality indicator for the supply-side interest where as demand users' convenience and cost of electric energy were for the demand-side interests. Attributes indicators represented significant supporting performance that must be taken into consideration and were assessed based on the performances of power generation, network and consumption components of a community system. Redundancy, adaptability, reliability and vulnerability were chosen as the attribute indicators because they are among the top attributes most representative of resilience. In addition, the interdependency among the proposed indicators and how key stakeholders can influence on the performance of the proposed indicators were explained.

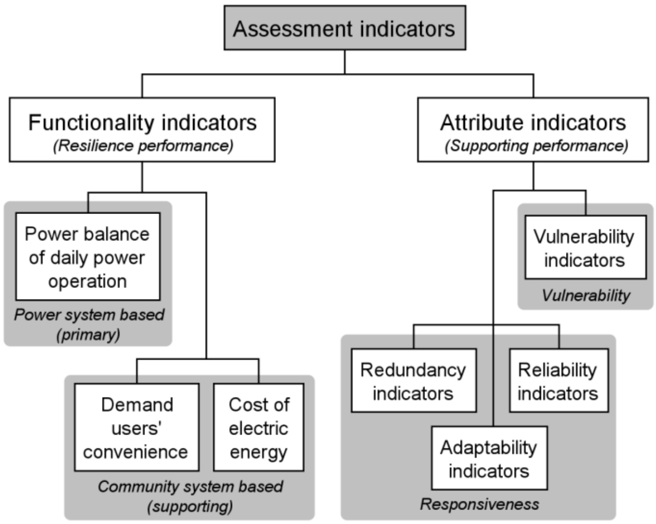

Figure 1 Categorization of assessment indicators

An analysis model was formulated to model a community system and its power components and simulate daily power operation of the community. The analysis result was used as the input for assessment model (Figure 2). Essentially, the modeling of a town-level community was based on bottom-up approach that modeling began from building level, then aggregating through neighborhood and village levels in between to finally arrive at the community level (Figure 3). The bottom-up approach was applied to model power supply, demand and demand response capacity (Figure 4). Community power demand is the total of power demand of different building types. Power demand of a building type was modeled by first summing up all of its unit demands per building floor area (BFA) for different energy uses such as heating, cooling, hot-water making and electric appliances and then multiplying it with the BFA of the building type. Regarding on the modeling of demand response capacity, as there was no available and reliable statistical information regarding the demand response potential of each building type, the best effort in this study was to estimate it as the percentage of ongoing power demand which can be turned off. This estimation approach was very similar to modeling power demand that demand response potential was estimated beginning from the unit demands per BFA for energy uses such as heating, cooling, hot-water making and electric appliances and then added up together to form the total demand response potential of the building type. Simulation of daily power operation was made by using the developed models and the power flow analysis was used as a means to verify the feasibility of each simulated result. Verifying and validating the analysis model are to a limited extent equal to verifying and validating the assessment model itself. While verification could be made, the validation of the assessment model was not feasible at the time of this study was made because the required information was not available or disclosed.

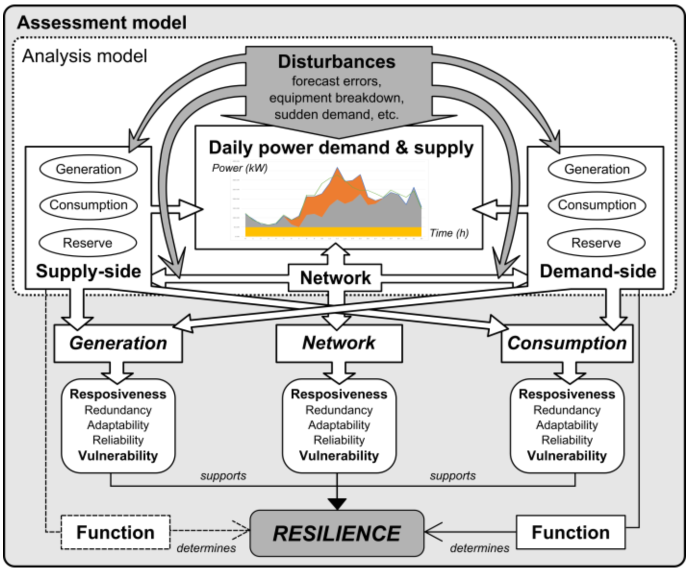

Figure 2 Assessment model

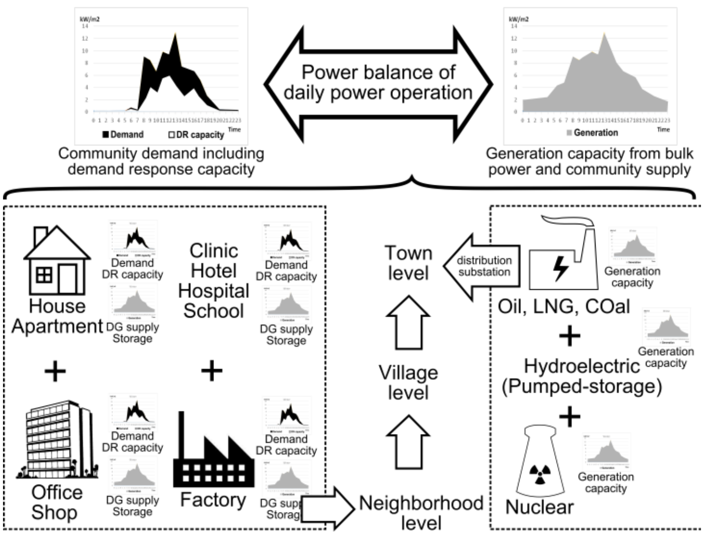

Figure 3 Modeling based on bottom-up approach

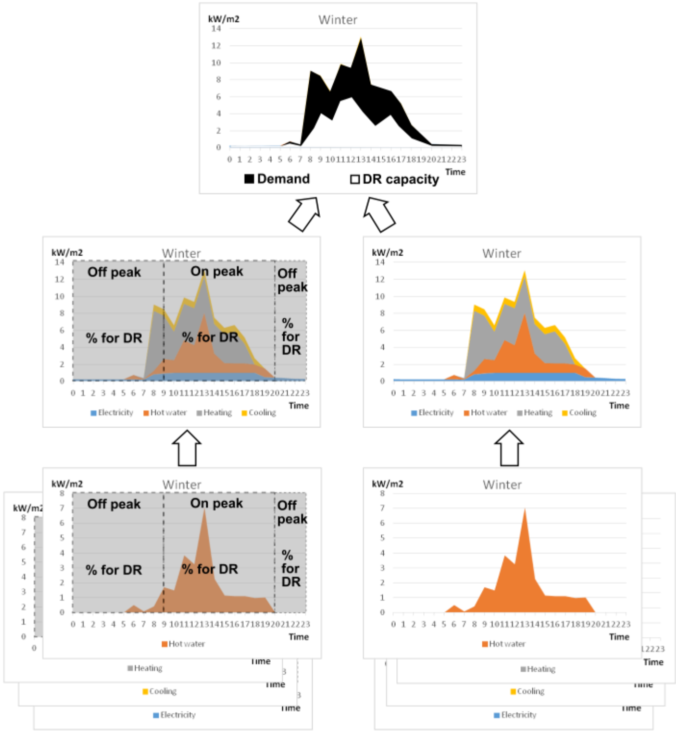

Figure 4 Modeling power demand and DR capacity

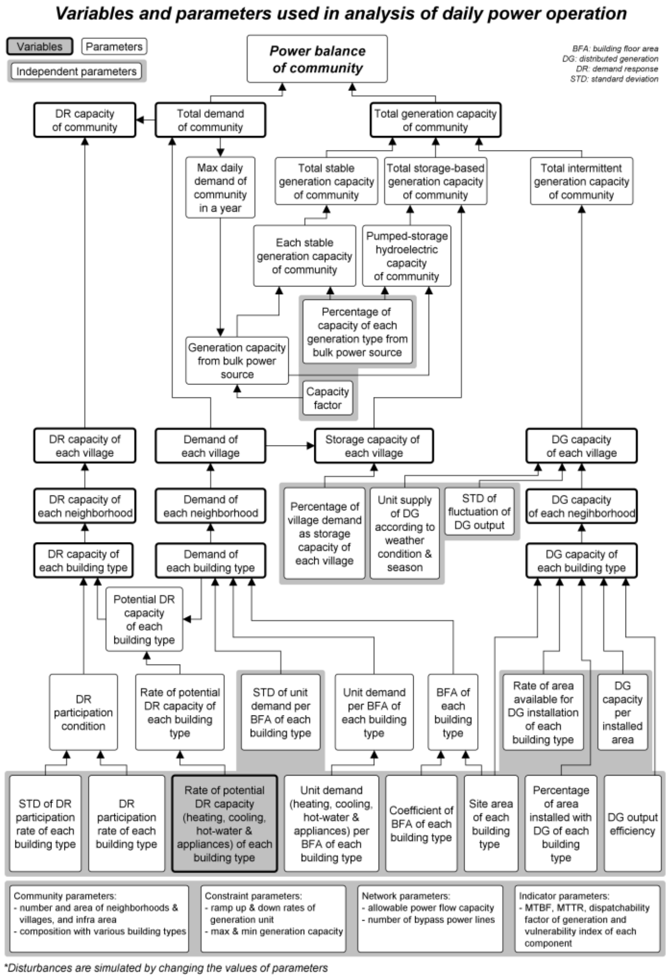

Figure 5 Variables and parameters used in analysis of daily power operation

5. Demonstrating applicability of assessment methodology through case studies

For the purpose of studying the effect of demand response to energy resilience of community systems under various disturbance conditions and demonstrating the usefulness of the proposed methodology in supporting decision-making process, a case study was made by using the developed analysis model. Three towns with different characteristics in the aspect of town composition were used (Figure 6). The town highly composed by residential building was represented by Umegaoka town in Setagaya district, the town highly composed of high-rise residential, office and commercial buildings was represented by Toyosu town in Koutou district and the town highly composed with residential buildings and consisted of a substantial percentage of small factories was represented by Kitakoujiya town in Oota district.

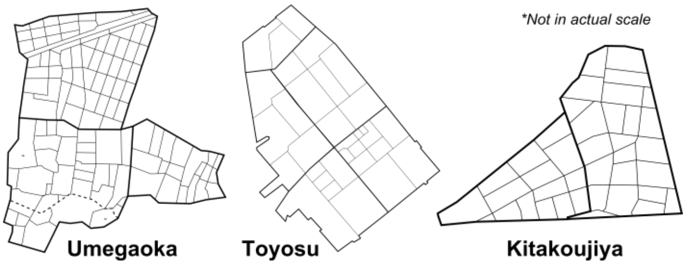

Figure 6 Three towns selected for case studies

Four disturbance cases (Case B, C, D and E) were prepared to simulate four different disturbance situations when decisions needed to be made. Case B is the main case used to discuss the core usage of this assessment model when used by energy suppliers and town planners. The other cases such as Case C, Case D and Case D are used to demonstrate additional usage of this assessment model in different situations. These disturbance cases were composed by 13 disturbance scenarios (Figure 7) which represented the reduction of generation capacity of the bulk power supply and service deterioration of some power components. In each disturbance scenario, the community system of every case study was modeled with five levels of demand response capacity (from DRC100: Ideal to DRC000: Zero) to examine how different levels of demand response capacity can contribute to and affect energy resilience. The preparation of the five levels of demand response capacity was based on extreme conditions that the analysis adopted the possible designs, instead of representative configuration of demand response capacity of a community.

Disturbance case	Disturbance scenarios
Case B	BAU, B1 to B5
Case C	BAU, C1, C2
Case D	BAU, C2, D1, D2
Case E	BAU, E1 to E3

Figure 7 Four disturbances cases

6. Demonstrating usefulness and implications of proposed methodology through discussion of case-study results

According to the analysis and overall assessment results (Figure 8 and Figure 9), Kitakoujiya town was the most resilient town among the three towns because it could achieve energy resilience in most disturbance scenarios whereas the other two towns were unresilient. Through discussing the result of each disturbance case, the usefulness and implications of the proposed methodology to decision makers such as energy suppliers, town planners and policymakers were explained.

Disturbance scenario	Level of available demand response capacity				
	DRC100	DRC075	DRC050	DRC025	DRC000
BAU	Resilient	Resilient	Resilient	Resilient	Resilient
B1	Resilient	Resilient	Resilient	Resilient	Resilient
B2	Resilient	Resilient	Resilient	Resilient	Resilient
B3	Resilient	Resilient	Resilient	Resilient	Resilient
B4	Resilient	Resilient	Resilient	Unresilient	Unresilient
B5	Resilient	Unresilient	Unresilient	Unresilient	Unresilient
C1	Resilient	Resilient	Resilient	Resilient	Resilient
C2	Resilient	Resilient	Resilient	Resilient	Resilient
D1	Resilient	Resilient	Resilient	Resilient	Unresilient
D2	Resilient	Resilient	Unresilient	Unresilient	Unresilient
E1	Resilient	Resilient	Resilient	Resilient	Unresilient
E2	Resilient	Resilient	Resilient	Resilient	Unresilient
E3	-	-	-	-	-

Figure 8 Performance of energy resilience of Kitakoujiya town

Case B can be a good case to demonstrate how energy suppliers can use the assessment model to support decision making. Nowadays, when a power system is becoming unstable, the usual practice is that energy suppliers will request the users to reduce their power demand as much as possible. Sometimes the amount of demand reduction is a lot more than the required amount to keep the power system stable. Unnecessary demand reduction deters human activities. However, the suppliers have to do it this way because currently not every building is equipped with building energy management system (BEMS) that the suppliers are unable to ascertain the actual demand reduction from the users. When BEMS is more widely adopted by the users and the suppliers manage to get hold of data and information about how users are acting in DR events, then the suppliers can use this assessment model to decide the required amount of demand reduction to request from the users. For example, the column of DRC100 in Figure 8 represent the current practice which the suppliers are doing to get as much demand reduction as possible from the users, whereas in fact the suppliers of Kitakoujiya town can decide to request the users to at least reduce 50% of their demand if the disturbance scenario is equal to B4, or 25% if it is D1. Users can then reduce the required amount of power demand based on the visualized consumption information from the BEMS. In this way, the assessment result can help to make the DR program to be more efficient that no unnecessary demand reduction has to happen. This situation also can help to create good relationship between the energy suppliers and the users because the users understand that the suppliers are professionally doing their jobs to keep the power system stable without overlooking the needs or performance at the bottom level. Based on the assessment results, the suppliers can also design and offer effective DR programs to the demand users.

A benefit of DR is to allow the energy suppliers to delay the expansion of generation capacity which involves large investment capital to build new power plants. However, a resilient community system should require not only a stable power operation but the community activities and functions must be maintained above acceptable level as well. Therefore, a DR program should not be used as a means to avoid building new generation facilities by making the users suffer. Instead, the suppliers should use this assessment model to support them in making decision about the right timing to start planning for generation expansion. For example in Figure 9, Toyosu town actually managed to achieve power balance in the B5 scenario with DRC100 and DRC075 but the cost of operation in this two scenarios exceeded the threshold value, which is why Toyosu town was considered as unresilient. This is the time when the suppliers should plan for new generation expansion so that other community-based functionalities can be maintained above acceptable level and a safe degree of resilience is ensured. The assessment methodology proposed here can be based on to develop resilient operation plans and strategies that meet the ends of both sides.

Disturbance scenario	Level of available demand response capacity				
	DRC100	DRC075	DRC050	DRC025	DRC000
BAU	Resilient	Resilient	Resilient	Resilient	Resilient
B1	Resilient	Resilient	Resilient	Resilient	Resilient
B2	Resilient	Resilient	Resilient	Resilient	Resilient
B3	Resilient	Resilient	Resilient	Resilient	Resilient
B4	Resilient	Resilient	Resilient	Unresilient	Unresilient
B5	**Unresilient**	**Unresilient**	Unresilient	Unresilient	Unresilient
C1	Resilient	Resilient	Resilient	Resilient	Resilient
C2	Resilient	Resilient	Resilient	Resilient	Resilient
D1	Resilient	Resilient	Resilient	Resilient	Unresilient
D2	**Unresilient**	**Unresilient**	**Unresilient**	Unresilient	Unresilient
E1	Resilient	Resilient	Resilient	Resilient	Unresilient
E2	Resilient	Resilient	Resilient	Unresilient	Unresilient
E3	Resilient	Resilient	Resilient	Unresilient	Unresilient

Figure 9 Performance of energy resilience of Toyosu town

Other usefulness and implications such as studying about attributes (redundancy, adaptability, reliability and vulnerability) of community systems, studying energy resilience at the bottom-level component, and optimization of community systems are shown in detail in the full thesis.

7. Limitations of this study

The largest limitation of this study is that the proposed methodology is limited to assess functionality performance when a system is resilient in terms of power balance but not when the system is unresilient (power imbalance). Assessing performance during an unresilient state is a very significant but complicated and dynamic issue which becomes much more difficult when the performance during both resilient and unresilient states need to be assessed together. This study goes as far as assessing and discussing how DR capacity can keep a system performance within normal or resilient states but does not discuss in great details about system performance during unresilient state.

The choice of this study to implement DR only when the power system is becoming unstable can be a limitation because it poses a limit to the flexible use of DR. In addition, this study assumes that pricing plan or fluctuation in all disturbance scenarios is the result of market demand and supply rather than a strategy purposely imposed to restrict power consumption. By doing so, the DR capacity or demand reduction considered in this study is all come from the reduction made when the users fulfil the DR request from the suppliers. The dynamics (reduction, increase and shift) of demand under the effect of pricing plan are not considered in detail. These dynamics are considered as already embedded into the forecasted demand which is based on historical data. However, this simplification can be a limitation to reflect the reality condition.

Also, the analysis of power operation was made in a stationary manner rather than dynamic. In fact, sometimes the power demand after a DR event can increase because the demand reduced could be just a shift of power consumption at later time. However, the analysis did not consider such dynamic condition which may increase the complexity of the discussion and that becomes another limitation of this study.

8. Conclusion

The conclusion of this study examined the extent of the objectives of this study have been achieved. This study proposed an assessment methodology, the proposed assessment methodology was used in a case-study analysis to study the effect of demand response capacity on energy resilience of communities and demonstrate the usefulness (and limitations) of the proposed methodology in decision-making process. Also, the analysis results conditionally supported the first generated hypothesis that a community with more demand response capacity is more resilient because DR capacity can be used as virtual power supply source to achieve power balance. This study could not support the second generated hypothesis that a community composed more uniformly by various building types is more resilient. It is important to note that the analysis was just a means to demonstrate the application of the proposed methodology, the results of the analysis and assessment from the case study are not supposed and cannot be used to establish any statistically significant relationships between demand response capacity and energy resilience.