Battery-Assisted Load Frequency Control Coordinated with Economic Load Dispatching

Dai ORIHARA and Hiroumi SAITOH
Department of Electrical Engineering, Graduate School of Engineering
Tohoku University
Sendai, Japan
dai.orihara.d6@tohoku.ac.jp

Abstract—**The Battery Energy Storage (BES) is expected to be a device supplying frequency control reserves in a power system penetrating large amount of Intermittent Renewable Energy Sources (IRES). The authors presented the Battery-Assisted Load Frequency Control (BALFC) as a novel BES utilization method contributing to enhance the LFC performance in previous works. In the BALFC, the BES compensates the slow responsivities of the LFC units by absorbing components of the LFC signal exceeding the maximum ramp rate of each unit. This paper proposes the Improved-BALFC in which the BES control signal is processed from the output signal of power plants including the control signal of Economic Load Dispatching (ELD) in addition to the LFC signal. A simulation study shows that the Improved-BALFC can suppress the frequency fluctuation larger than the BALFC when the load demand has long-period change.**

Index Terms-- **Battery Energy Storage, Economic Load Dispatching, Frequency Stability, Load Frequency Control, Ramp Rate Limit**

I. INTRODUCTION

Renewable energy sources such as photovoltaic generation (PV) and wind power generation (WP) are being penetrated rapidly to the power system in order to develop a sustainable power supply system. However, the intermittent and unexpected power production of PV and WP makes it difficult to maintain supply-demand balance and deteriorates frequency stability. Battery Energy Storage (BES) is one of the key devices which can solve the problem. The quick responsivity of the BES can be used to make contribution to a reduction of supply-demand imbalance which cannot be absorbed by existing power plants such as thermal power plants. In [1][2], the BES is used for absorbing short-period load fluctuation which the power plants cannot follow.

The previous works of the authors presented the Battery-Assisted Load Frequency Control (BALFC) [3] as a novel battery utilization method. The BALFC contributes to improve the performance of the LFC by driving the BES so as to compensate the LFC signal components which exceed the maximum ramp rate of the LFC unit. However, the BALFC is not enough for the BES to absorb load demand components which the power plants cannot follow. This is because the BALFC determine a battery control signal from the LFC signal even though the power plant signal is summation of control signals given from the LFC and the Economic Load Dispatching (ELD). This paper proposes the Improved-BALFC which is the BALFC coordinated with the ELD. In the method, the battery control signal is given as excess components of the power plant signal over the maximum ramp rate.

In [4], the coordination of LFC and EDC is discussed and a feedback controller that improves performance of both control system is proposed. Also, [5] proposed the economic Automatic Generation Control (AGC) in which frequency regulation is achieved economically by coordinating the Economic Dispatching (ED). Those method focus on optimization of the behavior of the existing generation power plants while this paper aims to optimize battery behavior so as to absorb fluctuations which cannot be responded by the existing plants.

To evaluate the validity of the Improved-BALFC, A simulation study is carried out based on a single power system model. The result shows that the Improved-BALFC can reduce frequency fluctuation compared with the BALFC when ramp change is occurred in the load demand. However, it is also found that the Improved-BALFC needs larger MWh capacity of the BES for reducing the effect of the ramp load change.

II. BATTERY UTILIZATION FOR LFC PERFORMANCE IMPROVEMENT COORDINATED WITH ELD

This section explains the roles of the LFC and the ELD in supply-demand balancing control at first. Next part shows the concept of the BALFC and points out a problem that the BALFC is not enough to compensate the slow responsivities of the power plants. Last part proposes the Improved-BALFC which can solve the problem and enhance the validity of the battery utilization.

A. Suuply-Demand Balancing Control in Power System

The supply-demand balance is maintained by a hierarchical control of the generation power plants including the LFC and the ELD. The LFC controls the power plant outputs so as to absorb short-period components of the load demand whose

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fluctuating cycle is within a range from a few minutes to 20 minutes [6]. On the other hand, the ELD absorbs long-period components of the load demand considering the economy of power plant operation.

B. Battery-Assisted Load Frequency Control (BALFC)

The LFC units are required to respond quickly to the LFC signal for a better performance. However, they cannot respond to LFC signal components violating a ramp rate limit which is equipped for a mechanical protection. The BALFC reduces the effect of the ramp rate limit on the performance of the LFC by driving the BES so as to absorb the excess components of the LFC signal. As shown in Fig. 1, the BES control signal is computed as a difference between the input and the output signal of the ramp rate limit block. Since the ELD signal is not considered in the process of signal generating, there is a possibility that the output signal of the power plants S_G which is a summation of the signals of the LFC and the ELD violates the ramp rate limit. In that case, the BES cannot compensate the slow responsivity of the power plants completely.

C. BALFC Coordinated with Economic Load Dispatching

In order to solve the problem, this paper proposes the Improved-BALFC which can compensate the slow responsivity of the power plants more precisely by considering a behavior of the ELD signal. The system configuration is shown in Fig. 2. In the proposed method, the ramp rate limit for the BES signal processing is placed on the power plant signal instead of the LFC signal. Since the power plant signal includes the ELD signal, adopting the method enables the BES to absorb the power plant signal components which the power plants cannot respond to.

III. Models for Simulation Study

The performance of the Improved-BALFC is evaluated by a simulation study. This section explains about the models used in the simulation.

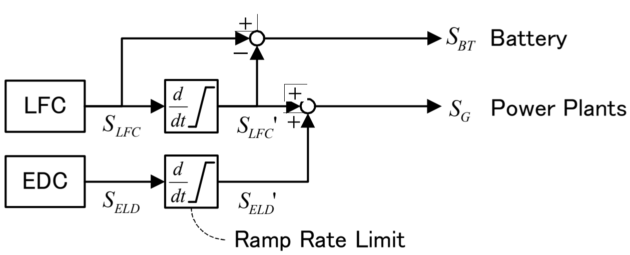


Figure 1. Signal Allocation in BALFC

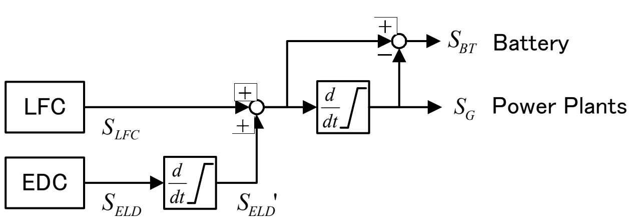


Figure 2. Signal Allocation in Improved-BALFC

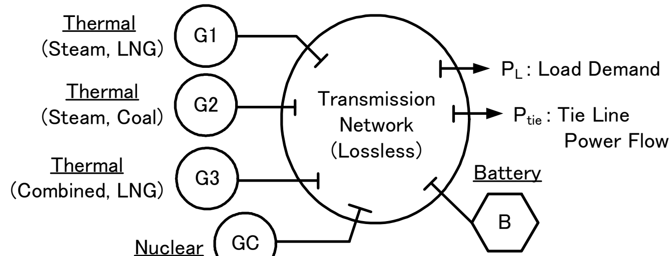


Figure 3. Power System Model

TABLE I. Capacities of Power Plants and BES

Plant	Rated Capacity
G1	3300 [MW]
G2	2700 [MW]
G3	3500 [MW]
GN	6000 [MW]
BES	40 [MW] / 20 [MWh]

A. Power System Model

Fig. 3 shows a single power system model which represents the power system in northeast area in Japan. The model is developed based on a part of 30-machine system model of Institute of Electrical Engineer of Japan (IEEJ) [7]. Thermal power plants G1, G2, G3 and a nuclear power plant are aggregated ones. Table I shows the rated capacity of the plants and MW/MWh capacity of the BES. The physical network of transmission lines is not modeled.

B. Simulation Model

Fig. 4 shows a simulation model, which is consist of 1) aggregated generator model, 2) power plant models, 3) BES model, 4) LFC model and 5) ELD model. A detail explanation of those models are shown below.

1) Aggregated generator model: A dynamic synchronous generaotr model is described as a swing equation shown in (1).

$$M_i \frac{d\Delta f_i(t)}{dt} = P_{mi}(t) - P_{ei}(t) \quad (1)$$

where i is index number of generator $\#i$. M_i is inertia constatnt, Δf_i is a deviation of frequancy from the reference value, P_{mi} is mechanical input of the generator, and P_{ei} is electrical output of generator.

In normal operation, all generators connected to a power system are synchronized and can be regarded as a generator with large inertia and capacity. The equivalent generator is modeled by aggregating the swing equations as shown in (2).

$$\left(\sum_i M_i\right) \frac{d\Delta f(t)}{dt} = \sum_i P_{mi}(t) - \sum_i P_{ei}(t) \quad (2)$$

where Δf denotes a common frequency deviation in all generators.

2) Power plant mode l: The models of thermal power plant G1, G2 and G3 are detailed ones which are developed by the Central Research Institute of Electric Power Industry (CRIEPI) in Japan for supply-dmand balancing simulation [8]. The model includes not only a governor and turbines but also a plant control and a boiler. The behavior of the model is highly matched with a real power plant even if simulated time is longer than several hours. The thermal power plants are used as LFC units in the simulation.

On the other hand, the dynamics of the nuclear power plant GN is not modeled since the GN is assumed to be operated so as to ouptut constant power.

3) BES model: Since the BES can charge and discharge power with very short time delay from the control signal, the BES model is developed so as not to include any delay factor. The magnitude of the charge-discharge power is limited by a saturation block representing MW capacity constraint.

In order to avoid fully charging and running out of charge of the BES which deteriorates charge-discharge capability, the State Of Charge (SOC) control is equiped with the BES. The SOC control corrects the control signal so that the SOC is maintained in a vicinity of initial value. The corrected battery control signal S'_{BT} is given as (3).

$$S'_{BT} = S_{BT} + K_{SOC}\Delta W_{BT} \tag{3}$$

where ΔW_{BT} means difference between stored energy of the BES and its initial value, K_{SOC} is a proportional gain of the SOC control.

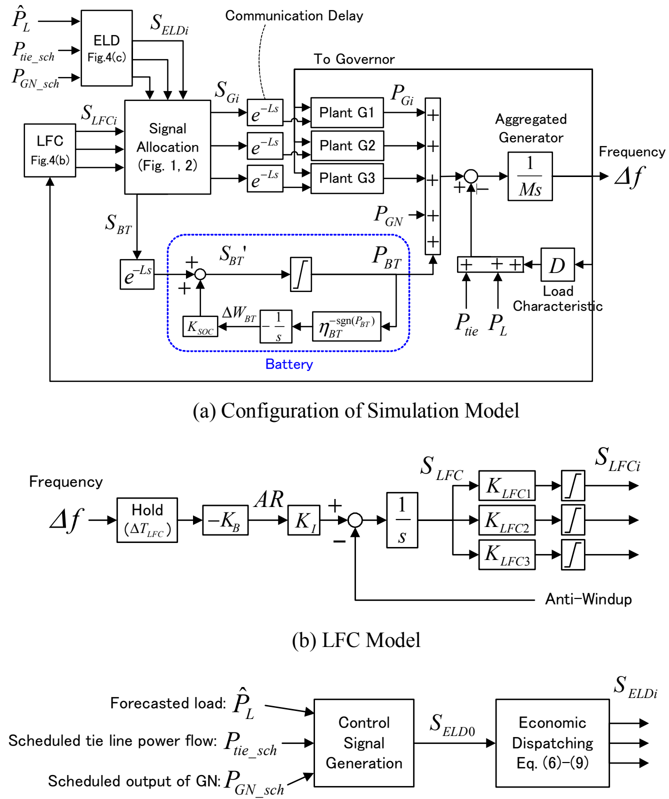
4) LFC model: The LFC is modeled as a integral control in which the frequency is controlled variable as shown in Fig. 4(b) [9]. At first, an estimated value of supply-demand imbalance is computed from the frequency as an Area Requirement (AR). Next, the AR is input to the integral controller and the LFC signal S_{LFC0} is gained as an output. S_{LFC0} is allocated to the LFC units in a ratio of maximum ramp rate $K_{LFCi}(i = 1,2,3)$ so that the responsivities of LFC units are efficiently used. To avoid windup of integral block, Anti-windup controller is added.

5) ELD model: The ELD controls load dispatching of the thermal power plants so that the total fuel cost is minimized. This paper uses a simplified model shown in Fig. 4(c) in which the ELD signal is determined from forecasted load $\hat{P}_L$ and operatoin schedule of tie line and base load unit while the data measured in real-time is also used in the real system. At first, the ELD signal S_{ELD0} is deterined. the residual load which the thermal plants must supply $\hat{P}_{L\_RES}$ can be computed from forecasted load $\hat{P}_L$, scheduled tie line power flow P_{tie_sch} and the schduled output of the nuclear power plant P_{GN_sch} according to (4). The ELD signal S_{ELD0} is determined as an average value of $\hat{P}_{L\_RES}$ in a every specified time period ΔT as shown in (5).

$$\hat{P}_{L\_RES}(t) = \hat{P}_L(t) + P_{tie\_sch}(t) - P_{GN\_sch}(t) \tag{4}$$

$$S_{ELD0}(t) = \frac{1}{\Delta T}\int_{n\Delta T}^{(n+1)\Delta T} \hat{P}_{L\_RES}(\tau)d\tau \tag{5}$$

$$(n\Delta T \le t < (n+1)\Delta T, \quad n = 0,1,\cdots)$$



(a) Configuration of Simulation Model

(b) LFC Model

(c) ELD Model

Figure 4. Simulation Model

where ΔT is control cycle of the ELD.

Next, the ELD signal S_{ELD0} is allocated to the ELD units. The optimal allocation which minimizes the total fuel cost is determined by solving an optimization problem shown in (6) to (9) in which the decision variables are allocated ELD signals $S_{ELDi}(\mathrm{i} = 1,2,3)$. The objective function (6) is minimization of the total fuel cost. The constraints are (7) supply-demand balancing constraint, (8) ramp rate limitation, and (9) maximum/minimum output limitation.

[Objective]:

$$\min \sum_{i=1}^{3} a_i + b_i S_{ELDi}(t) + c_i S_{ELDi}(t)^2 \tag{6}$$

[Subject to]:

$$S_{ELD0}(t) = \sum_{i=1}^{3} S_{ELDi}(t) \tag{7}$$

$$\underline{P_i} \le S_{ELDi}(t) \le \overline{P_i} \qquad (i = 1,2,3) \tag{8}$$

$$\underline{R_i} \le \frac{S_{ELDi}(t) - S_{ELDi}(t-\Delta T)}{\Delta T} \le \overline{R_i} \qquad (i = 1,2,3) \tag{9}$$

where,

S_{ELDi} : ELD signal allocated to the unit #*i*

$\overline{P_i}, \underline{P_i}$: Maximum and minimum output of the unit #*i*

$\overline{R_i}, \underline{R_i}$: Maximum and minimum ramp rate of the unit #*i*

ΔT : Control cycle of ELD.

IV. Performance Evaluation of The Improved-BALFC

A. Simulation Case Setting

The performance evaluations are carried out in two cases in which time variances of load demand are different. One is the flat case and the other is the ramp up case. Fig. 5 and Fig. 6 show load data and forecasted load data in both cases. The load data is made by summing up the forecasted load data and short-period fluctuation data which is common in both cases.

In the flat case, the load does not have a trend component while the load data in the ramp up case increases at constant rate. Compared with the results in both cases, an effect of trend change of load demand on the performance of the Improved-BALFC is analyzed.

B. Simulation Results

At first, the results in the flat case are explained. As shown in Fig. 7(a), the frequency fluctuation can be suppressed by using the BES but there is no difference between the performances of the BALFC and the Improved-BALFC. Fig. 7(b) and Fig. 7(c) show that time variance of the output power and the stored energy of the BES are same. In this case, the Improved-BALFC operates the BES as same as the BALFC since the ELD signal is constant.

Next, the results in the ramp up case is explained. Fig. 8(a) shows that the frequency fluctuation is highly suppressed by using the Improved-BALFC compared with the BALFC. The standard deviations of the frequency in each case are shown in Table II. Without use of the BES, the ramp change of the load increases the frequency standard deviation by 8.5%. The BALFC decreases the deviation by 21.8% and 21.7% in the flat case and ramp up case respectively, but the effect of the ramp change remains. The Improved-BALFC reduces the effect and

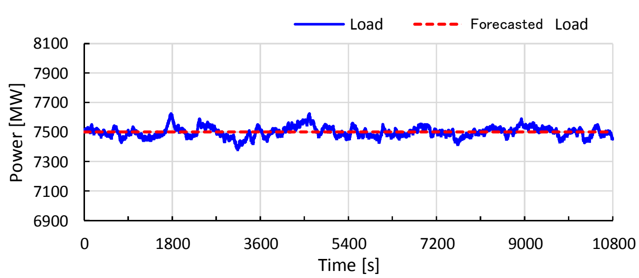


Figure 5. Load Demand in the Flat Case

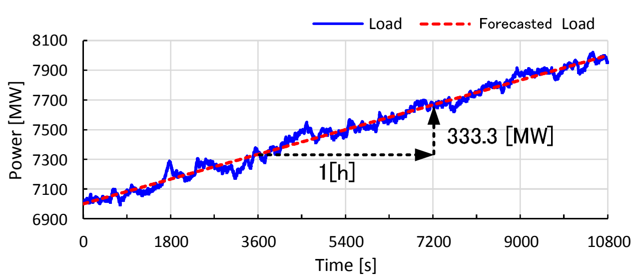
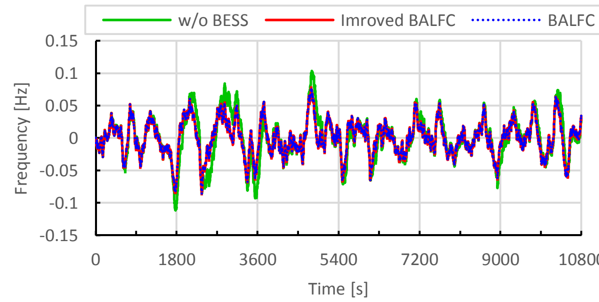
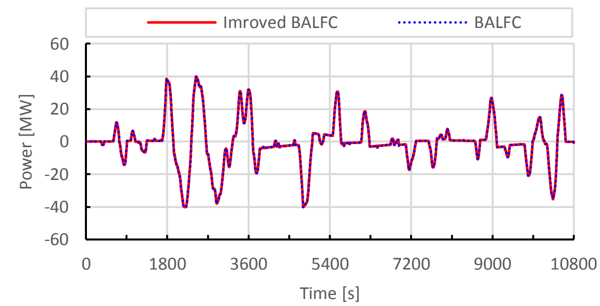


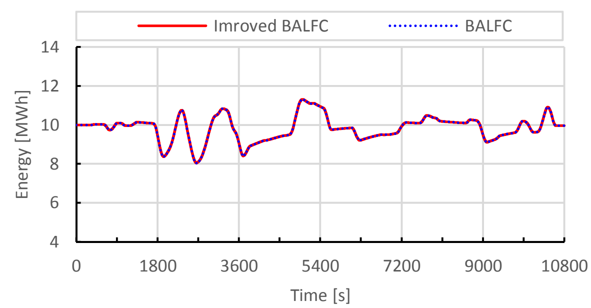
Figure 6. Load Dmenad in the Ramp Up Case



(a) Frequency Deviation



(b) Output of the BES



(c) SOC of the BES

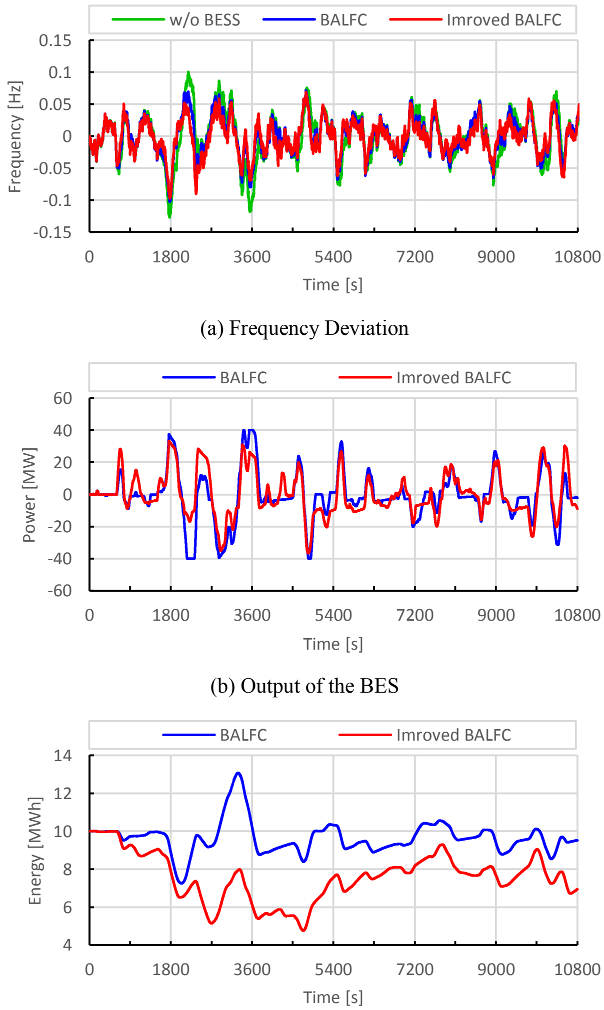
Figure 7. Simulation Rsults in the Flat Case

the standard deviations become almost same in both cases. The reduction ratio of the standard deviation arises 28.3%, which is 6.6% larger than that of the BALFC use.

As shown in Fig .8(b), the time variances of the BES output are different depending on the BES control method but there is not large difference. On the other hand, the behavior of the SOC is largely different. When the Improved-BALFC is used, the SOC becomes small compared with the BALFC use. In ramp up case, the output signals of the power plant frequently exceed their maximum ramp rate because of the ramping up in load demand. Since the BES compensates the excess components by discharging, the SOC of the BES decreases. The results show that the Improved BALFC is superior to the BALFC in frequency fluctuation suppressing but required energy (MWh) capacity is larger.

V. Conclusion

The authors proposed the Battery-Assisted LFC (BALFC) as a novel battery utilization method contributing to enhance the LFC performance in previous works. In the BALFC, the



(a) Frequency Deviation

(b) Output of the BES

(c) SOC of the BES

Figure 8. Simulation Results in the Ramp Up Case

TABLE II. STANDARD DEVIATION OF $\Delta f(t)$ [HZ]

Case	**w/o BES**	**BALFC**	**Improved-BALFC**
Flat	0.0339	0.0265 (−21.8%)	0.0265 (−21.8%)
Ramp up	0.0368 +8.5%	0.0288 (−21.7%)	0.0264 (−28.3%)

( ): Redution rate from the result of "w/o BES"

BES compensates the excess components of LFC signal over maximum ramp rate of LFC units. This paper proposes the Improved-BALFC which is the BALFC coordinated with the Economic Load Dispatching (ELD). The Improved-BALFC drives the BES so as to compensate the excess components of the output signal including the LFC signal and the ELD signal.

The simulation study was carried out by using a single power system model for the validity evaluation of the proposal. The results show that the Improved-BALFC can suppress the frequency fluctuation compared with the BALFC when the load demand has a ramp change. However, it is also found that there is a possibility for the Improved BALFC to require a BES with large MWh capacity to perform since the ramp change in the load causes bias of charging or discharging.

While this paper focused on the utilization of a large scale BES, the utilization of distributed resources such as electric vehicles and small scale BESs for households are very important challenge. The authors try to improve the BALFC so that the distributed sources are used effectively in the future.

TABLE III. PARAMETERS OF CONTROL SYSTEM.

System Frequency	f_0	50.0 [Hz]
Inertia Constant *	M	9.06 [s · puMW/puHz]
Load Damping Constant *	D	1.29 [puMW/puHz]
LFC Coefficient (Generation Rate Ratio)	K_{LFC1}	0.32
	K_{LFC2}	0.17
	K_{LFC3}	0.51
Integral Gain	K_I	0.02 [1/s]
System Constant *	K_B	0.036 [puMW/Hz]
Control Cycle of LFC	ΔT_{LFC}	5.0 [s]
Control Cycle of EDC	ΔT	300.0 [s]
SOC Control Gain	K_{SOC}	0.0011 [MW/MW · s]

* : Total generation capacity base

TABLE IV. PARAMETERS OF POWER PLANTS.

Parameter		**G1**	**G2**	**G3**
Max./Min. output $\overline{P_i}, \underline{P_i}$ [puMW]*		1.0 / 0.2	1.0 / 0.3	1.0 / 0.4
Max./Min. ramp rate $\overline{R_i}, \underline{R_i}$ [$\times 10^{-3}$puMW/min]*		1.5 /−1.5	1.0 /−1.0	2.5 /−2.5
Coefficient of fuel cost function [$\times 10^3$ yen]	a_i	585	715	2452
	b_i [/MW]	2400	1704	1165
	c_i [$/MW^2$]	80	60	77

* : Rated capacity base

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