THE OPEN ENERGY SYSTEM AS AN AUTONOMOUS DC MICROGRID

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ABSTRACT

The IPCC predicts that the average temperature rise of the earth and the cumulative amount of generated carbon dioxide since the industrial revolution until the end of this century would be approximately proportional. Because of climate change and the limits of non-renewable energy reserves, this cannot lead to a sustainable society. On the other hand, we know that the direct use of sunlight can cover the annual energy demand of all human activity. In this study, we propose an autonomous DC microgrid system with distributed power exchange control to increase the utilization of renewable natural energy and to ensure minimal energy supply in the event of a large-scale disaster. Each house included in this system can continue to provide power to appliances from their batteries and solar panels even in the event of disconnection from the transmission line or power outage. We call this system "Open Energy System" (OES).

INTRODUCTION

The imposed reduction of carbon dioxide emissions in many countries has helped increasing the prevalence of renewable energy. However, mega solar and large wind power plants include large equipment and a burden for the power grid to absorb the output fluctuations. In Japan, this is one of the main hurdles that hinder the increase the proportion of renewable energy. Indeed, as of 2012, renewable energy except hydropower only represents 1.6% of the country's electricity generation [1].

For this, self-sufficient power systems that do not dependent on the power grid and that can be deployed similarly to consumer electronics are gaining interest as a solution to both increase renewable power sources as well as to increase resilience in case of disasters [2, 3].

The system we propose uses as building blocks DC nanogrids including PV panels and secondary batteries in each house (Fig.1). These subsystems are interconnected via a DC power bus, which is used to share energy resources such as PV or also an emergency power supply way even during power outages due to disaster (Fig.2). An autonomous distributed grid system is thus built for a small community of houses. Furthermore, this system can flexibly expand over several layers by interconnecting not only houses, but entire grid systems in a hierarchical way. We named this kind of DC micro grid system *Open Energy Systems* (OES) [4].

In this paper, we focus on the control strategy of OES and propose an autonomous decentralized power exchange control for OES in order to improve the share of renewable energy within a community.

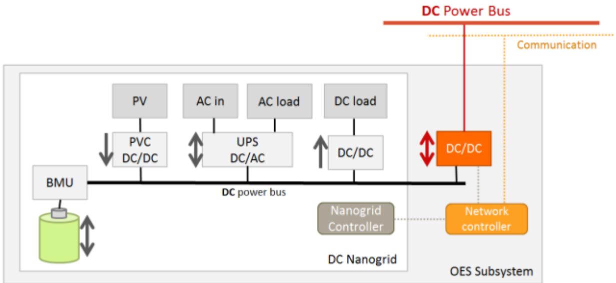

Figure 1. Elemental subsystem for OES: a DC nanogrid.

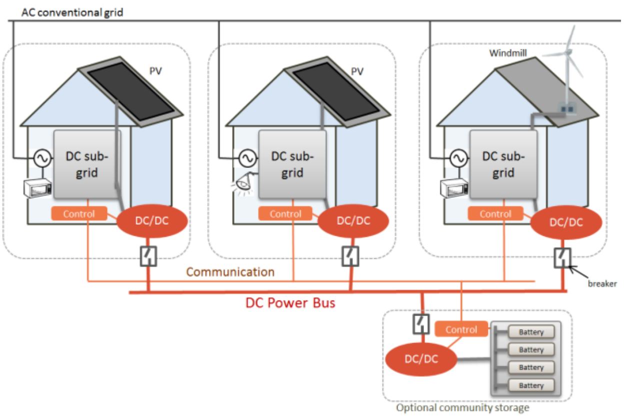

Figure 2. General system layout for OES.

RENEWABLE ENERGY USE FOR HOMES

In this research we consider solar PV systems as a renewable energy source for the residential community. The utilization efficiency of solar energy can be measured using two indicators: one is the Solar Replacement Ratio (SRR) R_{SRR} which is the percentage of the electricity demand energy that could be replaced with solar energy (Eq.1). The entire demand energy is given by E_{demand}, the energy from the AC grid is E_{AC}, and the energy corresponding to the battery state of charge (SOC) difference between start and end of simulation is $E_{\Delta SOC}$. Another indicator is the Solar Operation Ratio (SOR) R_{SOR}. This ratio indicates the actual solar generation energy E_{solar} compared to the maximum available energy $E_{unlimited\_solar}$ that could be obtained (Eq.2). Note that this indicator is inversely proportional to the introduction cost per unit power of solar power generation system.

$$R_{SRR} = \frac{E_{demand} - E_{AC} - E_{\Delta SOC}}{E_{demand}} \quad (1)$$

$$R_{SOR} = \frac{E_{solar}}{E_{unlimited\_solar}} \quad (2)$$

Solar energy is exposed to significant generation fluctuations that vary greatly throughout the day but also depend on weather and season. On the other hand, the electricity demand also experiences fluctuations according to human activity which usually presents a bottom demand for bedtime hours and peak demands in morning and evening hours. In addition, demand patterns also vary according to the season, depending on the time and day of the week as well as across households.

For the above reasons, it is necessary to consider the deviation of household demand pattern and solar power generation pattern when examining the energy balance of a residential community.

In a preliminary study we examined the annual energy balance between 20 houses' demand data (6KVA contract performance data, Kyushu, Japan) and the solar power generation expectation from NEDO's sunlight database (http://app7.infoc.nedo.go.jp/index.html, 3kW$_{peak}$, Naha, Okinawa, Japan). As shown in Fig.3, the demand-response requirements vary not only hourly throughout a day but also monthly throughout one year.

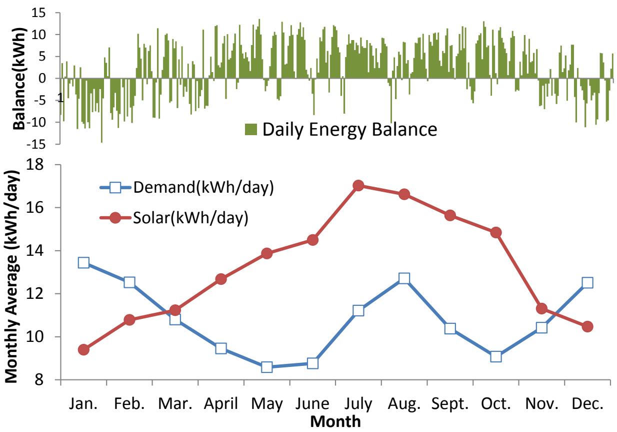

Figure 3. Demand and solar energy balance for a year.

In this case, PV system capacity is chosen so that the annual solar generation capacity is approximately 120% of the amount annual demand with medium sunlight year of the database.

There are two approaches to further improve the utilization of the solar PV: One is to connect each house to the power grid, which is a method for averaging the entire supply-demand balance to avoid full-charging and over-discharging of the battery. This approach improves both SRR and SOR. Another approach consists in actively transferring the surplus power that cannot be stored in the battery of one subsystem to another subsystem that can store it. If no subsystem can store the generated power, it may be provided to the utility grid. This can be considered as a kind of the Virtual Power Plant (VPP) in the reference [5]. VPP can not only improve the SOR but also reduce the load fluctuation of the conventional AC power grid.

OPEN ENERGY SYSTEM (OES) CONCEPT

The OES concept can be seen as an autonomous distributed DC microgrid system. Nanogrids with independent solar panels and secondary batteries in each home are the basic components. Nanogrids are then interconnected through a DCDC converter that serves as interface to the shared DC bus.

OES-subsystems are aimed at an easy deployment in homes as well as to be able to continue operation even during utility grid outages or when the subsystem is disconnected from the DC grid. Note that in the future, an auxiliary power supply such as a fuel cell connected to the DC grid could serve as emergency supply during bad weather or disaster. However, in this paper we only consider the conventional AC grid as power supply when solar energy is not sufficient.

Many current approaches focus on reverse power flow to the AC grid (feeding-in), but this adds a burden to the AC grid resulting into dropping feed-in tariffs or refusal of buying the solar energy by the utilities. Thus, for OES, we do not consider feeding-in to the AC grid and instead provide a distributed control mechanism that allows power exchange within the OES community. We consider only the DC grid in order to achieve the islanding operation as well as full autonomous operation during AC power failure.

FEASIBILITY STUDY ON THE REAL-TIME SIMULATOR

We made real-time, multi-domain simulations in MAT-LAB/Simulink/SimScape. Based on EV technologies, we build a physical model of four subsystems and the interconnections with different kinds of architectures and exchange strategies from conventional AC grid power system presented in JSAE Annual Congress [6]. In this paper, we present a further practical model consisting of 20 subsystems (Fig.4). Parameters for the model are shown in Table 1.

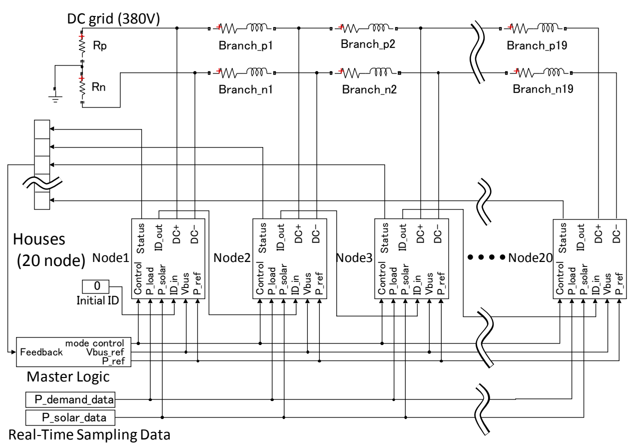

Figure 4. Physical simulation model sample of the OES

Table 1. Power Exchange simulation parameters

Item	Condition	Value
DC power cable (house to house)	8mm^{2}x100m	2.3Ω/km
Power Exchange Logic (SOC leveling)	ON: SOC>90% or SOC<10% or $\|SOC\text{-}SOC_{system}\|$>25% OFF: $\|SOC\text{-}SOC_{system}\|$<1%	Discharge 0~1kW (SOC_{system}<SOC) Charge 0~1kW (SOC_{system}>SOC)
DCDC converter Loss/Efficiency	Min(Sleep) Min(Operation) Peak Efficiency	5W 70W 95%
Solar PV system	3kW(peak) (per house)	Average13.2kWh/day
Demand Electricity	6kVA(max) (per house)	Average10.8kWh/day

Power exchange control method

At first, we examined the impact of the number of houses in an OES community on the Solar Replacement Ratio and consequently the effectiveness of the power exchange between houses. As shown in Fig.5, the SRR increases as the microgrid size increases. Thanks to the power exchange, demand and supply can be better managed compared to standalone houses and thus helps reducing peak demands and enhances solar utilization efficiency. We observe that the SRR stagnates to around 80% starting from 10 houses which represents the minimum number of nanogrids that should be connected for the power exchange to reach its potential to absorb local demand fluctuations.

To obtain these results, we used a model developed in our previous study which is based on a power interchange system for levelling battery levels that uses the DC grid intermittently. This system proved to be an effective strategy for charging the secondary battery [7]. Real demand data and solar generation power estimated from a solar irradiation database are used to verify the power interchange effectiveness throughout one year. We compared the three systems. The first system is a conventional PV system without batteries that uses the AC grid for matching the demand, meaning sunlight is only used directly (***direct PV***). The second system includes batteries in each house, thereby constituting in-house system that could be seen as standalone, one-house DC nanogrid where a PV charger and an internal controller regulate the charging/discharging of the battery (***standalone nanogrids***). The third system adds the power interchange between the nanogrid systems (***OES approach***). Exchange conditions are shown in Table 1. All three types of system assume an installed solar power system of 3kW$_{peak}$ in each of the 20 households. Each household is subscribed to a 6kVA contract with an average daily demand of 10kWh.

For the direct PV system, the SRR for each month is about up to 40% (Fig. 6) and approximately 35% of the electricity demand can be replaced by solar energy throughout the year (Table 2). In system 2, a portion of the night power can be provided by the solar energy stored in the battery which increases the SRR to about 70% (Table 2). The power interchange used in the third system (OES) could further increase the SRR to 77%. Moreover, an increase of the PV system's capacity to 6kW$_{peak}$ results in about 86% of the demand energy to be replaced by solar energy throughout a year (Fig. 7). But this means more solar panels need to be installed (higher initial costs) and hence the Solar Operation Rate (SOR) is much lower (Fig. 7).

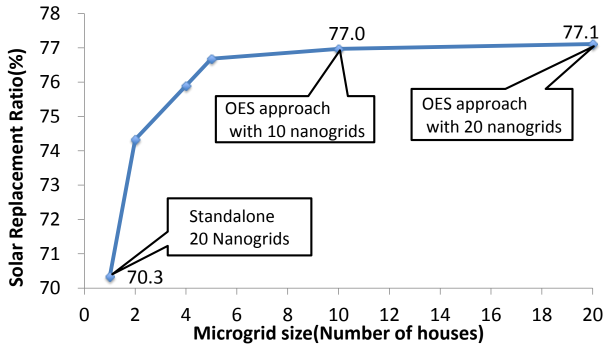

Figure 5. Solar Replacement Ratio in function of OES cluster size.

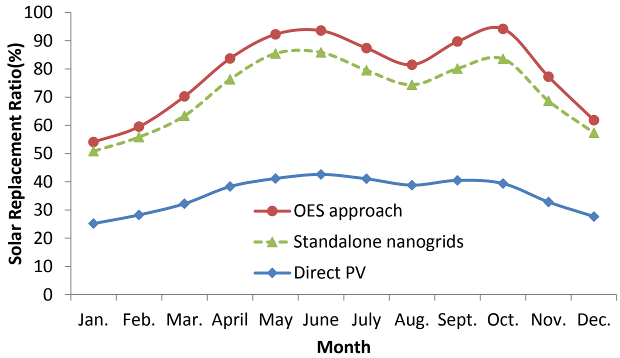

Figure 6. System type comparison using monthly SRR

Table 2. Simulation summary (1 year)

System Type	Solar PV	Battery	DC Power exchange	SOR	SRR
Direct PV	3kWp	-	-	28.7%	35.0%
Standalone nanogrids	3kWp	6kWh	-	57.9%	70.3%
OES approach	3kWp	6kWh	Yes	66.7%	77.1%

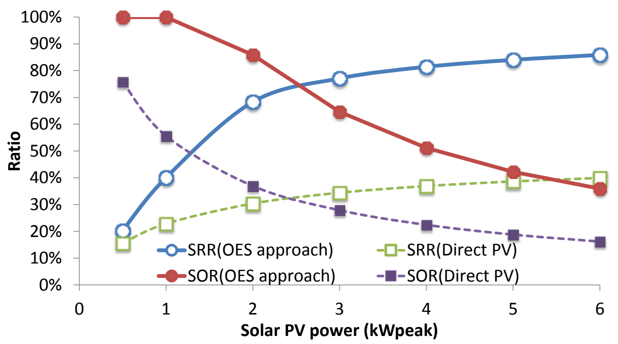

Figure 7. Solar Replacement Ratio and Solar Operation Ratio in function of the solar generation capacity

Virtual Power Plant

The solar power is generated in a narrow timespan during daytime, while power demand peaks in the mornings and evenings. In order to increase the Solar Replacement Ratio, additional solar panels are needed but that reduces the Solar Operation Ratio of the microgrid (Fig.7).
To solve this trade-off problem, various systems for using the surplus solar power energy or for supplying it to the outside have been proposed. One way could be to use the surplus solar energy for time-flexible, energy consuming processes such as the production of hydrogen on the DC grid. Another, more common method is to provide it to the conventional AC grid by reverse power flow (feed-in).
In this paper, we examine a system to sell surplus power to nearby customers through the AC grid. We assume to be able to estimate the excess energy for one day for the entire system, and to supply the energy to the AC grid in the short time window. Since this kind of system supplies the surplus power to the AC utility grid it can be seen as a Virtual Power Plant (VPP) in reference to [5].
Fig.8 shows the VPP energy source which is the average difference of the PV power generation and demand power of the 20 aggregated houses. The VPP output patterns were considered for two strategies (Fig.9): strategy 1 is to sell the surplus energy between 11:00 and 15:00 for meeting the peak demand caused by air-conditioning in commercial buildings; strategy 2 is to sell it in the two timespans from 7:00 to 9:00 and from 18:00 to 20:00 which corresponds to the peak demand of general households.

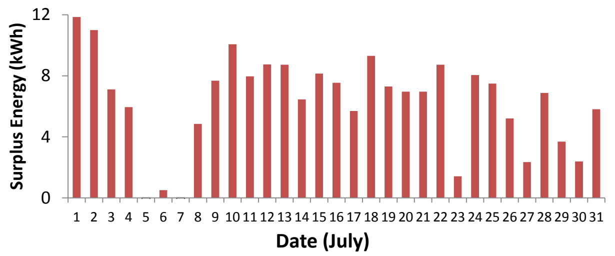

Figure 8. VPP energy source (Surplus energy per house)

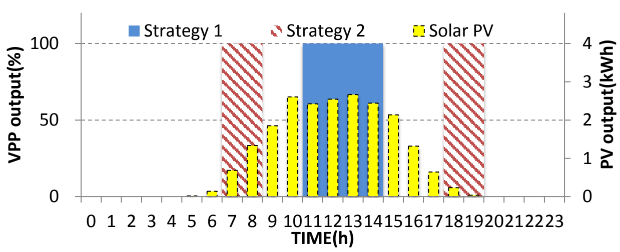

Figure 9. VPP output strategies

As shown in Fig.10 and Table 3, SOR is significantly improved up to 96.1% by VPP using strategy 1. When using strategy 2, the SOR is saturated in 68.4% for Full-SOC of batteries by time shifted demand from PV peak. In practice, the VPP system would need predictions of weather and electric power demand. Only with this information, the VPP system can improve the solar PV utilization.

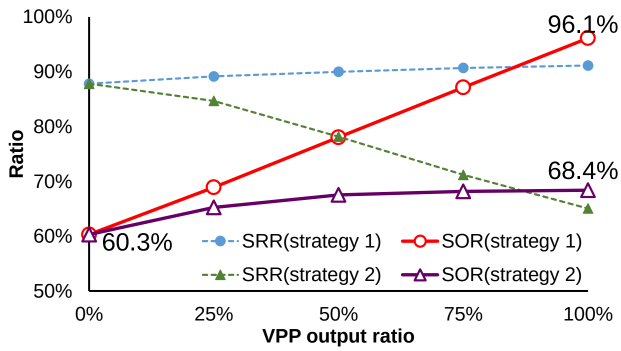

Figure 10. SRR and SOR in function of VPP strategies

Table 3. Power Exchange and VPP system merit (July)

System Type	VPP output	Time window	DC Power exchange	SOR	SRR
w/o VPP	-	-	Yes	60.3%	87.8%
Strategy 1	100%	11-15	Yes	96.1%	91.1%
Strategy 2	100%	7-9,18-20	Yes	68.4%	65.1%

FEASIBILITY STUDY IN THE REAL WORLD

Autonomous distributed control system

To put the OES approach in practice we came up with layered software that is able to fully control the power flow between the DC nanogrids and thus allows energy exchange between houses over a DC power bus. The procedure to regulate the bus voltage and current as well as the lower layer software are described in [7]. The highest software layer is responsible for performing the tasks required for the OES to handle power exchanges fully autonomously (without human intervention). The difference with most other systems is that this software is not centralized on one special logical unit, but entirely distributed over the subsystems that communicate with each other over message exchanges. To achieve this, we got inspired by one of the most widely adapted decentralized architectures: pervasive peer-to-peer networks as described in Tannenbaum's book on Distributed Systems [9]. Peer- to-peer systems are horizontally distributed meaning that all processes or systems are equal from a high-level perspective ensuring independence and reducing bottlenecks [9].

We adopted a MultiAgent System (MAS) approach which has been shown to work well to control intelligent grid systems made of less-intelligent entities (local controllers) [10]. We split the software in three main parts that are treated by a software agent. A simplified flow chart is shown in Fig.11.

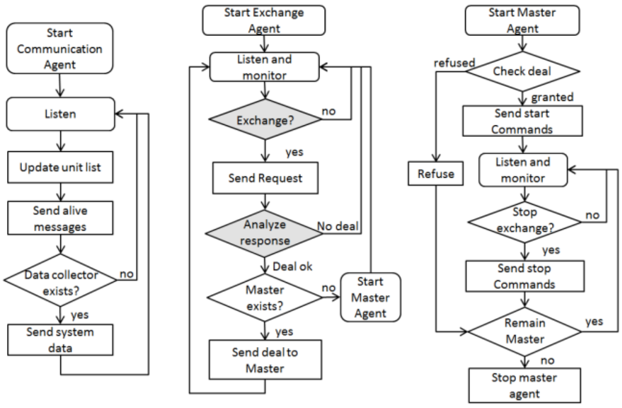

Figure 11. Simplified flowchart of three main agents for autonomous power transfer

Experimental prototype system

Both hardware and software are being developed and tested on several full scale prototypes: 3-subsystem experimental prototype in the Sony Computer Science Laboratory in Tokyo, another 3-subsystem prototype at the Okinawa Institute of Science and Technology (OIST) as well as our full scale platform at OIST which consists of a community of 19 inhabited houses, all equipped with a DC nanogrid and OES microgrid system (Fig.12).

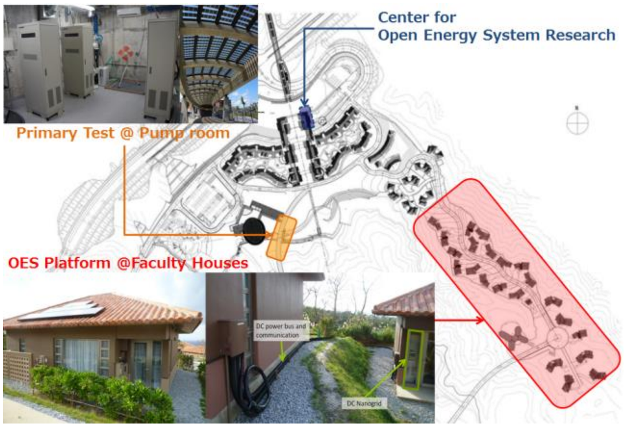

Figure 12. OES platform at OIST: primary test site and full scale platform at faculty houses.

We developed an SOC based autonomous control system as described in the simulation and the previous paragraph. Nanogrids can be added and removed dynamically in a configuration-less plug & play like way and request or respond to energy exchange request from other houses (third system – OES approach). In practice, feeding-in to the utility grid (VPP) is not implemented. Improvements of the control system, exchange strategy and efficiency are still in progress.

CONCLUSIONS

This ongoing research suggests a new type of DC based, distributed interconnection of DC nanogrids. In this paper, we propose the OES concept that applies to both in terms of hardware and software architecture and show the benefits on 20-node simulations using physical model. We analyzed this kind of interconnected microgrid system using SRR and SOR and compared it to direct PV systems as well as standalone nanogrid systems. We analyzed the impact of the cluster size and the PV capacity throughout a year using real consumer demand data and irradiation data. Finally, we studied the OES system as a VPP feeding in electricity to the utility grid. We further demonstrated the practical feasibility on a full-scale platform. Because of its modular open architecture it can develop gradually, one subsystem at the time, thus reducing infrastructural investment.

Acknowledgments

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