Coordinated Control of Demand Response for Large Installation of Renewable Energy Sources in Isolated Islands

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***Abstract*—Renewable energy sources are attractive for supplying electricity to isolated island power systems. When the penetration rate of Photovoltaic Systems (PVs) becomes large, the electricity demand cannot consume all of the PV output, but the PV output needs to be curtailed. Demand Response (DR) of heat pump water heaters and battery energy storage systems can reduce the curtailment. Waterworks systems are also suitable for DR resources because many of the waterworks systems have large tanks or dams as water storages. In order to utilize the large flexibility of waterworks systems fully, multi-daily coordinated control of the DR resources will be needed. This paper constructs the optimization model of the isolated power system with several DR resources as a first step of making coordinated control method. Comparing the operation of DR resources between 2-weeks optimization and 1-day optimization, the effect of long-term planning is analyzed with 5 PV capacity settings. Simulation results indicate that the suitable rules of DR coordinated control differ according to the seasons and installed PV capacity.**

***Index Terms*—Coordinated control, demand response, renewable energy source, waterworks system, optimization**

I. Introduction

Installation of Renewable Energy Sources (RES), especially photovoltaic Power Systems (PV) and Wind Turbines (WT) into isolated islands has been focused in recent years [1]. This is because generation costs of Diesel-engine Generators (DG) in isolated island systems tend to be higher than the generation costs in larger power systems.

However, when the ratio of the RES becomes higher, the curtailment of RES increases to keep the power balance inside the isolated islands. For example, in Japanese-islands Tanegashima and Iki, PV power was curtailed on more than 70 days in 2020 [2]. Also, because of such potential curtailment problems, the installation of the PVs is limited in many islands, which stagnates PV installation.

Installation of Battery Energy Storage Systems (BESS) and Demand Response (DR) of the existing loads have been focused in order to install RES more and to reduce its curtailment. Many papers have discussed energy management and planning in islanded microgrids with BESS and DRs [3], [4]. Especially in the residential sector, DR offered by the heat stored in Heat Pump Water Heaters (HPWHs) tanks must contribute to effective PV generation [5]. Reference [6] evaluated the reduction of RES curtailment by HPWH operation when the marginal cost of the power system is low. Reference [7] evaluated the cost reduction by DR with other flexibilities, concentrated solar power and pumped hydroelectricity, in island power system by use of optimal Unit Commitment (UC).

Waterworks system is also an important DR resource because they have large dams and water tanks [8]-[10]. Reference [11] proposed an Improved Dynamic Programming Algorithm (IDPA) considering Time of Use (ToU) tariff for two-stage water supply pumping station and applied the control and protection equipment that embeds IDPA at a high mountain village in China. Reference [12] proposed a framework for utilizing water pumps and tanks in water supply networks to absorb the RES surplus energy in the grid, assuming that the water network operator participates in an energy market through a DR program.

M. Imanaka *et al.* also have proposed the water level control scheme of waterworks systems for mitigation of short-term fluctuation of local PV [13], verified a control method of the variable-speed water pumps in consideration of water surges by field tests [14], and evaluated the impact of waterworks systems' DR on the increase of maximum PV integration capacity with the same curtailment level in Miyakojima [15].

However, when the PV capacity becomes much larger than the demand, coordinated control of various DR resources will be needed to reduce huge amount of surplus power efficiently. Especially, multi-day coordinated control of DR resources would be needed to utilize the DR potential of waterworks systems fully because the farm ponds can store water from 1 to several days of water demand. Coordinated control would be different according to not only the PV capacities but also climate conditions because the water demand changes largely by the climate conditions. However, studies multi-day coordinated control of DR resources including water system are limited.

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This paper constructs the optimization model of the isolated power system with several DR resources as a first step of making such coordinated control method of DR resources. Round-a-year simulations with the time-resolution of one-hour are run with 5 PV capacities and 2 optimization time-horizons. Comparing the operation of DR resources between the optimization with the time-horizon of 2 weeks (2-weeks optimization) and that of 1 day (1-day optimization), the effect of 2-weeks optimization are analysed in the viewpoint of seasons and PV capacities. Also, the important points of coordinated control in actual operation is discussed.

II. Configuration of System and Datasets

A. Power System and Resources

The focus of this research is Miyakojima, a sub-tropical island in Japan with a population of about 55,400. Various field tests of DER resource integration have been conducted in Miyakojima [16]. Fig. 1 shows the overview of the power system, DR resources and their energy storages. Table I shows their capacities in this study. The isolated island power is generated by PVs, WTs and DGs. Waterworks system, HPWHs and BESSs are assumed for DR resources. 128 MW installation of PV is the 2030 target of Miyakojima [17].

Waterworks systems are an important candidate of controllable load in Miyakojima. Fig. 2 shows the schematic view of waterworks systems. Water pumps (WPs) send water from huge groundwater dams to the farm ponds (FPs), and FPs send water to farmlands. The power consumption of WPs can be shifted according to DR signals because of their large dams and tanks. The total maximum power consumption of the WPs is around 5.5 MW, about 10% of the maximum power demand in Miyakojima. Table II shows the total WP capacity in farm ponds and their equivalent storage energy capacity.

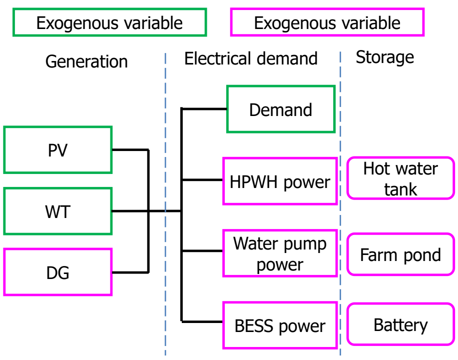


Fig. 1. Schematic view of power system and DR resources.

TABLE I: Capacities of Equipment

Name	MW Capacity	MWh Capacity
PV	64, 80, 96, 112, 128	-
WT	4.8	-
DG	10 × 6	-
HPWH	10	185 (thermal)
BESS	5	60

TABLE II: Water Pump and Farm Pond Capacity

Name	Water pump (MW)	Farm pond (MWh)
FP1	1.91	15.2
FP2	1.44	22.5
FP3	1.01	11.6
FP4	0.84	9.7
FP5	0.36	5.2

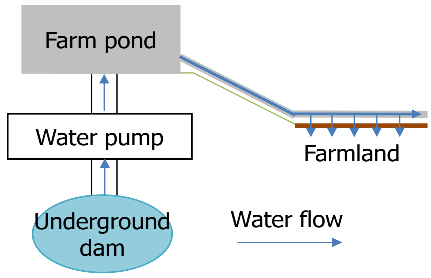


Fig. 2. Schematic view of waterworks system.

B. Datasets

Basically, dataset from 2014/4/1 to 2015/3/30 are used for simulations, but because of the data availability restriction, demand data are from 2017/4/1 to 2018/3/30. The temporal resolution of the data is 1 hour.

Because the demand data of Miyakojima is not available in public, the power demand, $P_D(t)$ [MW], has been calculated by Okinawa power demand, $P_{D\text{-}O}(t)$ [MW], [18] as

$$P_D(t) = (1-\alpha)(0.044 \times P_{D\_O}(t) - 11.3) \tag{1}$$

PV output data are calculated based on the horizontal solar irradiance data measured at Miyakojima Local Meteorological Office (LMO) [19] with the capacity factor of 15%. WT output data are calculated based on the measured wind speed at the same LMO with the capacity factor of 28%.

Though there are several capacities in Miyakojima, six DGs with 10 MW each are assumed in this study for simplicity. Existing operation requires at least 2 DGs, but the minimum operation number of DGs is one in this paper as a future assumption. Therefore, note that the amount of the curtailment will be reduced compared to the simulation under the existing operation rules. The minimum DG output is 50% of the rated power.

10,000 HPWHs are assumed to be installed in Miyakojima, which corresponds to 35% of the houses. They are aggregated to 1 large HPWH in the optimization model. Hot water usage pattens are set for each season, shown in Fig. 3. In this paper, "Spring" represents April and May, "summer" represents from June to September, "Autumn" represents October and November, and "Winter" represents December, January, February and March. Hot water demand is large in winter and small in summer.

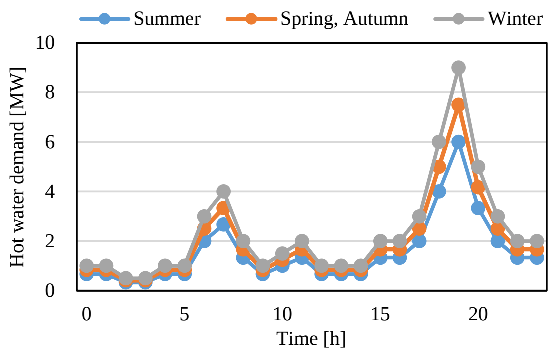


Fig. 3. Hot water demand pattern of HPWH.

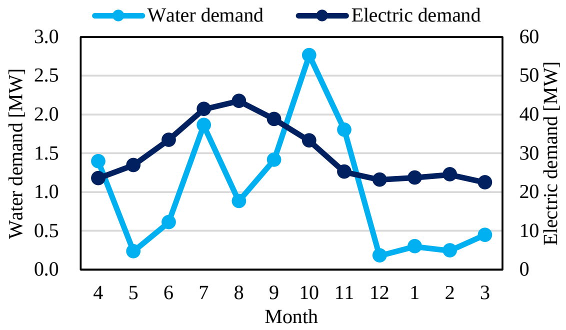


Fig. 4. Monthly average water demand and electric demand.

Water demand data of farm ponds were also obtained from Miyakojima, and data treatment was done for the lacked data. Hourly water demand is multiplied by 1.17 times considering the expansion of future farm area. Fig. 4 shows the monthly average water demand of the waterworks system, which is total of the 5 farm ponds. Fig. 4 also shows the monthly average electric demand in Miyakojima. Water demand highly depends on climate conditions; especially rain, irradiance and humidity. Usually, the water demand is high in July. Additionally, the water demand is also high in October and November in 2014 because of the drought. Water demand is small in winter because there are many cloudy days and because some of the sugar canes, the main crop in Miyakojima, is harvested before winter.

III. Optimization Model

A. Overview

Table III shows the nomenclature list.

TABLE III: NOMENCLATURE LIST OF OPTIMIZATION MODEL

Symbol	Unit	Explanation
C_{total}	Yen	Total cost
P	MW	Power output
$P_{\max}$	MW	Upper limit output
$P_{\min}$	MW	Lower limit output
D	MW	Demand
P_{norm}	-	Normalized output
PV_r	-	PV output ratio
WT_r	-	WT output ratio
U	-	Operation status (Running: 1, Stop: 0)
P^{Sho}	MW	Output of supply shortage
P^{Sur}	MW	Output of supply surplus
T	hour	End time to be targeted by Model
DG	-	Diesel engine generator
PV	-	Photovoltaic power system
WT	-	Wind turbine generator
PG	-	Discharging by BESS
PS	-	Charging by BESS
WS	-	Power consumption by the pump
WU	-	Water using from the farm pound
HS	-	Power consumption by HPWH
HU	-	Hot water using from HPWH
SOC	MWh	State of charging
SOW	MWh	State of water storage
SOH	MWh	State of hot water storage
COP	-	Coefficient of performance
η	-	Charge/discharge efficiency
i	-	Unit number
I	-	Total number of units
a^{DG}	Yen	Fuel cost coefficient
b^{DG}	Yen	Fuel cost coefficient
c	-	Penalty cost coefficient

Mixed integer linear programming (MILP) is used for the optimization [20]. Optimization time horizon is either 2 weeks or 1 day, from the midnight of the first day to 11 p.m. of the final day. The final values of SOC, SOW and SOH in one time period are used as initial values of those in the next time horizon for continuous simulation.

B. Objective Function and Restrictions

The objective function is shown in (2), which minimizes the sum of the DG fuel cost and penalties of shortage, surplus and the curtailment of PV and of WT:

$$\begin{aligned} C_{\text{total}} = \sum_{t=0}^{T} \Bigg\{ & \sum_{i=1}^{I^{\text{DG}}} \left(\frac{a^{\text{DG}} P_i^{\text{DG}}(t)}{100 P_{\max}^{\text{DG}}} + b^{\text{DG}} U_i^{\text{DG}}(t) \right) + \\ & c^{\text{Sur}} P^{\text{Sur}}(t) + c^{\text{Sho}} P^{\text{Sho}}(t) + \\ & c^{\text{PV}} P_{\max}^{\text{PV}} P_{\text{norm}}^{\text{PV}}(t)\left(1-\text{PV}_r(t)\right) + \\ & c^{\text{WT}} P_{\max}^{\text{WT}} P_{\text{norm}}^{\text{WT}}(t)\left(1-\text{WT}_r(t)\right) \Bigg\} \end{aligned} \tag{2}$$

The power balance restriction is expressed as

$$\begin{aligned} & \sum_{i=1}^{I^{\text{DG}}} P_i^{\text{DG}}(t) + P^{\text{PG}}(t) - P^{\text{PS}}(t) - \\ & \sum_{i=1}^{I^{\text{WS}}} P_i^{\text{WS}}(t) - P^{\text{HS}}(t) + P^{\text{Sho}}(t) - P^{\text{Sur}}(t) = \\ & D(t) - P_{\max}^{\text{PV}} P_{\text{norm}}^{\text{PV}}(t)\text{PV}_r(t) - P_{\max}^{\text{WT}} P_{\text{norm}}^{\text{WT}}(t)\text{WT}_r(t) \end{aligned} \tag{3}$$

Total power generation should be 10% greater than the load. Thus the reserve restriction is given as

$$\begin{aligned} & \sum_{i=1}^{I^{\text{DG}}} P_{\max,i}^{\text{DG}}(t) + \left(P^{\text{PG}}(t) - P^{\text{PS}}(t)\right) - \\ & \sum_{i=1}^{I^{\text{WS}}} P_i^{\text{WS}}(t) - P^{\text{HS}}(t) + P^{\text{Sho}}(t) - P^{\text{Sur}}(t) \geq \\ & 1.1D(t) - P_{\max}^{\text{PV}} P_{\text{norm}}^{\text{PV}}(t)\text{PV}_r(t) - P_{\max}^{\text{WT}} P_{\text{norm}}^{\text{WT}}(t)\text{WT}_r(t) \end{aligned} \tag{4}$$

The restrictions of DGs are as follows:

$$P_{\min}^{\text{DG}} U^{\text{DG}}(t) \leq P_i^{\text{DG}}(t) \leq P_{\max}^{\text{DG}} U^{\text{DG}}(t) \tag{5}$$

$$P_i^{\text{DG}}(t) \geq P_{i+1}^{\text{DG}}(t) \quad (i = 1,\ 2,\ 3,\ 4,\ 5) \tag{6}$$

BESS restrictions are expressed by

$$P_{\min}^{\text{PG}} U^{\text{PG}}(t) \leq P^{\text{PS}}(t) \leq P_{\max}^{\text{PG}} U^{\text{PG}}(t) \tag{7}$$

$$P_{\min}^{\text{PS}} U^{\text{PS}}(t) \leq P^{\text{PS}}(t) \leq P_{\max}^{\text{PS}} U^{\text{PS}}(t) \tag{8}$$

$$\text{SOC}(t) = \text{SOC}(t-1) - \left(\frac{P^{\text{PG}}(t)}{\eta^{\text{PG}}} - \eta^{\text{PS}} P^{\text{PS}}(t) \right) \tag{9}$$

Both η^{PG} and η^{PS} are set to 90%. Also, when BESS is discharging, output of PV and WT is prohibited to be curtailed. SOC should be always from 30% to 90%, and the final SOC should be greater than 35%.

The limits of WP power and SOW respectively are

$$P_{i,\min}^{\text{WS}} U_i^{\text{WS}}(t) \leq P_i^{\text{WS}}(t) \leq P_{i,\max}^{\text{PS}} U_i^{\text{WS}}(t) \tag{10}$$

$$\mathrm{SOW}_i(t) = \mathrm{SOW}_i(t-1) - \sum_{i=1}^{I^{WU},I^{WS}} \left(P_i^{WU}(t) - P_i^{WS}(t) \right) \quad (11)$$

SOW should be always from 30% to 100%. The final SOW in the optimization time period should be greater than 80% to ensure the water delivery of the next day, even when the water demand is large.

Similarly, the limits of HPWH power and SOH respectively are as follows:

$$P_{\min}^{\mathrm{HS}} U^{\mathrm{HS}}(t) \le P^{\mathrm{HS}}(t) \le P_{\max}^{\mathrm{HS}} U^{\mathrm{HS}}(t) \quad (12)$$

$$\mathrm{SOH}(t) = 0.99\mathrm{SOH}(t-1) - P^{\mathrm{HU}}(t) + \mathrm{COP} \times P^{\mathrm{HS}}(t) \quad (13)$$

SOH should be always from 30% to 100%, and the final SOH should be greater than 35%. The heat tank has the heat loss which equals to 1%/hour of the stored energy. COP of HPWH is set to 3.0.

C. Simulation Cases

Though precise 2-weeks-ahead forecasting of the irradiance or the water demand is difficult in the real world, this paper set the time horizon of the optimization to 1 day and 2 weeks. This aim is to understand the effect of the time shift of the coordinated control in ideal situation and to understand what kind of controls and forecasts will be important considering the coordinated control in actual situation.

To evaluate the effect of the 2-weeks optimization according to the PV capacity, 5 PV capacities, from 64 MW to 128 MW, are simulated. 64 MW is a little larger than the demand peak and 128 MW is the target in Miyakojima in 2030. Table IV shows the simulation cases.

TABLE IV: SIMULATION CASES

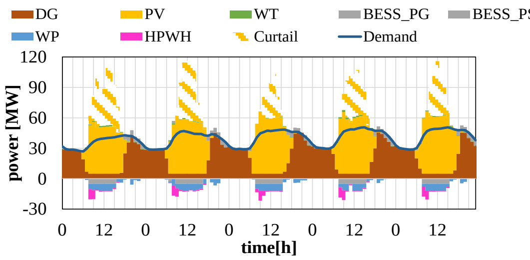
Cases	PV capacity [MW]	Time horizon [day]
Case 64-1d	64	1
Case 64-2w	64	14
Case 80-1d	80	1
Case 80-2w	80	14
Case 96-1d	96	1
Case 96-2w	96	14
Case 112-1d	112	1
Case 112-2w	112	14
Case 128-1d	128	1
Case 128-2w	128	14

IV. SIMULATION RESULTS AND DISCUSSION

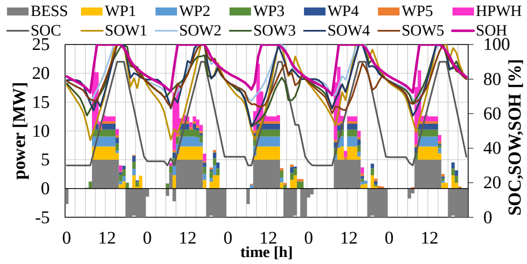
A. Comparizon of DR Resources Operation

In order to show the difference of DR resources operation under different PV capacities, time-series results of Case 64-1d, Case 64-2w, Case 128-1d, Case 128-2w are shown. Fig. 5, Fig. 6, Fig. 7, and Fig. 8 show the demand and supply of the power system and SOC, SOW and SOH on representative days, from July 2nd to 6th, respectively.

When PV capacity is 128 MW, shown in Fig. 5 and Fig. 6, PV output is curtailed largely every day because the PV generation is much higher than the demand. Part of the surplus power is consumed around 10 to 20 MW by DR resources. In Case 128-1d, the WPs need to send water not only by the daytime PV surplus but also by DG output during nighttime because the SOWs at midnight should be more than 80% to prevent the water shortage on following days. In Case 128-2w, the WPs operate less during nighttime with relatively small SOWs because WPs can recover the SOW by using the PV surplus, tomorrow, which reduces fuel consumption of DGs.

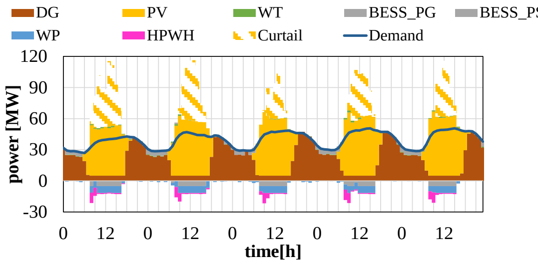


(a) Power system demand and supply

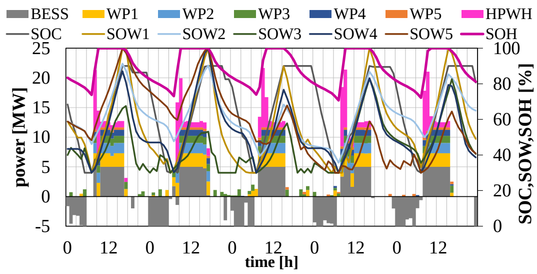


(b) DR operations

Fig. 5. Demand and supply, and DR operations (Case 128-1).

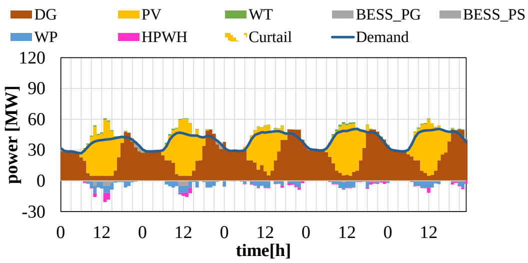


(a) Power system demand and supply

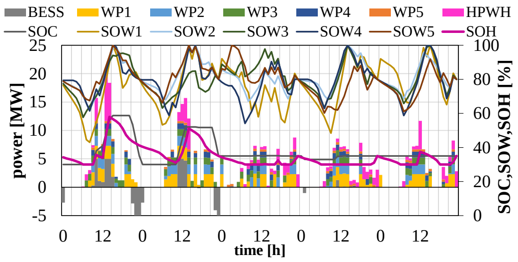


(b) DR operations

Fig. 6. Demand and supply, and DR operations (Case 128-2).

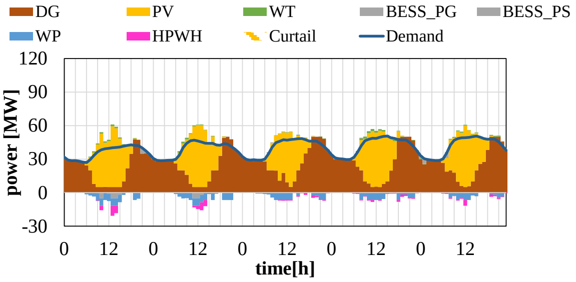


(a) Power system demand and supply

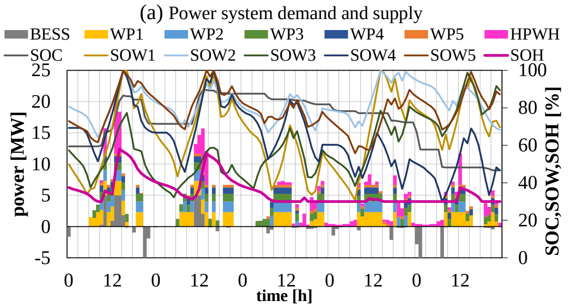


(b) DR operations

Fig. 7. Demand and supply, and DR operations (Case 64-1).



(a) Power system demand and supply



(b) DR operations

Fig. 8. Demand and supply, and DR operations (Case 64-2)

When the PV capacity is 64 MW, shown in Fig. 7 and Fig. 8, PV output is not curtailed because the output is close to the demand, which is higher in summer season. From July 4th to 6th, the surplus power is relatively small and most of the surplus power is used by WPs, not by the BESS. The reason is that WP operation shift doesn't arise any loss, but BESS operation arises energy loss. The HPWH partially uses the surplus power, but the priority of the HPWH is lower than those of the WPs. This is because the HPWH has the heat loss in proportional to the SOH, hence, the loss can be reduced when HPWH operates in the evening or in the morning, when hot-water demand is relatively high. This situation is almost the same between Case 64-1d and Case 64-2w, and the curtailment of PV is 0 in both Cases.

B. Annual Generation Mix

Fig. 9 shows the annual generation mix and the RES curtailment ratio (CR), defined by (14), in each case. Note that "PV+WT" means the total RES output after curtailment.

$$\mathrm{CR} = 1 - \sum_{t=1}^{8736} \frac{P_{\max}^{\mathrm{PV}} P_{\mathrm{norm}}^{\mathrm{PV}}(t)\mathrm{PV}_r(t) + P_{\max}^{\mathrm{WT}} P_{\mathrm{norm}}^{\mathrm{WT}}(t)\mathrm{WT}_r(t)}{P_{\max}^{\mathrm{PV}} P_{\mathrm{norm}}^{\mathrm{PV}}(t) + P_{\max}^{\mathrm{WT}} P_{\mathrm{norm}}^{\mathrm{WT}}(t)} \quad (14)$$

In 64 MW Cases, CR is less than 3%, which indicates that most of the PV surplus power is effectively used by DR resources. When the PV capacity increases, the DG generation reduces, and PV generation increases with saturation because the CR increases rapidly. When the PV capacity is 128 MW, even though DR resources consume part of PV surplus power, CR is more than 28%.

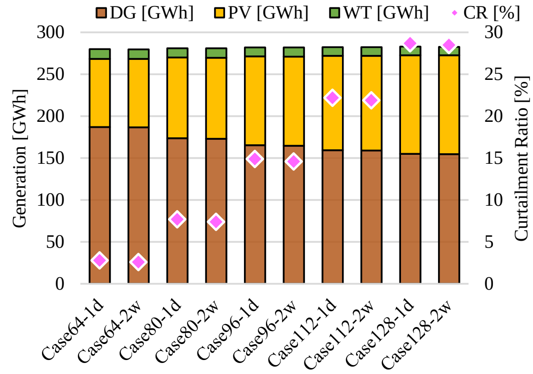


Fig. 9. Annual generation mix and curtailment ratio (CR).

C. Seasonal Characteristics

Differences of both DG and RES utilized energy for each PV capacity, $E_d^{\mathrm{DG}}(n)$ and $E_d^{\mathrm{RE}}(n)$, are calculated by (15) and (16), respectively, to quantify the effect of the 2 weeks optimization compared to the 1day optimization (2-weeks optimization effect) in each time period.

$$E_d^{\mathrm{DG}}(n) = \sum_{t=1}^{336}\sum_{i}^{I^{\mathrm{DG}}} P_i^{\mathrm{DG}}(t,n,2w) - \sum_{t=1}^{336}\sum_{i}^{I^{\mathrm{DG}}} P_i^{\mathrm{DG}}(t,n,1d) \quad (15)$$

$$E_d^{\mathrm{RE}}(n) = \sum_{t=1}^{336}\left(\mathrm{PV}_u(t,n,2w) + \mathrm{WT}_u(t,n,2w)\right) - \sum_{t=1}^{336}\left(\mathrm{PV}_u(t,n,1d) + \mathrm{WT}_u(t,n,1d)\right) \quad (16)$$

In (15) and (16), time period n is the number of each 2 weeks from n=1 (2014/4/1-2014/4/14) to n=26 (2015/3/17-2015/3/30). PV_u and WT_u are used power of PV and WT, respectively.

Fig. 10 shows the water demand and electrical demand, and Fig. 11 shows the curtailment with 1 day operation in each n.

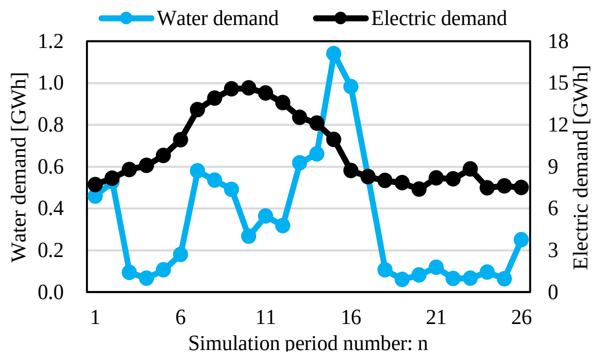


Fig. 10. Water demand and electric demand in each time period.

Fig. 12 shows $E_d^{\mathrm{DG}}(n)$ and $E_d^{\mathrm{RE}}(n)$. When the PV capacity is 64 MW, the difference is relatively large in winter (n=23~26) and spring (n=1~4) because PV power is curtailed mainly in some of the winter days, and water demand is also relatively small in winter. Hence, the limited water demand can be pumped up concentratedly to the PV surplus power in 2-week optimization. Fig. 12 shows that in Case64-1d, PV output is rarely curtailed in summer and autumn (n=7~22) because of high electricity demand in summer and relatively low PV output in autumn. In such conditions, the simulation result is almost same as shown in Fig. 7 and Fig. 8.

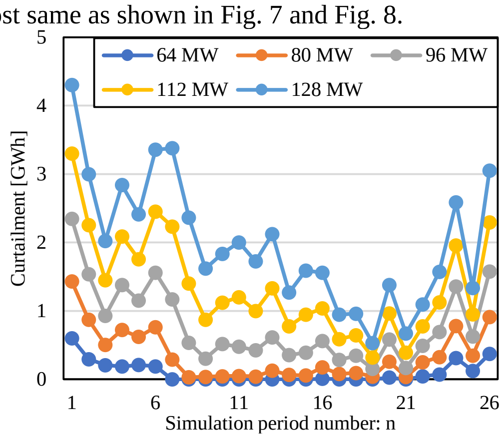
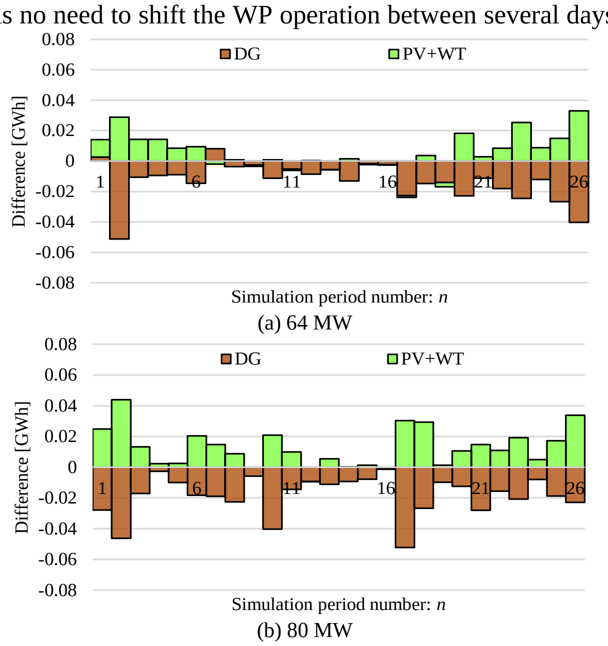


Fig. 11. PV curtailment with 1 day optimization.

On the contrary, when the PV capacity is 128 MW, the difference is largest in summer (n=6~12) because large surplus power arises almost every day even in summer (Fig. 5 and Fig. 6 (a)), hence, two-weeks optimization can reduce the evening WP operation and DG operation, as discussed in IV-*A*. In winter, even in one-day optimization, most of the WP power can be delivered by PV surplus because large surplus power arises almost every day. Hence, 2-weeks optimization effect is small in winter.

From Fig. 12, it is revealed that when PV capacity is increased from 64 MW to 112 MW, the 2-weeks optimization effect increases in summer and autumn because the curtailment increases as shown in Fig. 11. On the contrary, 2-weeks optimization effect in winter reduces from 80 MW to 112 MW because the PV output begins to be curtailed largely almost every day and there is no need to shift the WP operation between several days.



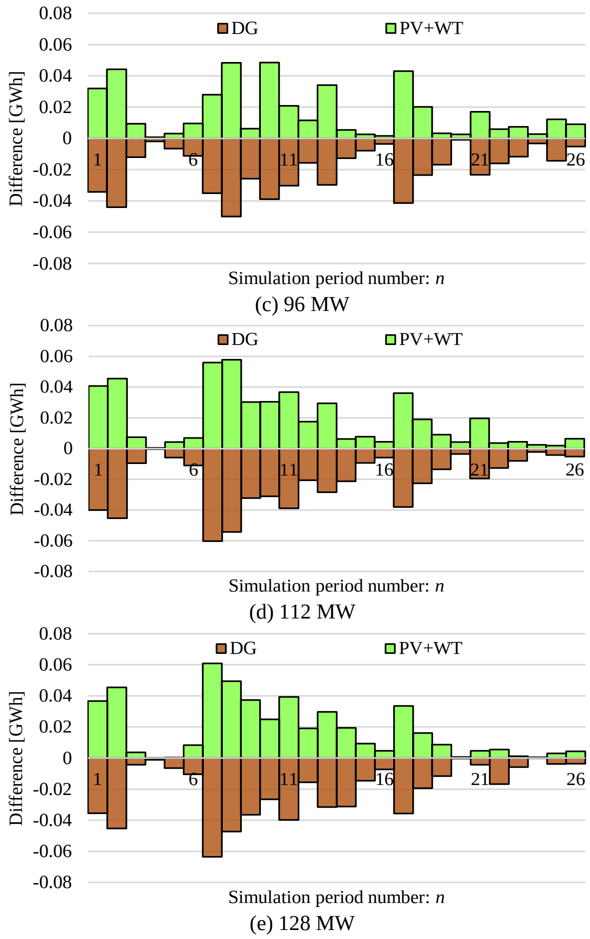


Fig. 12. Difference of energy between optimization periods

When n = 5, 15, 16, 19, 24, the difference of PV+WT generation is less than 0.01 GWh in all Cases. This can be categorized into two groups. One group includes n = 5, 19, 24. In this group, the water demand is very low (Fig. 10), and shiftable energy itself is very small. The other group includes n = 15, 16. In these time periods, though water demand is extremely high, the 2-weeks optimization effect is very small. The reason can be explained with Fig. 13. Even in 1 day optimization, WP always operates fully when the PV is curtailed, which means there is no room to increase the WP operation with PV curtailment.

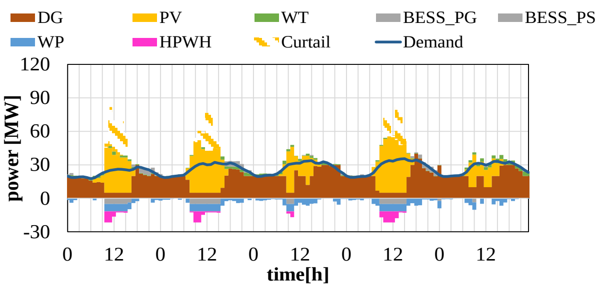


Fig. 13. Demand and supply with large water demand (Case 128-1)

D. Insights for Actual Operation

Based on the results obtained by optimization, some insights are obtained for the actual operation of coordinated control of DR resources. When PV installation is relatively small (64 MW in this simulation), the surplus power of PV is also limited in summer and autumn. Therefore, one-day planning is enough for the operation. In winter and spring, PV curtailment happens in some of the days. Hence, the based on the forecast of the PV curtailment and of water, operation with planning several days will be important. However, existing meso-scale model of grid point values (MSM-GPV) [21] can predict only up to basically 39 hours (51 hours in two initial time [22]) in Japan, further feasibility study is needed for several days planning.

When the PV installation is larger (more than 100 MW in this simulation), the 2-weeks optimization effect is larger in summer and in autumn. One of the most important elements for this coordinated control is the precise forecast of water demand during nighttime and next daytime, in order to reduce the night WP operation while keeping the SOW level. MSM-GPV has enough time-horizon for this.

Though most of the water is sprinkled to farmlands either manually or timer control, internet of things (IoT) based sprinkler irrigation systems are focused [23]. IoT-sprinkler field test is also done in Miyakojima. Such IoT-based sprinklers may increase the forecastability and controllability of the water demand.

V. Conclusion

This paper constructs the optimization model of the isolated power system with several DR resources including waterworks system to make coordinated control methods for the future massive integration of renewable energy sources. Comparing the operation of DR resources between two-week optimization and one-day optimization with 5 PV capacity settings, the effect of long-term planning is analyzed.

Through one-year optimization simulations with the time-resolution of one-hour, key findings are following.

- When PV capacity is a little larger than the maximum demand (64 MW in this simulation), 2-weeks optimization effect exists in winter and summer. Several-days-shift of water pump operation is important for actual operation.
- When PV capacity is twice to the maximum demand (more than 100 MW), 2-weeks optimization effect exists in summer and autumn. Precise forecast of water demand during night and next day is important.
- When the water demand is either very low or very high, 2-weeks optimization effect is small.

Future work includes the construction of rule-based coordinated control method for each season in order to verify the effect in actual operation. For the verification, the forecast errors of both irradiation and water demand will have large effect and construction of forecast of water demand will be the key part to develop.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Masaki Imanaka and Shunsuke Toyoda made simulation models and prepare the manuscript. Shigeyuki Sugimoto and Takeyoshi Kato supervised and gave ideas to the research. All authors had approved the final version.

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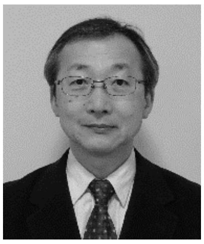

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