Operation of Solar-Storage-Hydrogen-Charging System by Value Stream Analysis

Xiaoen Li\textsuperscript{1,2}\textsuperscript{*} and Ting Lu\textsuperscript{1,3}

\textsuperscript{1}National Institute of Clean-and-Low-Carbon Energy, Beijing, China
\textsuperscript{2}Department of Electrical Engineering, Tsinghua University, Beijing, China
\textsuperscript{3}School of Electrical Engineering, Beijing Jiaotong University, Beijing, China
Email: shawnli89@163.com

Abstract. The topology of the clean energy system is a flexible structure with PV, wind power, hydrogen storage, battery storage. Thus, the construction and operation of the clean energy system should pay more attention to the temporal and spatial variations. This paper discussed a solar-storage-hydrogen-charging demonstration to accommodate the diverse temporal and spatial features of the clean energy system. The present study developed a Modelica library to support the cooperative control of this clean energy system based on value stream analysis. The result shows that the sold electricity profit of the electric storage system can reach 2.3 times than the electricity purchase cost. Though the hydrogen charging demand in the demonstration is small compared with the electric load demand, the hydrogen charging profit can be 1.7 times of the energy cost.

1. Introduction
Sustainability has gradually become one of the top priorities for the future energy system. However, solar power, wind power, electric storage, hydrogen storage, fuel cell vehicles are normally planned separately due to the different equipment suppliers or regulations \cite{1}. The temporal and spatial coordination optimization of these subsystems can effectively improve the energy efficiency of the clean energy system. At the same time, it can effectively solve the fluctuation problem of the clean energy system by reducing the solar/wind curtailment. Thus, the modeling and process simulation of the clean energy system is an important means to ensure the proper configuration and optimal operation of the energy storage system \cite{2}.

System modeling can be divided into the causal model and the acausal model based on the solution method \cite{3}. The causal model has an explicit relationship between input variables and output variables, where the signal transmission direction between modules is explicit. Most system modeling languages have adopted this approach since the modular continuous system modeling language was proposed in 1967 \cite{4}, e.g. Simulink. The acausal model does not emphasize the relationship of input-function-output but focuses on the known-unknown-equation. The acausal model does not require an explicit direction of signal transmission between modules, which is more suitable for bi-directional flow scenarios. Common modeling tools for acausal systems include Modelica, 20sim, gProms, etc.

System modeling can also be divided into the dynamic model and the static model. The static model is often used in the equilibrium process and (quasi-) steady state. The input variables and output variables don’t change with time in the static model. The commonly used steady-state modeling tools include Aspen, Ebsilon, VALI (Belsim), Thermoflow. The dynamic model contains time variables, which can calculate the derivative of variables with time to simulate the dynamic process.
There have been researches focusing on the dynamic analysis of clean energy system with energy storage system, e.g. Refs. [5-6]. Ref. [7] divided the interaction process between electricity and heating systems into four stages, and each stage was a quasi-steady state with a multi-energy flow model. The advantage of this method is that the mathematical model can be used to solve the multi-objective optimization problem under complex constraints, but the non-object-oriented method needs a high demand for computing performance. However, the forecasting of the net demand is challenging, as both aspects of energy supply and demand need to be accurately estimated [8]. Thus, the major solution is the day-ahead scheduling method for the generation side that includes an energy storage system and renewable energy sources.

The previous studies exist the following problems. The information layer model is not decoupled from the optimization algorithm, which means the model needs to be rebuilt when the topology structure or the optimal control target changes. Besides, the equipment model and parameters are usually separated from the real operating data, which results in a disconnection between the information layer and the physical layer.

Therefore, this paper focuses on the analysis of system value flow at the operation optimization level and considers the boundary conditions such as time-of-use electricity price, load demand, PV power generation solar curtailment, energy storage parameters. Based on a solar-storage-hydrogen-charging demonstration, the modeling and simulation of this clean energy system are applied by the value stream analysis method. It adopts an acausal model based on Modelica, an object-oriented equation-based simulation language. The applicability and reliability of this method were verified with the real operation data. Finally, the operation economy of the clean energy system was improved compared with the old operation strategy given by the equipment suppliers.

2. Optimal Control Based on Value Stream Analysis

The optimal control problem of the clean energy system is solved based on value stream analysis. In this section, we focus on the methodology of value stream analysis and the use of dynamic programming for optimal control strategy.

2.1. Methodology of Value Stream Analysis

The value stream analysis is difficult to deal with only with the flow variable and potential variable. Because the value stream is bi-direction and its unit price depends on the upstream side. The connector of the energy storage system is bidirectional. Thus, when the energy storage system is adsorbing electric, the unit price is the time-of-use electric price. While, when the energy storage system supplies electricity to the load, the unit price is set by the energy storage system supplier. Therefore, flow variables, potential variables and unit price variables need to be processed respectively in Modelica.

The unit price variable refers to the price flow out from the component. It should be noted that for energy storage with the bi-directional flow, the value of the unit price variable is determined by the upstream energy. The calculation value of the unit price variable is always determined by the upstream:

\[
 c_{\text{cal}}(t) = \begin{cases} 
 c(t) & \text{if} \ f(t) < 0 \\
 c_{\text{upstream}}(t) & \text{if} \ f(t) > 0 \\
 0 & \text{if} \ f(t) = 0 
\end{cases}
\]

where \( c_{\text{cal}} \) represents the value of the unit price variable during the calculation of the model, and the lower corner of the upstream represents the upstream outflow location. It should be noted that unit price variable \( c(t) \) relies on a material flow or energy flow, namely the flow variable \( f(t) \) in equation (3). When \( f(t) \) is negative, the stream flows out from the connector, and \( c_{\text{cal}}(t) \) is the unit price of the outlet connector. When \( f(t) \) is positive, the stream flows into the connector, and \( c_{\text{cal}}(t) \) is the upstream unit price \( c_{\text{upstream}}(t) \). When \( f(t) \) is zero, the material flow or energy flow supported by the value stream is zero, and the unit price can be set as zero. In summary, the calculation value of the unit price variable is always determined by the upstream side.
The unit price variable has the characteristic of equation (4), namely the value balance equation.

\[ \sum_i f_i(t) \times c_{\text{cal}}(t) = 0 \]  

(2)

2.2. Optimal Control Strategy Based on Dynamic Programming

The mathematical description of the optimal control problem is as follows:

\[
\begin{align*}
\min_{u(t)} J &= \int_{t_0}^{t_f} H(x(t), u(t), p(t), t) \, dt \\
\text{s.t.} & \quad \dot{x}(t) = f(x(t), u(t), p(t), t) \\
& \quad x(t_0) = x_0, \ x(t_f) = x_f \\
& \quad g(x(t), u(t), p(t), t) \leq 0
\end{align*}
\]

(3)

where the minimum objective function \( J \) is the grid electric cost from \( t_0 \) to \( t_f \). While \( x(t) \), \( u(t) \) and \( p(t) \) are state variables, control variables and environment variables, respectively. The state variable \( x(t) = [x^{(i)}(t), \ldots, x^{(n)}(t)] \) and the control variable \( u(t) = [u^{(i)}(t), \ldots, u^{(n)}(t)] \) can be a vector for \( t \in [t_0, t_f] \), e.g. the state and control signals for the electric storage system and the hydrogen storage system. \( \dot{x}(t) = f(x(t), u(t), p(t), t) \) is the state transfer function, which represents the transfer relation of the system state from \( x(t) \) to \( \dot{x}(t) \) within the control of variable \( u(t) \). \( p(t) \) is the environment variable used for storing the time-dependent variables, e.g. the time-of-use electric price. The path constraint is expressed in \( g(x(t), u(t), p(t), t) \leq 0 \). This dynamic programming problem is solved in Modelica.

3. Case Study

3.1. Introduction of the Studied Clean Energy System

To reduce the energy cost of the demonstration, the value stream analysis method has been carried out with the Modelica simulation. The simplified structure of the solar-storage-hydrogen-charging system is shown in figure 1. L1 contains a 100 kWP photovoltaic, a 500 kWh / 50 kW energy storage system and end-user loads. L2 includes an 80 kWP photovoltaic and end-user loads. L3 involves a solid polymer electrolyte (SPE) system and a hydrogen storage system with a 5 kg hydrogen vehicle.

![Figure 1. The structure of the studied clean energy system.](image-url)

An old control strategy provided by the equipment suppliers is shown in table 1. However, several points can be improved for this control method.

1. This control method doesn’t calculate the benefits of hydrogen and solar power generation. 
2. The battery discharge power may exceed the load demand and there might be solar curtailment without the consideration of the boundary condition. 
3. It considers the time-of-use electric price only on the peak and valley period. Thus, it is important to improve the old control strategy by value stream analysis to gain the maximum profit.
Table 1. The old control strategy provided by the equipment suppliers.

| Time          | Battery Charge | SPE on | Hour | Electric valley | Price (CNY) |
|---------------|----------------|--------|------|-----------------|-------------|
| 23:00-7:00    | Stop           | off    | 8h   | flat            | 0.3648      |
| 7:00-10:00    | Discharge      | off    | 3h   | Peak (summer)   | 0.8645      |
| 10:00-15:00   |                |        | 5h (2h) | flat (summer) | 1.3902      |
| (11:00-13:00*)| Discharge      |        | 3h (1h) | peak          | 0.8645      |
| 15:00-18:00   |                |        | 3h   | flat            | 1.3902      |
| (16:00-17:00) | Stop (discharge) |        | 2h   | flat            | 0.8645      |
| 18:00-21:00   | Discharge      |        |      |                 |             |
| 21:00-23:00   | Stop           |        |      |                 |             |

Note: * in July and August.

3.2. Value Stream Analysis

The case study is based on a typical working day in September and the corresponding time-of-use electric price is shown in figure 2. The load forecast data comes from the historical average load, while the PV power generation data is based on the historical PV power curve and the weather forecast. The predicted load demand and PV power generation are shown in figure 3. It shows that electricity consumption is higher from 8:00 a.m. to 8:00 p.m., but it decreases at noon. Meanwhile, the photovoltaic power generation reaches the peak at noon and is even higher than the load demand from 12:00 to 15:00, which means there will be solar curtailment without the energy storage system.

Figure 2. The time-of-use electric price in this case study.

Figure 3. The load forecast data and the PV generation data based on the historical curve.

Based on the structure of the solar-storage-hydrogen-charging system, a Modelica simulation model was built for this clean energy system according to the equipment parameters. The minimum objective function $J$ is the electric purchasing cost in 24h. The state variable $x(t)$ is the real-time capacity of the electric storage and the hydrogen storage system. The control variable $u(t)$ is the real-time charge/discharge power of the electric storage and the hydrogen storage. The state transfer function is embedded in the Modelica system structure. The path constraints including the rated power parameters of PV, electric storage, SPE, hydrogen storage, hydrogen vehicle.

The charge/discharge strategy of the electric storage system and hydrogen storage system is shown in figures 4 and 5. The reliability analysis of this charging and discharging strategy is as follows:

1) This optimal strategy takes the minimum purchased electric as the optimization objective with the consideration of the peak-valley price arbitrage. Therefore, the electric storage system is normally charging at the valley period and discharging at the flat and peak periods. As shown in figure 4, charging is carried out in the valley period from 00:00 to 5:00, while the discharging is normally carried out in the flat and peak period from 8:00 to 21:00. Moreover, from 15:00 to 23:00, the amount
of discharging electric during the peak period is larger than that of the flat period, which will further reduce the electric costs.

Figure 4. Operation strategy of the electric storage system based on value stream analysis. Figure 5. Operation strategy of the SPE and hydrogen storage based on value stream analysis.

(2) PV power generation and the capacity and power limits of the energy storage system are all considered in the path constraints. The electric storage is adsorbing electric from 12:00 to 15:00 to prevent the solar curtailment. Besides, as a path constraint \( x(t_0) = x(t_f) \) is added in this case, the electric storage is shut off after it reaches this restriction at 21:00.

(3) The SPE and hydrogen storage system are operating simultaneously. SPE is working only during the valley period to reduce energy costs. In this case, the SPE produced 3 kg hydrogen and the hydrogen storage system provide 2.5 kg hydrogen to filling the hydrogen vehicle.

The Sankey diagrams of energy flow and value stream within 24 hours are shown in figures 6 and 7. The following results can be found from the energy flow and the value stream analysis:

Figure 6. The Sankey map for the energy flow analysis in the case study. Figure 7. The Sankey map for the value stream analysis in the case study.

(1) Energy sources. According to the energy flow Sankey map in 24 hours, the power purchased from the grid is 1,195 kWh, which is slightly higher than the solar power generation. However, according to the value stream Sankey map, the value provided by PV is 1057 CNY, which is slightly higher than the power provided by the grid. This is because the grid electricity tends to be purchased during the valley price period, while the PV generation is normally used during peak price period.

(2) Energy storages. The electric storage system gains the accumulated stream value by peak valley arbitrage. For instance, the electric storage absorbed 277 kWh electricity in 24h and the corresponding power purchase cost is 143.9 CNY. Meanwhile, its profit is 332.5 CNY, which is about 2.3 times higher than the cost. The hydrogen system gains the stream value by generating hydrogen with the
valley period electric price. Thus, it makes the revenue gain from 87.5 CNY to 150 CNY after the SPE, which means the hydrogen filling profit is 1.7 times larger higher than the energy cost.

4. Conclusion
This paper discussed an operation problem of a solar-storage-hydrogen-charging demonstration. The reliability of modeling and optimization is verified by a peak-valley arbitrage case. This method is especially suitable for structural and control optimization of the clean energy system with energy storage. The major conclusions include:

(1) The value stream analysis method is suitable for the peak valley arbitrage problem. The profit of the proposed electric storage control strategy is 1.5 times higher than the strategy given by the equipment supplier. The electricity selling profit of the electric storage system can reach 2.3 times than its electricity purchase cost.

(2) The hydrogen system gains the stream value by generating hydrogen with the valley period electric price. The hydrogen filling profit can be 1.7 times of the energy cost.

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