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Operation planning of energy storage system considering multiperiod energy supplies and demands

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Abstract−The energy storage system (ESS) is recently drawing an increasing attention as an efficient and affordable tool in energy systems. While most interest has been concerned with developing better ESS technology, attention should be given to constructing a rigorous decision-supporting framework for operating the ESS. Motivated by this need, a mathematical modeling framework for the operation of an ESS is proposed in this paper. The proposed framework allows us to prepare ESS operations such as when to charge or discharge by which amount over multiple time periods. Numerical examples are presented to illustrate the applicability of the proposed framework.

Keywords: Energy System, Energy Storage System (ESS), Mathematical Modeling, Optimization

INTRODUCTION

Climate change has become a global economic issue. As witnessed in the 2015 U.N. climate change conference in Paris, stringent regulations are under way to enforce the reduction of fossil fuels. On the other hand, it is inevitable to increase the portion of renewable sources. This is going to pose unprecedented challenges for the operation of process industries. Potential problems that may occur in the forthcoming energy system in the process industry should be prepared for to minimize the resulting penalty. The expertise in the process systems engineering (PSE) community can play a certain role in tackling the problem. This paper is illustrates one such case in the context of operating energy storage system (ESS). The process planning and its optimization framework will be employed to address the operation planning of ESS.

Process industries have been coping with varying energy demand using mostly fixed supply so far. With the increasing portion of renewable sources, varying customer demands should be met by varying renewable energy sources. ESS has recently been drawing increasing attention as an effective tool to tackle this unprecedented challenge. The excess energy which would have been discarded can be used again by way of ESS. The benefits of ESS can be attributed to multiple factors, such as cost saving by lowering peak demand, improving grid reliability, and integrating renewable energy sources [1].

ESS markets have been growing substantially in terms of hardware: electronic batteries that are the main part of ESS have been deployed in various industries such as electronics and transportation. Electronic transportation and hybrid transportation vehicles use the energy stored in the electronic batteries. Many portable electronic devices such as mobile phones, hand carried tablets, notebooks are introduced in the market. The manufacturing cost of ESS products is rapidly decreasing. Most researchers currently focus on improving the performance of ESS itself. On the other hand, how to utilize the ESS has been relatively neglected, as there is little research on ESS in terms of investigating the development of its decision-support tool.

We investigated the energy system of the process industry, which has not been addressed much in PSE community. The importance of the energy system can be explained in terms of two perspectives. At first, energy takes a significant portion of the total cost of the industry; the energy system plays a pivotal role in the profitability of the industry. The cheaper the energy supply, the more profitable the industry becomes. Secondly, the management of the energy system seriously affects the main process. The operation of the process is based on the on-time, sufficient, energy supply. So far, the industry has simply assumed that enough energy is available whenever it is requested. However, the external environment of the energy system has become uncertain due to rising oil costs, climate change, global warming, sustainability, etc.

The performance of the energy system can be improved by taking advantage of the expertise of PSE principles. They may look too simple and straightforward in the PSE community, but can be novel and very effective in addressing the issues in the energy system.

Furthermore, the energy system has been neglected and underestimated in the PSE community in spite of its potential contribution to the process industry. It has also come time for the PSE industry to actively investigate the issues in the energy system. There is considerable PSE expertise that can be employed for the system, particularly in the scope of renewable energy generation such as fuel cell, battery, etc.

The rest of this paper is organized as follows: recent works on ESS will be briefly outlined to motivate the need for the present paper. The operation of energy systems with ESS will be constructed into a mathematical modeling framework. Examples are presented to illustrate the proposed framework with some remarks.

ESS plays the role of inventory in an energy system: when the energy supply is insufficient to meet the demand, the previously

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charged energy in the ESS can be used to meet the difference between supply and demand. Therefore, the availability of ESS allows us to reduce the maximum energy supply or so-called peak energy. The potential additional over investment can be prevented due to the presence of ESS.

Various ESS manufacturing technologies have been actively investigated: (1) electrochemical batteries including Li-Ion and NaS, (2) capacitors, (3) compressed air energy storage (CAES), (4) pumped hydro energy storage system, (5) flywheels. Some argue that the markets of advanced energy storage systems would be a value of 15.95 Billion dollars by 2020 [2]. Instead of listing all theory and progress so far, it would be appropriate to mention some review papers addressing various ESS technologies as a reference for further study.

Some ESS technologies were reviewed in terms of major development, such as Chen et al. [3]. Dunn et al. [1] briefly cover key material issues in sodium-sulfur, redox-flow, and lithium-ion electrical battery systems. Rehman et al. [4] studied the progress on the pumped hydro energy storage system. Sebastián and Alzola [5] presented an overview of flywheel energy storage technologies. The past research on redox flow batteries was covered by Alotto et al. [6].

The PSE community began to notice the potential opportunity of storing energy. Samsatli and Samsatli [7] addressed the transport energy system consisting of energy generation, conversion, transport, and storage. They considered design and operations features of the system simultaneously. The hydrogen network was used as an illustrative case study. Nease and Adams [8] studied the integration of a fuel cell and a compressed air energy storage system. They applied a rolling horizon optimization for the operation of the integrated system and carried out Monte Carlo simulation. Fazlollahi et al. [9] studied the operational optimization of a district heating system involving storage tanks. Process design and energy balances were considered. Soroush and Chmielewski [10] discussed potential PSE research opportunities in power generation, storage, and distribution.

As can be seen in the analysis of past works, it is necessary to investigate how we utilize ESS for maximizing its potential in the process industry. Motivated by this need, this paper aims to develop systematic operation framework for ESS operation planning.

Energy systems take an important position in the chemical and petrochemical process industries. On-time energy supply at the affordable price is essential for the successful operation of any process. Energy demands from these processes are constantly subject to variation due to multiple reasons such as varying demand and economic environment change. PSE communities have been addressing energy from the perspective of a customer. They have been concerned with minimizing the overall consumption of energy, mostly in terms of power, steam, or the associated amount of sources such as oil and gas. The only interest was how to minimize the overall cost, for example, by integrating the overall amount or reusing some of discarded energy streams. In the PSE literature, relevant application areas are heat integration and utility system optimization, recently minimizing the emission of greenhouse gases in the context of carbon capture and storage (CCS).

It may be argued that redundant energy of more than demand is stored and used in the event of demand shortage. Then, how to select the discharging amount should be decided. The forecasted generated output is computed and demand forecast is made. It might be economically feasible to discard the energy considering the high cost of energy storage, including charging and discharging. There may be a new opportunity by optimizing these multiple issues simultaneously. A large amount of energy cannot be stored indefinitely. There should a limitation in terms of capacity and time. A decision-supporting framework should be developed. There is a research opportunity for addressing optimization because it is quite expensive to purchase an ESS facility.

Large amounts of energy have been wasted by the imbalance between energy supply and demand. The increasing portion of renewable energies may increase the amount of the wasted energy. A systematic tool should be developed to minimize the imbalance. The importance of ESS will be highlighted with the increasing use of renewable energy sources. Because chemical processes are very energy-intensive, energy saving represents a huge financial incentive. It is thereby financially motivating to evaluate the feasibility of operating ESS under the changing energy environment. This is a clear financial motivation for ESS operation decision-supporting tool.

There is a gap between the importance of ESS and the corresponding research. To bridge the gap, this paper proposes a mathematical model representing the operation of energy supply and demand networks including ESS. To play a flexible role of inventory that can be used when the supply is bigger than demand and demand is bigger than supply, ESS should be available whenever necessary.

For the process industry which relies heavily on the steady and stable energy supply, renewable energy sources that are subject to variation cannot be welcomed as a new energy source. ESS can play the role of buffer to minimize the negative impact. Systematic methods should be implemented to minimize their negative response during the implementation of renewable energies.

Although ESS is expected to provide a great deal of flexibility for the energy consuming process, it can meet the expectation only when we have the proper ESS operation methodology that allows us to take the full utilization of them. The next section addresses the formulation of the ESS operation planning model.

FORMULATION OF ESS PLANNING MODELS

This paper is concerned with developing a decision-making framework for operating ESS in the energy system. The proposed framework is based upon the following assumptions:

- All energy supply amounts are known and fixed at each time period.
- All energy demand amounts are also known and fixed at each time period.
- An ESS is assumed to have been constructed and already available when it is requested in an energy system.

In an energy system, the generated energy more than demand has been mainly regarded as useless and curtailed. The concept of storing energy allows us to use the previously curtailed energy again by charging it at ESS. For the operation of the ESS, there are

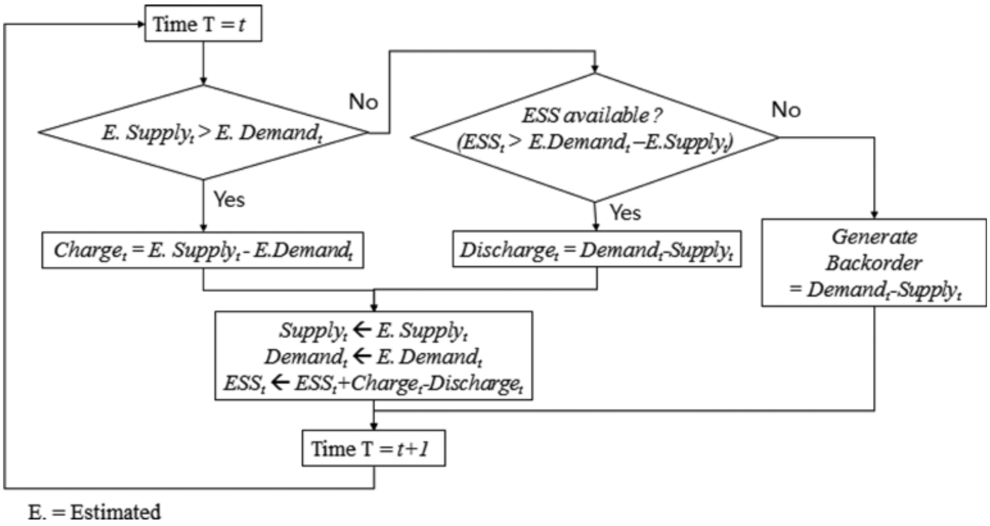

Fig. 1. An illustration of the procedure for energy system planning.

mainly three mode of decisions: One is to charge some of the currently available energy supply in ESS, another is to discharge some energy from the ESS, and the other is to hold. In the hold case, the demand is met by only available supply at that time period. The mode can be determined based on the condition of the energy system.

The mode can be determined based upon the procedure illustrated in Fig. 1.

An energy system consisting of multiple suppliers and multiple demands is illustrated in Fig. 2.

Consider an energy system that has energy supply, i (i=1, …, N), $\text{Supply}_{i,t}$ providing energy to meet multiple demands, $D_{j,t}$ (j=1, …, M) at time period t. The energy supply at time period t can play two roles, which are the actual energy supply for multiple demands at the current time period, and energy for charging ESS for later time periods.

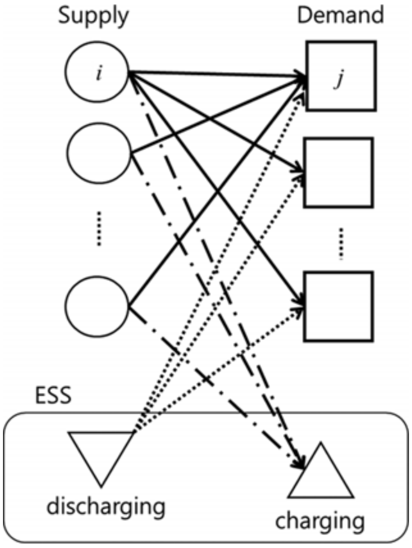

Fig. 2. Schematic diagram of an energy system with multi supply, multi demand and an ESS.

The energy supply amount for energy supply i can be represented as follows:

$$\text{Supply}_{i,t}=\sum_j x_{i,j,t}+w_{i,t}\quad \forall i, t \tag{1}$$

where $x_{i,j,t}$ denotes the specific energy supply from supply i for demand j at current time period t, and $w_{i,t}$ denotes the charging energy amount for ESS from supply i at time period t.

On the other hand, a demand is met by multiple supplies at the same time or the discharged energy from ESS:

$$D_{j,t}=\sum_i x_{i,j,t}+z_{j,t}\quad \forall j, t \tag{2}$$

where $z_{j,t}$ is the discharging energy for demand j at time period t from ESS.

The energy balance for this energy system can be formulated into the following constraint in a sense that all demands should be met by multiple supplies and ESS:

$$\sum_i\sum_j x_{i,j,t}+\sum_j z_{j,t}=\sum_j D_{j,t}+\sum_i w_{i,t}\quad \forall t \tag{3}$$

Eq. (3) represents that the energy supply is used either for meeting the current energy demand and charging the level of ESS for future time periods. It also indicates that the demand can be met by the current energy supply or the discharged energy from ESS.

The discharging amount at ESS at a certain time period should be less than the ESS level at the just previous time period:

$$0\le\sum_j z_{j,t+1}\le \text{ES}_t\quad \forall t \tag{4}$$

The charging amount of ESS at each time period should be less than the current supply:

$$0\le\sum_i w_{i,t}\le\sum_i \text{Supply}_{i,t}\quad \forall i, t \tag{5}$$

The level of ESS at each time period is updated by considering the discharged and charged energy at each time period.

$$\text{ES}_{t+1}=\text{ES}_t+\sum_i\sum_j x_{i,j,t}-\sum_j z_{j,t}\quad \forall t \tag{6}$$

The objective function of the energy system is to maximize the profit, PF, which is the difference between revenue and cost as shown in Eq. (7). The revenue, REV, is expressed as the product of the actually supplied energy amount with its unit price. On the other hand, the cost consists of energy production cost, transportation cost from a supply to a demand, backorder cost occurring by failing to meet the demand, and ESS cost. The ESS cost includes ESS charging, discharging and holding cost.

$$\mathrm{PF}=\mathrm{REV}-\mathrm{SPCOST}-\mathrm{TrCOST}-\mathrm{BackCOST}-\mathrm{ESSCOST} \tag{7}$$

The revenue is computed by multiplying the total generated supply with the unit price.

$$\mathrm{REV}=\sum_i \mathrm{p}_t(\mathrm{S}_t+\mathrm{dchg}_t) \tag{7-1}$$

The energy generation cost, SPCOST, is considered in the objective function as well.

$$\mathrm{SPCOST}=\sum_t \mathrm{gn}_t(\mathrm{S}_t+\mathrm{chg}_t) \tag{7-2}$$

The transmission cost, TrCOST, from supply to demand is considered:

$$\mathrm{TrCOST}=\sum_t \mathrm{gtr}_t\mathrm{S}_t \tag{7-3}$$

When the demand is not met by the supply, a backorder cost is generated. Otherwise, there is no penalty. The backorder, $\mathrm{bkorder}_{j,t}$, and the corresponding backorder cost, BackCOST, can be mathematically formulated as follows:

$$\mathrm{BackCOST}=\sum_t\sum_j \mathrm{bkc}_{j,t}\mathrm{bkorder}_{j,t} \tag{7-4a}$$

$$\mathrm{bkorder}_{j,t}\geq \mathrm{D}_{j,t}-\Big(\sum_i \mathrm{x}_{i,j,t}+\mathrm{z}_{j,t}\Big)\quad \forall \mathrm{j, t} \tag{7-4b}$$

$$\mathrm{bkorder}_{j,t}\geq 0\quad \forall \mathrm{j, t} \tag{7-4c}$$

where $\mathrm{bkorder}_{j,t}$ denotes the backorder amount of demand j at time period t and bkc_t denotes the backorder cost coefficient.

ESSCOST denoting discharging and charging cost in addition to storage holding cost is formulated as follows:

$$\mathrm{ESSCOST}=\sum_t\Big(\mathrm{gc}_t\sum_i \mathrm{w}_{i,t}+\mathrm{gd}_t\sum_j \mathrm{z}_{j,t}+\mathrm{gh}_t\mathrm{ES}_t\Big) \tag{7-5}$$

where gc_t, gd_t, and gh_t denote charging, discharging and storage cost coefficient, respectively.

The first term in the left hand side in (7-5) denotes the charging cost. The second and third indicate discharging and storage holding cost, respectively.

The overall operation of the energy system can be transformed into the following mathematical model with an objective of maximizing the profit that is the difference between the revenue and cost:

$$\begin{aligned}\max \mathrm{PF}=&\sum_t\sum_j \mathrm{p}_{j,t}\Big(\sum_i \mathrm{x}_{i,j,t}+\mathrm{z}_{j,t}\Big)-\sum_t\sum_i \mathrm{gn}_{i,t}\Big(\sum_j \mathrm{x}_{i,j,t}+\mathrm{z}_{j,t}\Big)\\ &-\sum_t \mathrm{gtr}_t\mathrm{S}_t-\sum_t\sum_j \mathrm{bkc}_{j,t}\mathrm{bkorder}_{j,t}\\ &-\sum_t\Big(\mathrm{gc}_t\sum_i \mathrm{w}_{i,t}+\mathrm{gd}_t\sum_j \mathrm{z}_{j,t}+\mathrm{gh}_t\mathrm{ES}_t\Big)\end{aligned}$$

s.t.

$$\begin{aligned}&\mathrm{Supply}_{i,t}=\sum_j \mathrm{x}_{i,j,t}+\mathrm{w}_{i,t}\quad \forall \mathrm{i, t}\\ &\mathrm{D}_{j,t}\leq\sum_i \mathrm{x}_{i,j,t}+\mathrm{z}_{j,t}\quad \forall \mathrm{j, t}\\ &\sum_i\sum_j \mathrm{x}_{i,j,t}+\sum_i \mathrm{w}_{i,t}=\sum_j \mathrm{D}_{j,t}+\sum_j \mathrm{z}_{j,t}\quad \forall \mathrm{t}\\ &\mathrm{ES}_{t+1}=\mathrm{ES}_t+\sum_i\sum_j \mathrm{x}_{i,j,t}-\sum_j \mathrm{z}_{j,t}\quad \forall \mathrm{t}\\ &0\leq\sum_j \mathrm{z}_{j,t+1}\leq \mathrm{ES}_t\quad \forall \mathrm{t}\\ &0\leq\sum_i \mathrm{w}_{i,t}\leq\sum_i \mathrm{Supply}_{i,t}\quad \forall \mathrm{t}\\ &\mathrm{bkorder}_{j,t}\geq \mathrm{D}_{j,t}-\Big(\sum_i \mathrm{x}_{i,j,t}+\mathrm{z}_{j,t}\Big)\quad \forall \mathrm{j, t}\\ &\mathrm{bkorder}_{j,t}\geq 0\quad \forall \mathrm{j, t}\\ &\mathrm{ES}_t,\ \mathrm{x}_{i,j,t},\ \mathrm{w}_{i,t},\ \mathrm{z}_{i,t}\geq 0\quad \forall \mathrm{i, j, t}\end{aligned} \tag{8}$$

where $\mathrm{p}_{j,t}$, gn_t, gtr_t, bkc_t, gc_t, gd_t, gh_t denote unit cost coefficient at time t.

EXAMPLES

Two numerical examples illustrate the applicability of the proposed modeling framework. The first example illustrates the generic role of ESS and the associated energy supply planning in response to varying demand over multiple time periods. The next example deals with an energy system consisting of ESS, multiple demands,

Table 1. Demands over multiple time periods for example 1

Time period	Demand (kw)	Time period	Demand (kw)
1	1,000	25	2,200
2	1,100	26	2,300
3	900	27	2,000
4	1,200	28	1,800
5	1,100	29	1,700
6	1,300	30	1,500
7	1,600	31	1,000
8	1,800	32	1,400
9	2,000	33	1,200
10	2,100	34	1,100
11	1,800	35	2,200
12	1,400	36	2,300
13	1,900	37	2,000
14	2,100	38	1,800
15	2,200	39	1,700
16	2,300	40	1,500
17	2,000	41	1,000
18	1,800	42	1,400
19	1,700	43	1,200
20	1,500	44	1,100
21	1,000	45	2,200
22	1,400	46	2,300
23	1,200	47	2,000
24	1,100	48	1,800

Table 2. Operation plan result for example 1 according to the proposed framework

Time period	Demand (kW)	Total supply (kW)	Supply (kW)	Charging ESS (kW)	ESS level (kW)	Discharging ESS (kW)	Failed demand backorder (kW)
1	1,000	1,000	1,000	0	0	0	0
2	1,100	1,100	1,100	0	0	0	0
3	900	900	900	0	0	0	0
4	1,200	1,400	1,400	200	0	0	0
5	1,100	1,800	1,800	700	200	0	0
6	1,300	1,800	1,800	500	900	0	0
7	1,600	1,800	1,800	200	1,400	0	0
8	1,800	1,800	1,800	0	1,600	0	0
9	2,000	2,000	1,800	0	1,600	200	0
10	2,100	2,100	1,800	0	1,400	300	0
11	1,800	1,800	1,800	0	1,100	0	0
12	1,400	1,800	1,800	400	1,100	0	0
13	1,900	1,900	1,800	0	1,500	100	0
14	2,100	2,100	1,800	0	1,400	300	0
15	2,200	2,200	1,800	0	1,100	400	0
16	2,300	2,300	1,800	0	700	500	0
17	2,000	2,000	1,800	0	200	200	0
18	1,800	1,800	1,800	0	0	0	0
19	1,700	1,700	1,700	0	0	0	0
20	1,500	1,500	1,500	0	0	0	0
21	1,000	1,000	1,000	0	0	0	0
22	1,400	1,400	1,400	0	0	0	0
23	1,200	1,200	1,200	0	0	0	0
24	1,100	1,100	1,100	0	0	0	0

Table 3. Operation plan result for example 1 according to the proposed framework (continued)

Time period	Demand (kW)	Total supply (kW)	Supply (kW)	Charging ESS (kW)	ESS level (kW)	Discharging ESS (kW)	Failed demand backorder (kW)
25	1,000	1,000	1,000	0	0	0	0
26	1,100	1,100	1,100	0	0	0	0
27	900	900	900	0	0	0	0
28	1,200	1,400	1,400	200	0	0	0
29	1,100	1,800	1,800	700	200	0	0
30	1,300	1,800	1,800	500	900	0	0
31	1,600	1,800	1,800	200	1,400	0	0
32	1,800	1,800	1,800	0	1,600	0	0
33	2,000	2,000	1,800	0	1,600	200	0
34	2,100	2,100	1,800	0	1,400	300	0
35	1,800	1,800	1,800	0	1,100	0	0
36	1,400	1,800	1,800	400	1,100	0	0
37	1,900	1,900	1,800	0	1,500	100	0
38	2,100	2,100	1,800	0	1,400	300	0
39	2,200	2,200	1,800	0	1,100	400	0
40	2,300	2,300	1,800	0	700	500	0
41	2,000	2,000	1,800	0	200	200	0
42	1,800	1,800	1,800	0	0	0	0
43	1,700	1,700	1,700	0	0	0	0
44	1,500	1,500	1,500	0	0	0	0
45	1,000	1,000	1,000	0	0	0	0
46	1,400	1,400	1,400	0	0	0	0
47	1,200	1,200	1,200	0	0	0	0
48	1,100	1,100	1,100	0	0	0	0

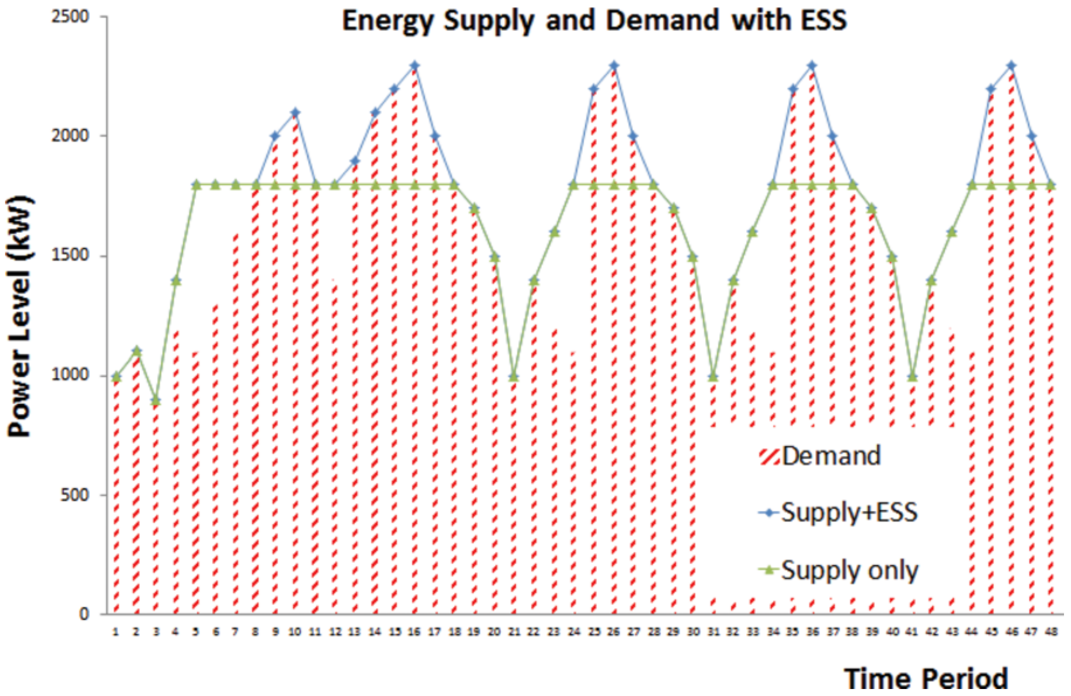

Fig. 3. Graphical representation of operation planning according to the proposed framework.

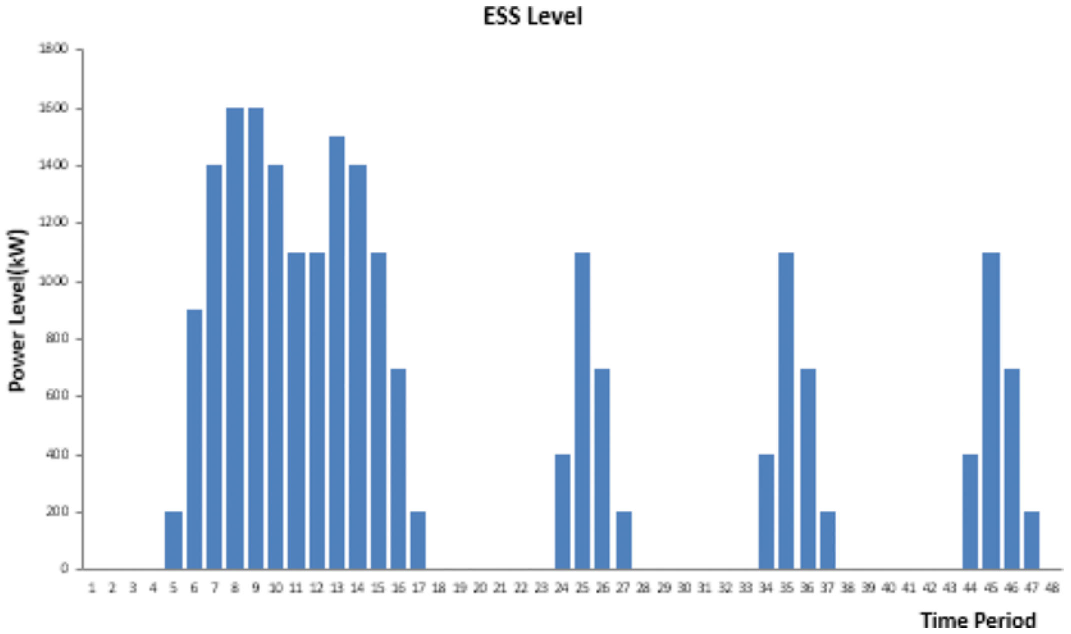

Fig. 4. Graphical representation of ESS operation plan according to the proposed framework for example 1.

and multiple types of energy sources including solar, wind power and natural gas combustion generation.

1. Example 1

Consider an energy system where its demands over multiple time periods are summarized in Table 1. The demands over multiple time periods should be met while minimizing the overall associated cost. An ESS is available in the energy system to meet the demand by discharging the previously energy.

The proposed model is implemented by using the modeling tool, GAMS. The solution of the model is computed using CPLEX solver. The resulting energy system operation plan according to the proposed modeling framework is summarized in Tables 2, 3, and Figs. 3, 4, 5, 6.

At first, we can see that a backorder was not generated because all demands were met over multiple time periods from Tables 2 and 3 and Fig. 3.

Secondly, the supply does not directly follow the trend of demand variation. The results show a stable supply profile over time, as can

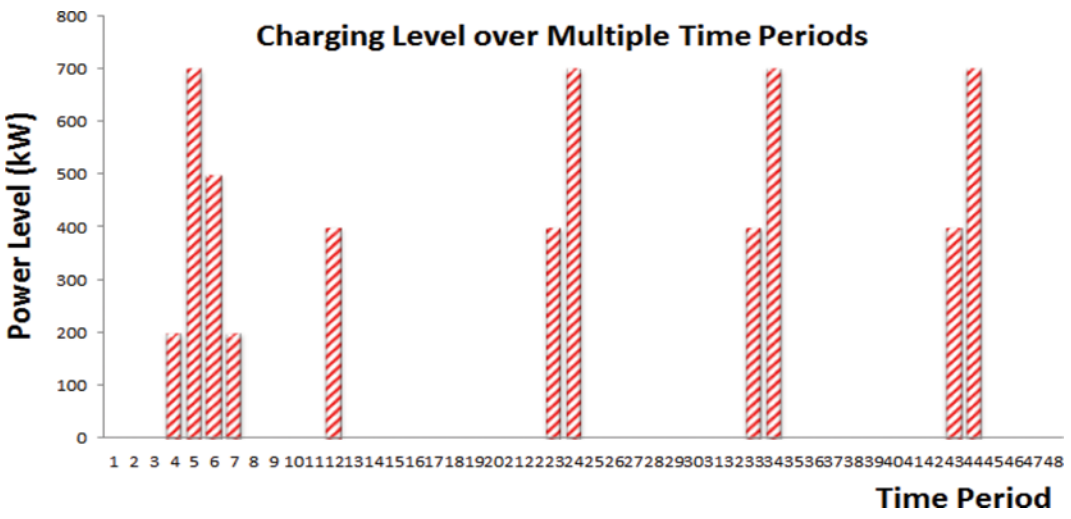

Fig. 5. Graphical representation of ESS charging plan according to the proposed framework.

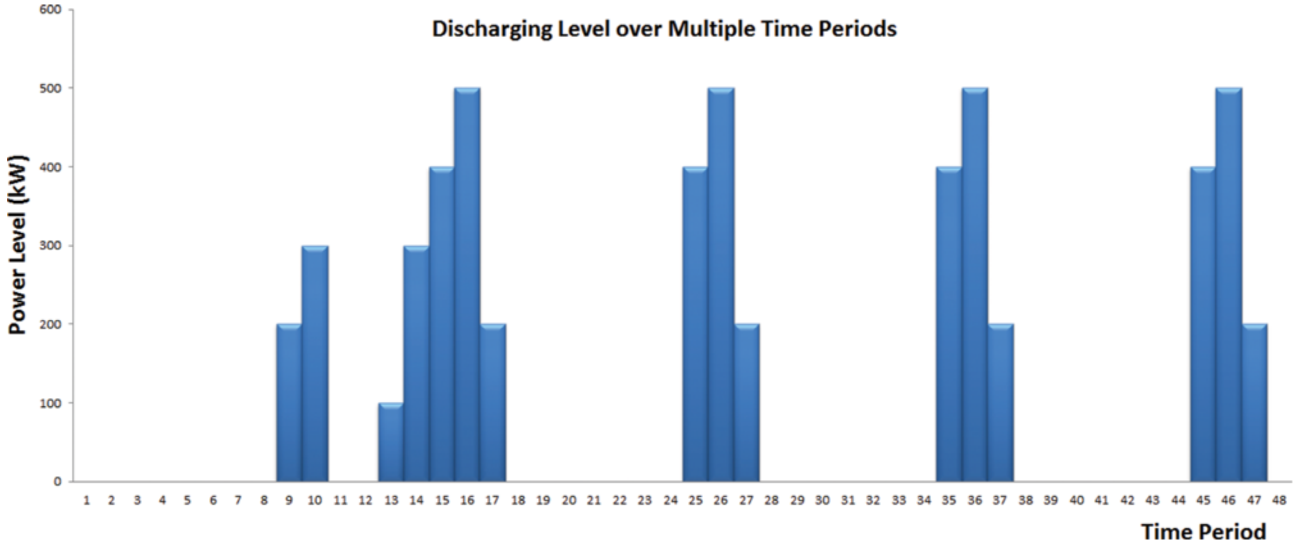

Fig. 6. Graphical representation of ESS discharge plan according to the proposed framework.

be seen in Fig. 3. It illustrates that the peak load of demands was reduced and the overall supply trend was flattened due to the ESS. This can be further explained in terms of quantitative manner: the standard deviation of demands is 414.9, but that of supplies is only 329.4 with a reduction of about 21%. Therefore, a much stable energy supply can be made and the corresponding energy generation can be safely managed while meeting continuously varying demands.

Thirdly, the upper bound of ESS was not directly limited in this example. When an upper bound is set, the profile of supply and ESS would be changed, and its stabilizing effect as an alternative power source could be reduced. But the capacity of ESS cannot be on a large scale. There should be a boundary. It will be a further research topic to compute the capacity of ESS considering both of economic feasibility and operation stability simultaneously.

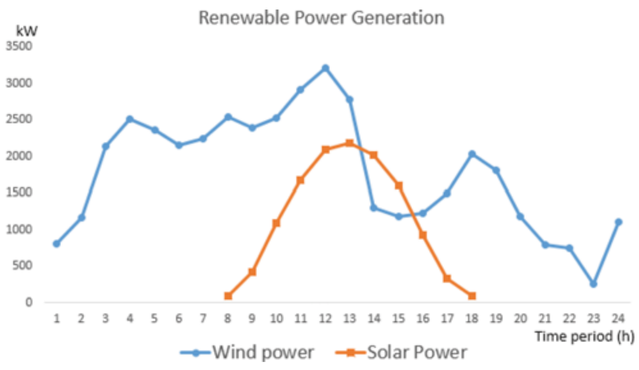

Fig. 7. Data for example 2: Renewable energy supply.

2. Example 2

Consider an energy system consisting of a set of suppliers including a wind farm, a solar power generator, and a natural gas generator, an ESS, and a set of demands. A snapshot of the renewable power output is summarized in Fig. 7. The solar power generation data is obtained from solar power generators in Gyeongju,

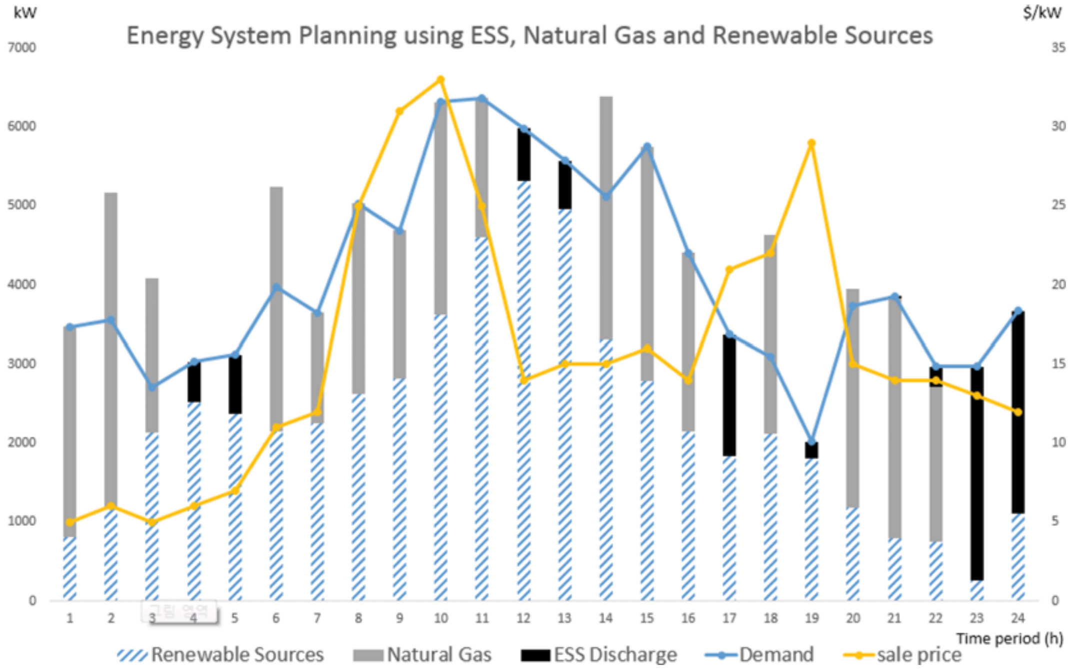

Fig. 8. Graphical representation of operation planning for example 2.

South Korea. The wind power data is obtained from the WIND Toolkit data in NREL [11].

The operation planning of ESS according to the proposed modeling framework is summarized in Fig. 8 with the variation of energy price. The time horizon of 24 hours is considered in this example. The computation has been implemented using GAMS, CPLEX as the solver.

The sum of wind and solar power generations is basically used and the remaining is satisfied by the natural gas power generation and ESS. One type of energy price is considered here.

The presence of ESS allows us to incorporate the further advanced condition into the energy system modeling. For example, additional constraints such as restriction on the operation hour of some specific power plants, different prices of energy sources, incentives to increase the deployment of renewable energy sources.

The key point is that this paper proposes a mathematical programming based decision-supporting framework. Therefore, more realistic operation planning can be made by using the framework.

In terms of computational statistics, the execution time was 0.015 seconds in GAMS 23.6.3 using intel Core i5 Windows machine with 4 GB memory. The number of variables and equations was 391 and 582.

3. Discussion

Let's consider some issues regarding the proposed methodology. At first, there might be negative opinion on employing ESS in practice. It would be still expensive for purchasing and installing ESS on a large scale in the current energy system. However, even before the ESS market is fully matured, it is still important to develop its rigorous decision making framework. The importance of ESS will be stressed more as the energy generation cost increases. The corresponding energy system operation framework should incorporate the impact of ESS. Also its deployment in practice can be accelerated by developing a systematic ESS operation strategy.

Second, process industries will seriously investigate how to deploy ESS in the process industry in the coming years. The process industry is very energy intensive and energy takes a significant portion of its total cost in this regard. Any novel methodology associated with saving energy costs will be welcome. Under an economic environment with an increasing portion of renewable sources, it is therefore quite natural to give special attention to the ESS. Further research will be made on the operation of ESS. Third, this paper deals with electricity in terms of energy type because most operations of the process industry are based upon electricity. There may be other forms of energy that can be charged and discharged, but that is beyond the scope of this paper. Fourth, this paper is not explicitly limited to the specific ESS technology or parameters. One can mention that the parameters in the case study may be based on the actual practice. Depending on the feature of specific ESS technology, the value of these parameters can be different. Besides, various energy storing technologies are under development and each energy system may employ a different kind of ESS technology. The proposed methodology is not limited to any specific individual technology. The key point of this paper is to demonstrate the applicability of the proposed modeling framework.

Finally, the presented example may look too simple and does not convey the key message. Our main aim is not to improve the existing PSE principle for conventional chemical engineering problems, but to explore the existing PSE expertise for addressing the emerging issues in the operation of the energy system. The concept that more than the current demand can be reserved and used later is well established in the PSE community. The resulting mathematical formulation has been studied actively; however it is a novel idea. It is only recently that the concept of energy inventory has become possible in the context of the energy system due to the technological development of energy storing equipment such as the Li-Ion battery. Because of this feature, a case that looks too simple in fact represents a significant research expansion in the decision-making in energy systems.

CONCLUDING REMARKS

The importance of ESS in the energy system will be stressed more with the increasing portion of renewable sources. The buffering role of ESS in coping with the varying demand with varying renewable supply should be drawing more attention because the mismatch between energy supply and demand is a serious problem in terms of process operation and economic profitability.

With the increasing portion of renewable energy sources in the energy system, the overall energy investment planning such as [12] is going to be an important issue. ESS should be also considered as a potential option in the planning. The systematic decision making framework should be employed in handling the challenging issue. Further works similar to this paper are expected to follow due to the increasing attention. The proposed modeling framework is a good starting point. PSE expertise can be used to tackle many real world energy problems.

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NOMENCLATURE

Indices and Sets

i : index of supplier (i=1, …, N)
j : index of demand (j=1, …, M)
t : time index (t=1, …, T)

Parameters

$D_{j,t}$: energy demand amount for demand j at time period t [kw]
$p_{j,t}$: unit revenue coefficient for demand j at time t [\$/kw]
gn_t : unit cost coefficient at time t [\$/kw]
gtr_t : energy supply unit cost coefficient at time t [\$/kw]
bkc_t : backorder unit cost coefficient at time t [\$/kw]
gc_t : ESS charging unit cost coefficient at time t [\$/kw]
gd_t : ESS discharging unit cost coefficient at time t [\$/kw]
gh_t : ESS operation holding unit cost coefficient at time t [\$/kw]

Variables

$x_{i,j,t}$: energy supply from supply i for demand j at current time period t [kw]
$w_{i,t}$: charging energy amount for ESS from supply i at time period t [kw]
$z_{j,t}$: discharging energy for demand j at time period t from ESS [kw]
$Supply_{i,t}$: energy supply amount from supply i at time period t [kw]
ES_t : energy level of ESS at time period t [kw]
$bkorder_{j,t}$: backorder energy for demand j at time period t [kw]
PF : profit [\$]

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