The Pennsylvania State University

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SIZING AND TECHNO-ECONOMIC ANALYSIS OF HYBRID-COMBINED HEAT AND POWER -PV-BATTERY STORAGE SYSTEMS OF COMMERCIAL AND INDUSTRIAL BUILDINGS

A Thesis in

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by

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ABSTRACT

This paper focuses on simulating hybrid solar energy-combined heat and power-battery storage systems with different sizes, types, and number to determine the optimal system configurations with the goal of minimizing life-cycle cost and maximizing fossil energy savings. A micro-grid solar photovoltaic generation subsystem operated in parallel with, a gas-fired engine and a battery storage subsystem and operating within a macro-grid connected environment is modeled. The hybrid system supplies the micro-grid system dynamic electrical and thermal demands, which is simulated by HOMER (Hybrid Optimization of Multiple Electric Renewables). In this study, solar energy is to meet the peak micro-grid system electrical demand. Considering the fluctuations of solar energy production, the gas-fired engine is used to supply unmet, micro-grid electrical demands. The engine is sized with part load operating characteristics to allow excess PV-engine-battery generation for sales back to macro-grid on high solar flux, high macro-grid demand days. Because the hybrid system choices could change with key factors variations, this study takes into account some factors, like demand profile from two building types, initial component installment cost, and the energy price to make technical and economic analysis. For instance, commercial and industrial buildings with different electrical and thermal demand profile should be considered separately and decreasing PV system price and fuel price could be an opportunity for hybrid system. Also, the study evaluates the potential impact of dispatch strategies on energy savings and explore the correlations between each operating component size and energy cost.

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1. Introduction

The urgent concerns of energy scarcity and environment problem have led to the development of hybrid combined heat and power-PV-battery storage systems micro-grid application. The hybrid system is regarded as an effective alternative to save energy and decrease capital cost. Because configurations allocating different components can affect the optimal results dramatically, so the big challenge is how to select the optimal configurations and how to operate them at an optimal level. Several studies have evaluated the potential values for applying hybrid micro-grid system, For instance, [1] T. Givler and P. Lilienthal found certain load threshold in the case study to determine whether a PV-battery systems or a hybrid PV-generator-battery system is the optimal configuration. Also, reliability requirements, solar resource, and fuel price all shift the exact threshold for a particular situation. [2] Kunal K. Shah et al. have demonstrated that such PV + CHP + battery hybrid systems can provide all of the necessary electricity in Prescott, Arizona (representing a hot climate), Sacramento, California (representing a moderate climate) and Houghton, Michigan (representing a cold climate). [3] G.J. Dalton et al. found that hybrid (Renewable Energy Supply) RES component PV or wind energy conversion system (WECS) have significant potential for use in large-scale tourist resorts and hotels in combination with grid-connected power supplies. [4] W Gu et al. reviewed the current development of micro-grid and summarized that the real-time control strategies and day-ahead optimal scheduling should be combined to establish a robust energy management method that provides good performance even when the forecast renewable energy value deviates significantly from the real value. [5] R Banos et al. concluded that the use of heuristic approaches, Pareto-based multi-objective optimization, and parallel processing are promising research areas in the field of renewable and sustainable energy.

However, few research papers evaluate the hybrid system performance on different building types with different electric and thermal demand profile.

This study focuses on simulating hybrid systems with different sizes, types and number to determine the system configurations with the lowest life-cycle cost and carbon emissions. Because the optimal choices could change with key factors variations, this study takes into account various factors to evaluate the performance of hybrid system in different situations. For instance, commercial and industrial buildings with different electrical and thermal demand profile should be considered separately and decreasing PV system price and fuel price could be an opportunity for hybrid system. Also, the relationship between each system component size and energy cost is simulated in this study.

2. Study objectives

This study evaluates the performance of hybrid systems on economic savings and carbon emissions savings in commercial building and industrial. With the following three specific objectives:

1) Determining the sizes and equipment types of hybrid system that has the best performance on economic and carbon emissions savings.
2) Making sensitivity analysis to determine the impacts of market value variations on the performance of hybrid system.
3) Evaluating the impact of dispatch strategies on energy savings.

3. Research methods

3.1 HOMER introduction

HOMER (Hybrid Optimization of Multiple Electric Renewables) simplifies the task of evaluating the economic and technical feasibility of many possible system configurations. HOMER has its three core capabilities: simulation, optimization, and sensitivity analysis

- Simulation: HOMER simulates a viable system for all possible combinations.
- Optimization: The optimization step is that all simulated systems are sorted and filtered according to the total net present cost (NPC)
- Sensitivity analysis: This step can verify the impact of other variables that are not considered in before simulations, such as electric rate, fuel costs, etc. This process can show the impact of market value variations on the selections of system configuration.

3.2 Hybrid combined heat and power- PV- battery storage system introduction

The hybrid systems have PV system, battery, generator, grid, and supplemental boiler to supply the electric demand and thermal demand. PV panels transfer solar energy into direct current electricity to supply electric demand and the excess electricity is stored in the battery bank and then be used later. Because building electric demand requires alternating current, DC-AC inverter and AC-DC rectifier are supposed to add to the systems. In the HOMER software, the component called converter can work as both inverter and rectifier to make the transformation between alternating current and direct current. The gas-fired generator with combined heat and power function can supply both electric and thermal demand to increase the energy use efficiency.

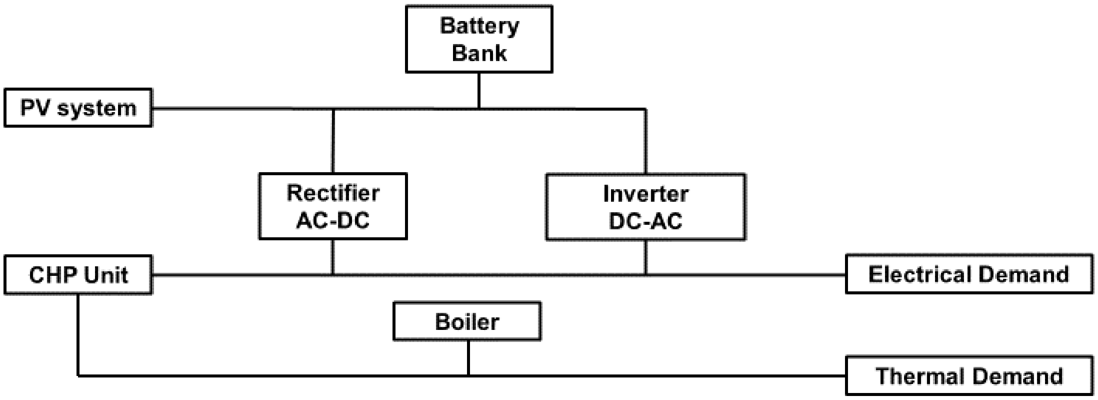


Fig.1 Hybrid system description

3.2.1 Characteristics of hybrid systems

The majority of difference between hybrid systems and conventional systems are the initial equipment cost and operating cost. The high initial equipment cost in hybrid systems is due to the purchase of many components. However, the PV systems and combined heat and power applications in hybrid systems increase the energy use efficiency, thereby decreasing the operating cost. In addition, the advantages and disadvantages of each component are listed at the below table.

Table-1 Hybrid systems pros and cons

	Pros	Cons
PV	No emissions	High capital cost
	Free energy	Uncertainties
Battery	Increase PV credits	High capital cost
	Buy low sell high from grid	High control requirement
Generator	Use waste heat to supply heat demand	High capital cost
	Electricity is cheaper than grid	High control requirement
Overall	Low operating cost	High capital cost
	Low carbon emissions	

3.3 Commercial buildings vs Industrial buildings

3.3.1 Commercial buildings

The typical example of commercial building is office building where people stay in the daytime and leave at night. Therefore, the typical daily demand profile of commercial buildings has a peak during the daytime shown at Fig.2. This study uses the real electric and heating billing data from Bldg.661 at Navy Yard to input the building demand.

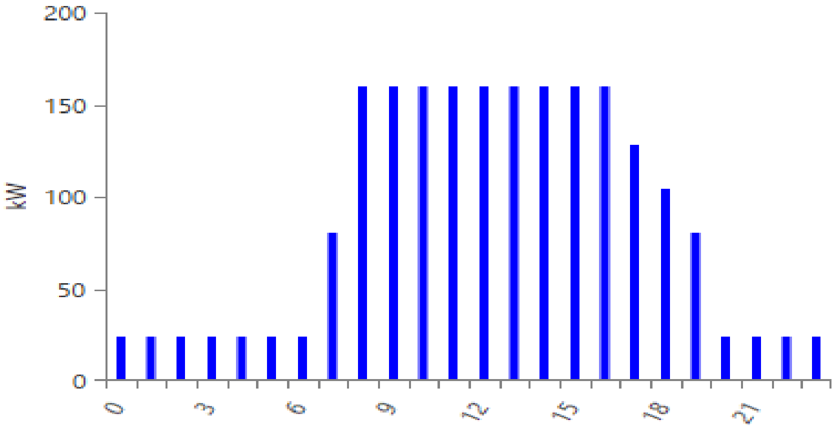


Fig.2 typical commercial building daily load profile

3.3.2 Industrial buildings

Industrial buildings, like the factory, hospital and hotel usually consume huge energy with lower power variations compared to commercial buildings. Those buildings requires electricity and hot water all the time so that the building demands are relatively constant. The building demand in this study is based on an existing hospital hourly electric and thermal data.

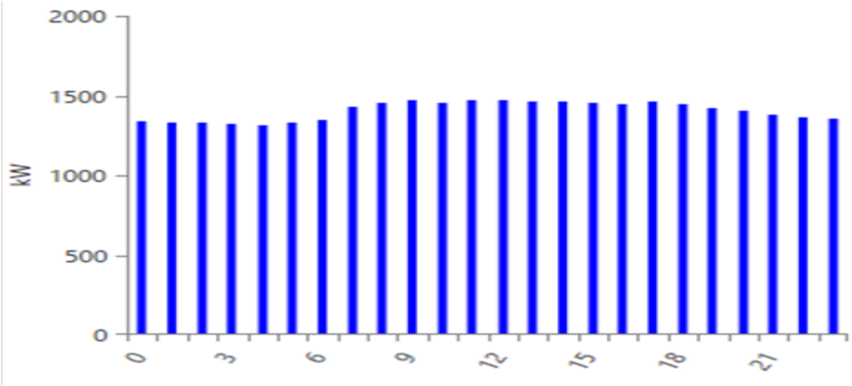


Fig.3 hospital daily electric demand profile

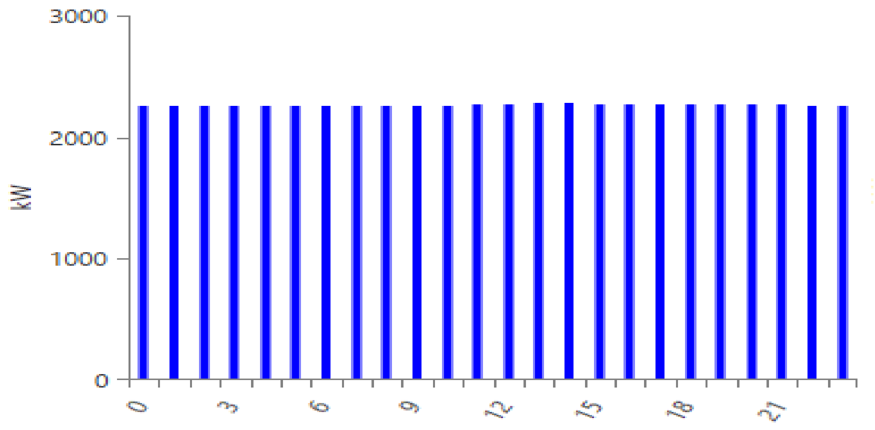


Fig.4 hospital daily thermal demand profile

Table-2 Two buildings information

Building information	Commercial building	Industrial building
Type	Bldg.661 office building	Hospital
location	Navy Yard in Philadelphia, PA	New Jersey
average electric demand (kWh/day)	829	41087.35
average thermal demand (kWh/day)	314.47	37432.85

3.4 Components of hybrid combined heat and power-PV-battery storage systems

3.4.1 Battery Types

Lead acid battery has been widely used for decades and is regarded as mature and reliable technology. Also, the low initial price of lead-acid is the advantage to make significant savings. However, the lead acid battery is easy to damage if it discharged too quickly or deeply.

Lithium-ion battery is durable and portable compared to lead-acid, so it can be discharged more deeply and be used for long time. However, the high initial cost of lithium-ion battery is an obstacle to apply in some projects.

Table-3 Lead acid battery vs lithium-ion battery

Battery	**Lead acid**	**Lithium-ion**
Initial cost	Relative low	Relative high
Battery lifetime	Relative short	Relative long

The battery price in this project is shown at Table-4, which is supplied by one of the manufacturers.

Table-4 Battery parameters in HOMER

Battery		**Lead acid**	**Lithium-ion**
Initial cost ($/kWh)		225	300
Replacement ($/kWh)		225	300
Battery lifetime	Lifetime (years)	8	15
	Throughput (kWh)	980	3831.8

3.4.2 Generator Selections

The reciprocating engines transfer chemical energy to mechanical energy and then allow pistons to convert pressure into rotational motion. For combined heat and power application, engines have multiple recovery heat sources and are able to follow variable load.

Turbine is a rotary mechanical device that can transfer chemical energy into useful work. Micro-turbine is a small gas-fired turbine that can use gaseous fuels and then produce high quality and high-pressure steam with high heat to power ratio.

It is hard to say that either turbine or reciprocating engine is better than the other, because both generators attributes have advantages for certain conditions. Therefore, this study takes into account both generators for simulations.

Table-5 Generators parameters in HOMER

Generator	Reciprocating Engine	Micro-turbine
Initial cost ($/kW)	1801	2500
Replacement ($/kW)	1140	1710
O&M ($/hr)	0.016	0.01

3.4.3 Variables input summary in HOMER

Table-6 Cost parameters input summary

Equipment	Reciprocating Engine	Micro-turbine	Lead acid	Lithium-ion	PV System	Inverter
Initial cost ($/KW)	1801	2500	225	300	2000	150
Replacement ($/KW)	1140	1710	225	300	2000	150
O&M ($/year)	140.16	87.6	10	10	10	N/A

Table-7 Size parameters input in Bldg.661 summary

Equipment	Reciprocating Engine (kW)	Micro-turbine (kW)	Lead acid Strings (#)	Lithium-ion Strings (#)	PV System (kW)	Inverter (kW)
Search space	0-100	0-100	0-50	0-50	0-100	0-200

In HOMER simulation, each lead-acid battery bank is 1kWh with 12V. 40 batteries are connected at series to maintain building voltage: 480 V, so the string size is 40kWh. Each lithium-ion battery is 1kWh and its voltage is 6 V. 80 batteries are connected at series to maintain 480 V, so the battery size for each string of is 80 kWh.

Table-8 Size parameters input in hospital summary

Equipment	Reciprocating Engine (kW)	Micro-turbine (kW)	Lead acid Strings (#)	Lithium-ion Strings (#)	PV System (kW)	Inverter (kW)
Search space	0-2000	0-2000	0-50	0-50	0-2500	0-4000

4. Initial simulation results

HOMER has simulated the variable inputs and evaluated the feasibility of all possible system configurations. After simulation, HOMER sorted all the feasible system configurations based on NPC (net present cost) which is a life-cycle cost value and regarded the lowest NPC as the optimal system configuration. Also, study has sorted all the feasible systems based on carbon emissions to compare the results that based on NPC.

4.1 The optimal system configurations

4.1.1 The optimal system configurations in bldg.661

The lowest NPC system configuration in bldg.661 is the separate heat and power case that has no any component. Because of the low initial equipment cost, this system is competitive on economic savings, thereby decreasing the life-cycle cost. Therefore, the optimal system configuration based on NPC is the conventional system without any component.

Table-9 Optimal system ranking based on NPC

PV (kW)	Reci (kW)	Micro (kW)	1kWh LA	1kWh LI	Converter (kW)	NPC ($)	Operating cost ($/year)	Initial capital ($)
N/A	N/A	N/A	N/A	N/A	N/A	5.69E+05	4.40E+04	0.00E+00
0.1	N/A	N/A	N/A	N/A	0.3	5.69E+05	4.40E+04	3.01E+02
N/A	N/A	N/A	40	N/A	2.2	5.90E+05	4.49E+04	9.33E+03
1.5	N/A	N/A	40	N/A	3.3	5.91E+05	4.47E+04	1.25E+04
N/A	N/A	50	N/A	N/A	N/A	6.07E+05	3.73E+04	1.25E+05
0.1	N/A	50	N/A	N/A	0.3	6.07E+05	3.73E+04	1.25E+05

However, the lowest carbon emission system configuration is a hybrid system with 1.5kW PV panel, 50 kW capacity micro-turbine, 1 string lithium-ion battery, and 3.3 kW converter. Because the PV panels generate electricity without carbon emission and the hybrid system is able to reduce electricity purchase from grid, thereby reducing the carbon emission. In the case study for Bldg.661, conventional system has its advantages on economic over hybrid system, but is not the best environmentally friendly choice. Even though the hybrid systems generate relatively low carbon emissions, the expensive initial equipment cost is one of the biggest obstacle for application. Hence, once the initial equipment cost decreases, the hybrid system has an opportunity for large-scale application in the future.

Table-10 Optimal system ranking based on carbon emissions

PV (kW)	Reci (kW)	Micro (kW)	1kWh LA	1kWh LI	Converter (kW)	CO_2 (kg/year)	Operating cost ($/year)	Initial capital ($)
1.5	N/A	50	N/A	80	3.3	1.91E+05	3.86E+04	1.53E+05
1.5	50	50	N/A	80	3.3	1.91E+05	3.75E+04	2.43E+05
1.5	N/A	50	40	N/A	3.3	1.91E+05	3.81E+04	1.38E+05
1.5	50	50	40	N/A	3.3	1.91E+05	3.70E+04	2.28E+05
0.1	N/A	50	N/A	N/A	0.3	1.92E+05	3.73E+04	1.25E+05
0.1	50	50	N/A	N/A	0.3	1.92E+05	3.63E+04	2.15E+05

4.1.2 The optimal system configurations in hospital

The lowest NPC system configuration in hospital has a 1200 kW micro-turbine with grid connection. There is an advantage to apply gas-fired turbine in the hospital case due to the building demand profile. For one thing, hospital has large thermal demand compared with Bldg.661, so it is not economic to supply all the thermal demand by boilers. For another, the hospital requires electricity and hot water all the time, so the daily demand profile is relatively constant. In that case, gas-fired turbine has taken the advantages of CHP to supply both electrical and thermal demand, thereby increasing energy cost savings.

Table-11 Optimal system ranking based on NPC

PV (kW)	Reci (kW)	Micro (kW)	1kWh LA	1kWh LI	Converter (kW)	NPC ($)	Operating cost ($/year)	Initial capital ($)
N/A	N/A	1200	N/A	N/A	N/A	2.97E+07	2.07E+06	3.00E+06
3.2	N/A	1200	N/A	N/A	5.2	2.97E+07	2.07E+06	3.01E+06
N/A	N/A	1200	40	N/A	41.6	2.98E+07	2.07E+06	3.02E+06
38.2	N/A	1200	40	N/A	62.6	2.98E+07	2.06E+06	3.10E+06

When all the feasible system configurations are sorted by carbon emissions, the system configuration with lowest carbon emissions has 38.2 kW PV panel, 1200 kW capacity micro-turbine, 1 string lithium-ion battery, and 62.7 kW converter. The optimal system ranking based on two different values is different, but one of the hybrid systems is listed in both rankings. The hybrid system with 38.2 kW PV panel, 1200 kW capacity micro-turbine, 1 string lead acid battery, and 62.7 kW converter is the potential optimal choice considering both economic savings and carbon emissions savings.

Table-12 Optimal system ranking based on carbon emissions

PV (kW)	Reci (kW)	Micro (kW)	1kWh LA	1kWh LI	Converter (kW)	CO_2 (kg/year)	Operating cost ($/year)	Initial capital ($)
38.2	N/A	1200	N/A	80	62.7	9.3E+06	2.1E+06	3.1E+06
38.2	N/A	1200	40	N/A	62.7	9.3E+06	2.1E+06	3.1E+06
3.3	N/A	1200	N/A	N/A	5.2	9.3E+06	2.1E+06	3.0E+06
N/A	N/A	1200	N/A	80	41.7	9.4E+06	2.1E+06	3.0E+06

4.2 Sensitivity analysis

This study assumes the project lifetime is 25 years and then calculates the life cycle cost. During the period of project time, some market value variations can affect the selections of hybrid systems. This study takes into account three major factors: PV systems price, electric rate and natural gas price.

4.2.1 PV system price sensitivity analysis for Bldg.661

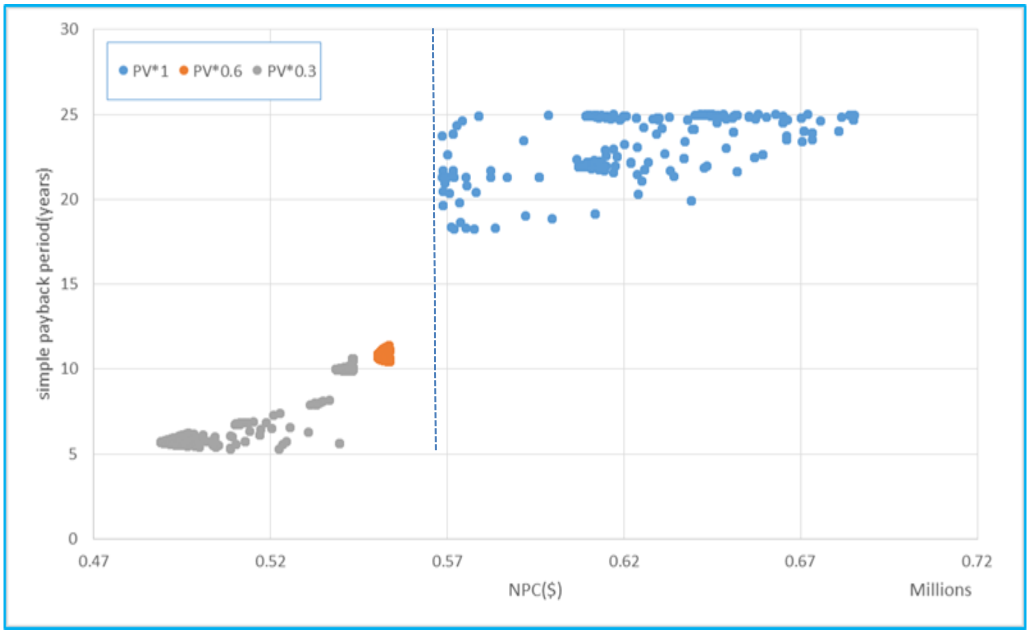


Fig.5 simple payback year vs NPC with PV system price variations

The figure above shows that 2000 system configurations NPC and simple payback years variations. The blue line presents the NPC of base case, which separate heat and power. When PV system price is the original, all the configurations have higher NPC than that of the base case. When the price multiple 60%, all the 2000 system configurations is better than the base case on NPC. When the price reduces to 30% original price, both payback years and NPC has obvious further reduction. Because of lower PV system price, large-scale PV panels can be applied into the project, thereby generating more electricity and decreasing the demand from grid. Therefore, lower PV price is an opportunity to apply hybrid system in Bldg.661.

4.2.2 Electric rate sensitivity analysis for Bldg.661

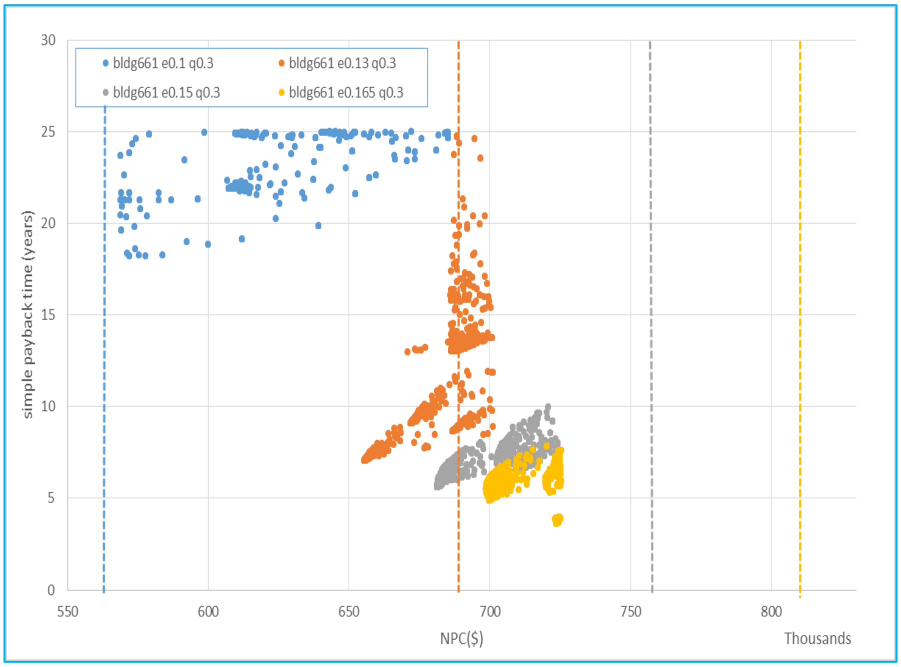


Fig.6 simple payback year vs NPC with electric rate variations

The original electric rate and fuel price input in HOMER are 0.10$/kWh and 0.3$/m^3 respectively. This sensitivity analysis change the electric rate from 0.10 to 0.165 $/kWh, which is based on the average price from different states in the United State of America. The NPC and simple payback year differences of 2000 system configurations are shown in the above figure. According to the figure, the data shows that hybrid systems have more advantages over the base case when the electric rate increases from 0.10 to 0.165$/kWh in Bldg.661. Therefore, the electric rate has significant impact on the hybrid system selections. Therefore, the states with electric rate is an opportunity for hybrid system.

4.2.3 Fuel cost sensitivity analysis for Bldg.661

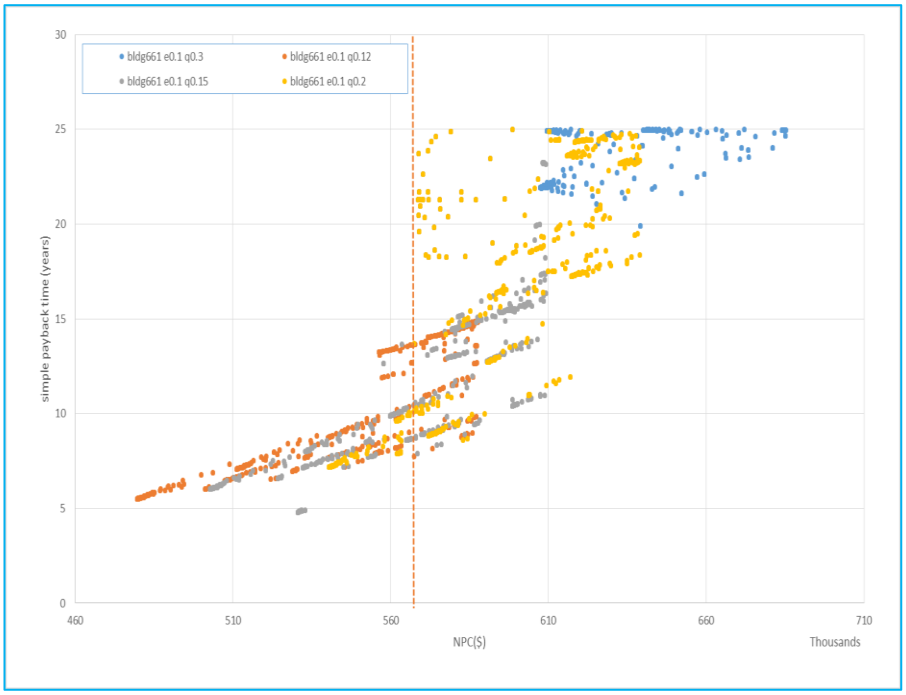


Fig.7 simple payback year vs NPC with fuel price variations

The original electric rate and fuel price input in HOMER are 0.10$/kWh and 0.3$/m^3 respectively. This sensitivity analysis changes the natural gas price from 0.30 to 0.12 $/m^3. From the results, when the natural gas price is the cheapest value, only parts of system configurations are better than the base case on NPC. Thus, the fuel price is not an important factor that affects the optimal system configuration selections. This is probably caused by low thermal demand in Bldg.661.

4.2.4 PV system price sensitivity analysis for hospital in New Jersey

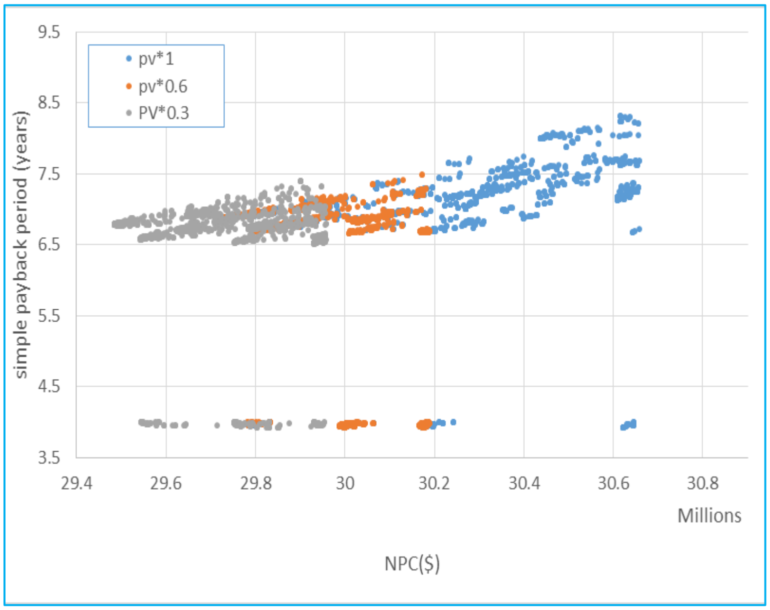


Fig.8 simple payback year vs NPC with PV system price variations

The figure above shows the sensitivity analysis for PV system price case in hospital. The NPC of base case (separate heat and power system) is above 30.8 million that beyond the figure. The data in the figure shows that the PV price variations have significant impact on the reduction of life-cycle cost and payback years. Therefore, lower PV system price is an opportunity for the hospital to make economic savings and carbon emissions savings.

4.2.5 Electric rate sensitivity analysis for hospital in New Jersey

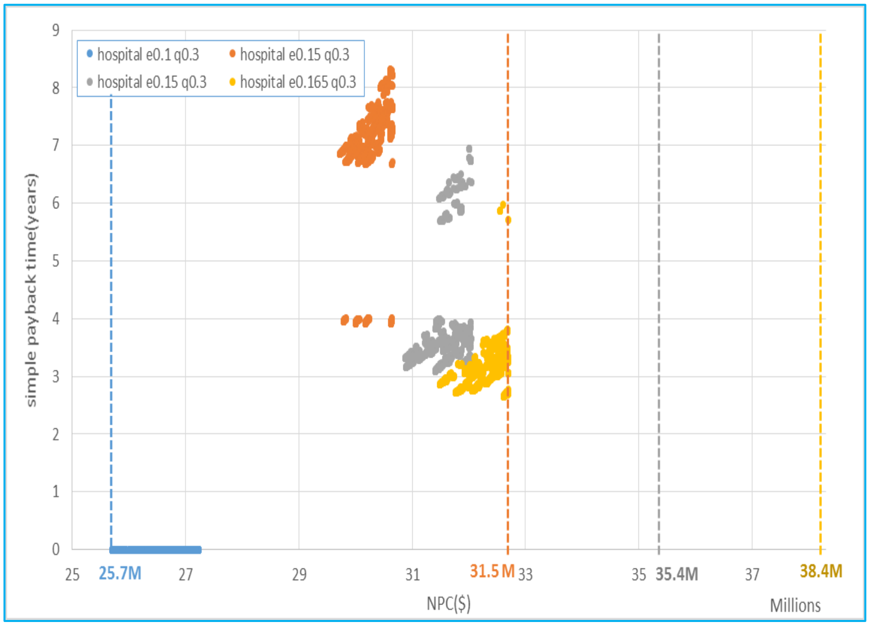


Fig.9 simple payback year vs NPC with electric rate variations

The original electric rate and fuel price input in HOMER are 0.13$/kWh and 0.3$/m^3 respectively. This sensitivity analysis change the electric rate from 0.10 to 0.165 $/kWh. According to the figure, if the electric rate decreases to 0.10$/kWh, all the system configurations have more NPC over the conventional system. While the electric rate increases from 0.13 to 0.165 $/kWh, the difference of NPC between 2000 hybrid systems and base are larger, and simple payback years also have a tendency to decrease. Therefore, the electric rate is a vital factor to influence the hybrid system selection in hospital.

4.2.6 Fuel price sensitivity analysis for hospital in New Jersey

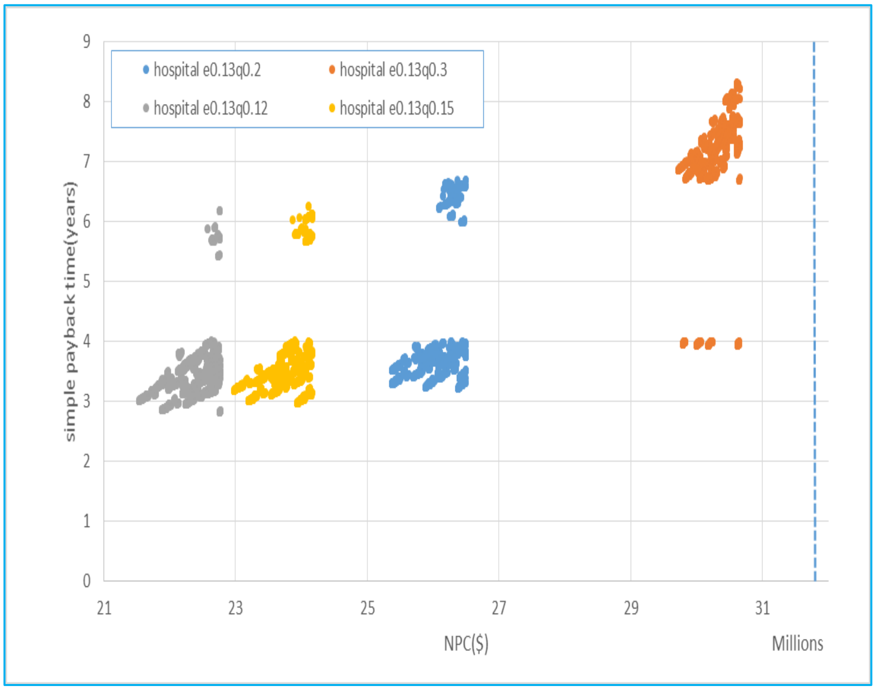


Fig.10 simple payback year vs NPC with fuel price variations

The original electric rate and fuel price input in HOMER are 0.13\$/kWh and 0.3\$/m^3 respectively. This sensitivity analysis changes the natural gas price from 0.30 to 0.12 \$/m^3. The analysis results showed that the fuel prices make abundant economic savings. When the fuel price changes from 0.3\$/m^3 to 0.2\$/m^3, the NPC savings are about \$4 million during the 25 years. The hospital has high magnitude thermal demand with less variation, which is suitable for generator running constantly to supply thermal demand. Therefore, the lower fuel price decreases all the system configurations life cycle cost with significant effects on this hospital.

5. Dispatch Strategy Analysis

The dispatch strategy analysis focuses on investigating the correlation between the energy savings and the impact of operating each system component. In order to determine the impact of each component on the energy cost savings, this analysis does not take initial equipment cost into account. In this study, the energy cost is the sum of purchased electricity and fuel cost.

The evaluation is based on the date from HOMER simulation results. Also, this analysis includes two cases: grid-connected mode and island mode. In each mode, the study discussed the results from hospital and Bldg.661.

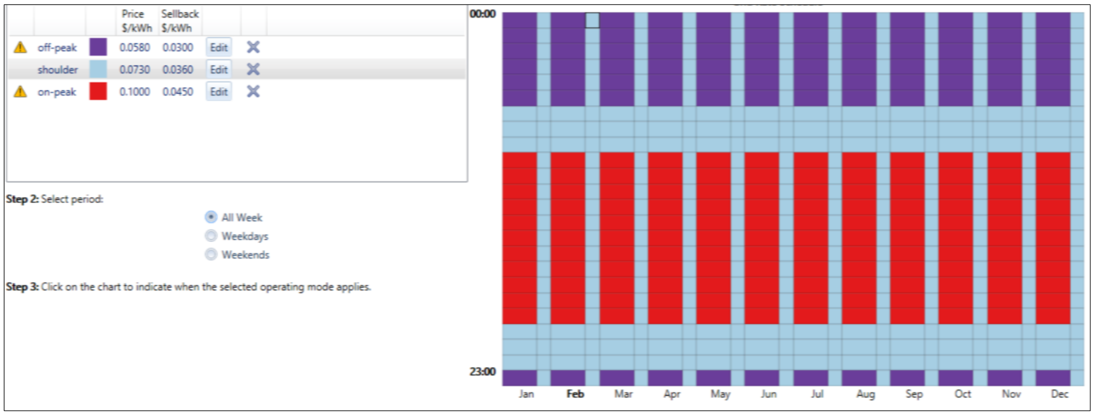
5.1 Grid-connected

In grid-connected mode, it is necessary to introduce two concepts: grid arbitrage and net-metering, because they are the opportunities for hybrid PV-CHP-battery storage system to make more benefits.

Grid arbitrage

The previous simulation results are assumed that the electric rate is constant. However, Utilities develop rates according to different time periods throughout the day. The real grid rate is high during the on-peak period and low for the off-peak period. Thus, customers who use batteries are able to make economic savings if they purchase electricity with cheap rate and then use it when electric rate is expensive. This strategy is called grid arbitrage.

In this study, the on-peak period is 9:00 am-7:00 pm on weekday, while the off-peak time is 11:00 pm-5:00 am. The rest of time is shoulder time, and the details of schedule with electric rates are shown at Fig.13.



			Price $/kWh	Sellback $/kWh		
⚠	off-peak	🟪	0.0580	0.0300	Edit	✕
	shoulder	🟦	0.0730	0.0360	Edit	✕
⚠	on-peak	🟥	0.1000	0.0450	Edit	✕

Step 2: Select period:

● All Week
○ Weekdays
○ Weekends

Step 3: Click on the chart to indicate when the selected operating mode applies.

Fig.11 grid rates schedule

In order to use batteries to make the energy savings, the control parameter settings in HOMER are as followed.

For peak rate, “Prohibit grid from charging battery” is selected. For the off-peak rate, the option “Prohibit grid sales from battery” is checked.

Net-metering

Net-metering is a billing mechanism that allows customers to sell back their surplus power to the grid and the customers can get the credits from utility to offset the power cost. The majority of the net-metering benefit is that the electricity sold back to grid is equal to the price customers purchased. Therefore, the hybrid system, especially the PV system can take the advantages to make further energy cost savings because of the net-metering.

5.1.1 Energy cost vs Generator size

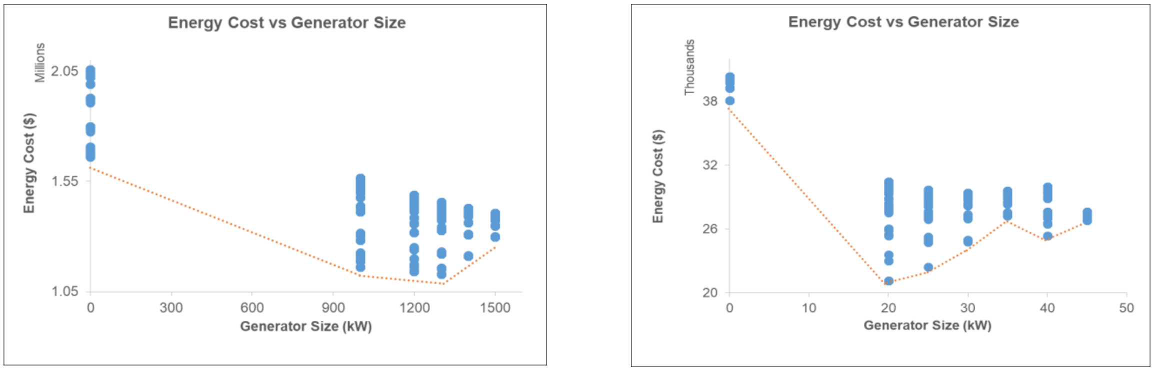


Fig.12 Energy cost vs Generator size (Left: hospital. Right: Bldg.661)

Before discussing the results from Fig.12, it is supposed to explain why the dots lined up vertically on the plot, which is to clarify the reason why the energy cost is different from each generator size. The energy cost difference is due to another component size, and the Table-13 is an example to show the details.

Table-13 Difference of system energy cost in hospital case

PV (kW)	**Recip (kW)**	**GasGen (kW)**	**1kWh LA**	**1kWh LI**	**Energy Cost ($Million/year)**
N/A	N/A	1300	N/A	N/A	1.455
N/A	N/A	1300	N/A	320	1.455
N/A	N/A	1300	320	N/A	1.455
416. 7	N/A	1300	N/A	160	1.419
416. 7	N/A	1300	80	N/A	1.423
1666.7	N/A	1300	N/A	N/A	1.221
2500	N/A	1300	1320	N/A	1.152

When the generator size is the same, other component sizes, especially the PV system, affect the system energy cost. In that case, even though the dots are lined up vertically for each generator size, there is an obvious correlation between generator size and system energy cost. Fig.12 illustrates a tendency that energy cost goes down and then goes high when the generator size increases. For each generator size, the points show the total annual energy cost with the same generator capacity size but with different capacity size of other components.

In hospital, several systems with 1300kW capacity generator have low annual energy cost. Because the base load of the hospital is around 1300kW, there is probably a correlation between the energy saving and generator size that is around building base load.

The results from Bldg.661 strengthen the correlation mentioned above, because systems with 20 kW generators have the lowest annual energy cost, while the electric base load in Bldg.661 is around 20 kW.

Therefore, utilizing the generator with maximum capacity to supply the building baseload probably make the largest energy cost savings.

According to the simulation results, the generator runs all the time in the hospital case, while the generator turns off at daytime when the electric rate is low in the Bldg.661 case.

5.1.2 Energy cost vs PV size

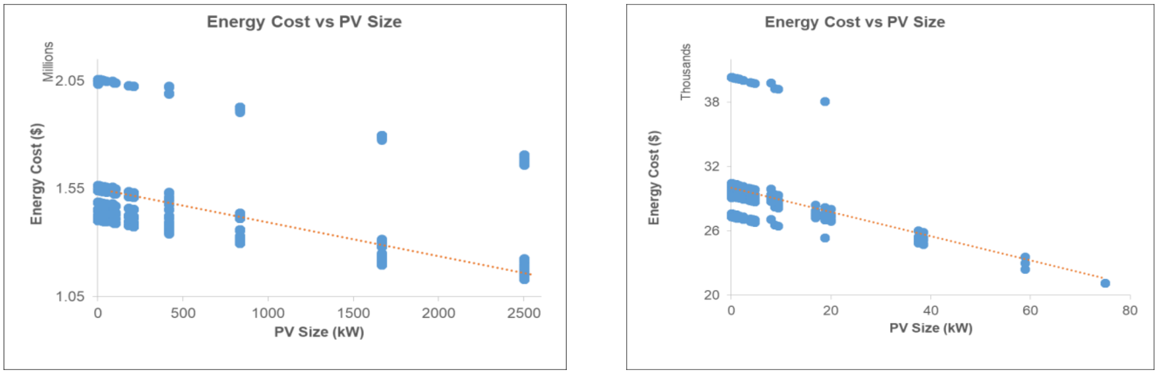


Fig.13 Energy cost vs PV size (Left: hospital. Right: Bldg.661)

Fig.13 shows that annual 2000 system configurations energy cost versus PV size. Large PV size has significant impact on energy cost savings. The results are straightforward because the large PV panels generate more electricity without energy cost, thereby decreasing the total energy cost. Therefore, the larger PV panel, the larger energy cost savings if PV price is cheap enough.

5.1.3 Energy cost vs Battery size

HOMER allows the battery to discharge when the cost of discharge from battery is lower than other alternatives, like the electricity cost from generator or grid. The cost of discharge from battery is the sum of two values: battery wear cost, and the energy cost charged to the battery.

$$C_{batt,Discharge} = C_{batt,wear} + C_{batt,Energy}$$

$$C_{batt,wear} = \frac{C_{batt,repl}}{Q_{lifetime}\sqrt{\eta_{rt}}}$$

$C_{batt,repl}$ is the replacement cost of the battery, $Q_{lifetime}$is the lifetime throughput, and η_{rt} is the battery efficiency.

$$C_{batt,Energy,n} = \frac{\sum_{i=1}^{n-1} C_i}{\sum_{i=1}^{n-1} E_i}$$

$C_{batt,Energy,n}$is the average energy cost that the battery bank charged in all time step before time step n.

$C_i$is the energy cost charging the battery in time step i. E_i is the amount of energy in the time step i.

If $C_{batt,Discharge}$is lower than the other alternatives, HOMER will discharge the batteries. If not, HOMER will use the other cheaper sources at first.

Because of the large wear cost, $C_{batt,Discharge}$is high so that HOMER usually prohibits the battery discharge electricity. In order to simulate the battery impact on energy savings, this study assumes the replacement cost of battery is zero, thereby decreasing the wear cost of battery to zero. In the other word, this is a best scenario study to evaluate battery's effect on energy savings.

5.1.3.1 Energy cost vs Battery size in hospital

In order to interpret the simulation results, understanding how HOMER uses the battery is important.

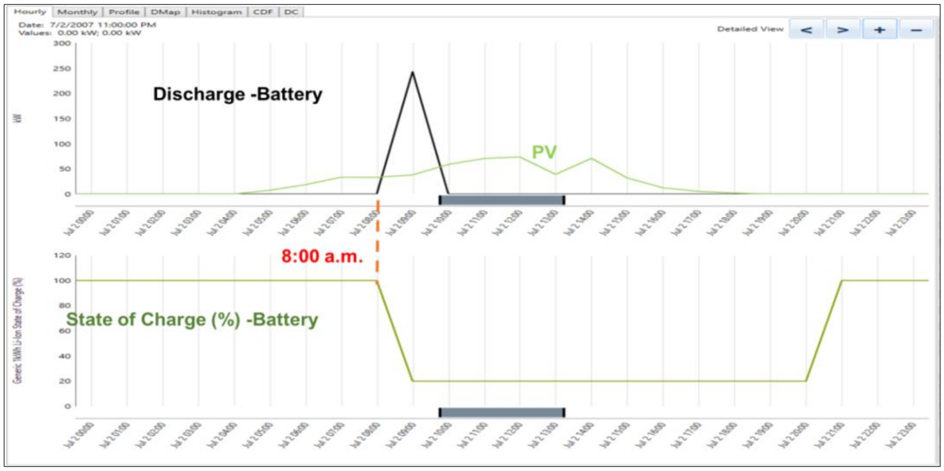


Fig.14 Battery state of charge

The state of charge of battery from one of the system configurations is shown in Fig.14. The figure shows that the batteries are only charged at night when the electric rate is low, and then use it at the time with high electric rate, while the solar power is sold directly back to the grid. Because of the net-metering, the extra solar power sold back to grid can make more benefits than that stored in battery.

Because generator supplies base load with the largest energy cost savings, charging the battery from generator is not economic. Therefore, the only chance the battery can make energy savings is to buy the low price electricity and then use it when the electric price is expensive.

Because generator supplies the base load, the rest of fluctuating electric demand has three sources: PV, battery, and grid. In consideration of lowest energy cost, the priority choice is solar power, and the second one is to discharge the battery. Therefore, once the PV capacity size is small or the solar intensity is low, the battery can have an opportunity to discharge the electricity to make energy savings.

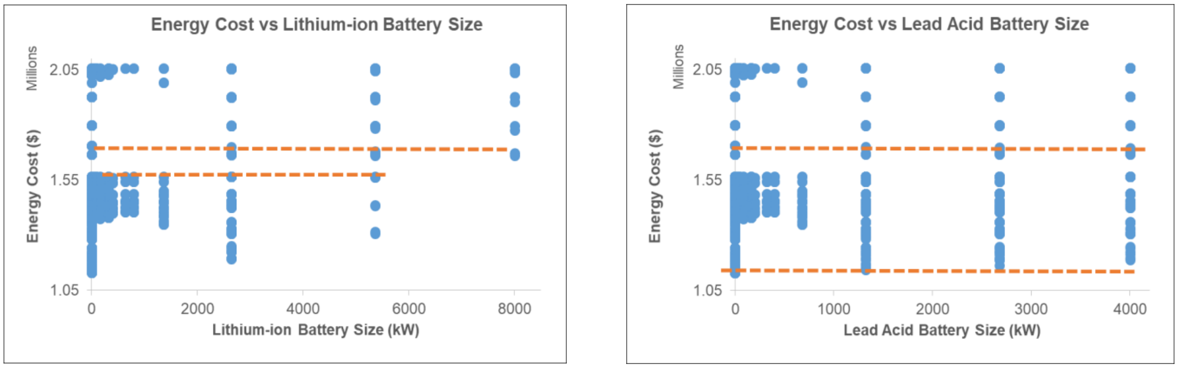
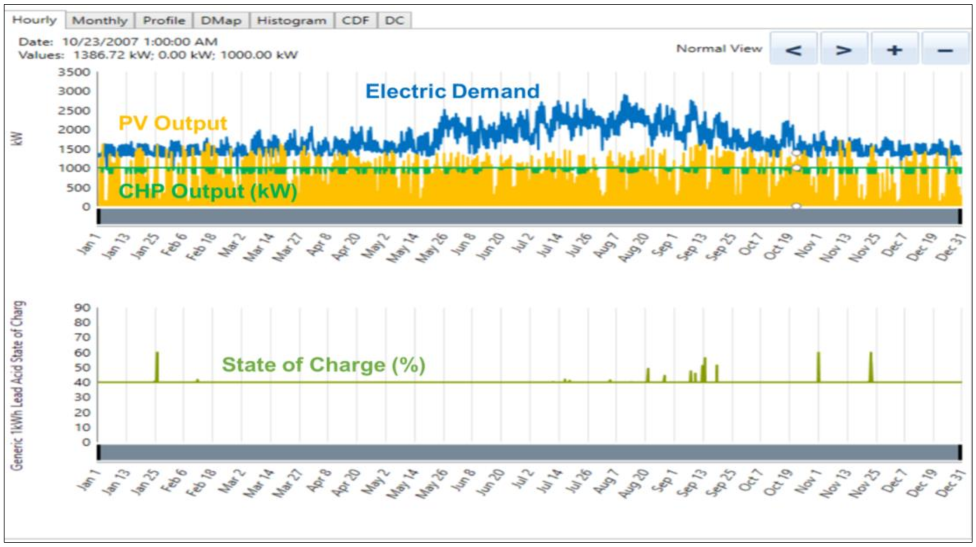


Fig.15 Energy cost vs battery size in hospital

As shown in Fig.15, it is difficult to understand the results, because there is no obvious tendency of energy cost when the battery size increase no matter what the battery type is. Because the figures take into account all the system configurations with various component sizes, other factors like PV size and generator can influence the results. After comparing the results from PV and generator, the points above 1.55 million present the hybrid systems without generators, and the points close to 1.05million showcase the systems with large capacity PV system. If the systems include large capacity size of PV system, there is mere chance for batteries to discharge electricity.

Fig.16 shows an example of the state of charge for lead-acid battery. According to the figure, the batteries maintain the minimum state of charge at 40%. Therefore, the results from this figure support the point of view.



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Values: 1386.72 kW; 0.00 kW; 1000.00 kW

Fig.16 State of charge for lead-acid battery

In order to determine the impact of battery, the study evaluates the systems with 1200kW generator and without PV panels. Because the benefit of battery is to decrease the purchase cost from grid, the relationship of grid cost and battery size are shown as the followed.

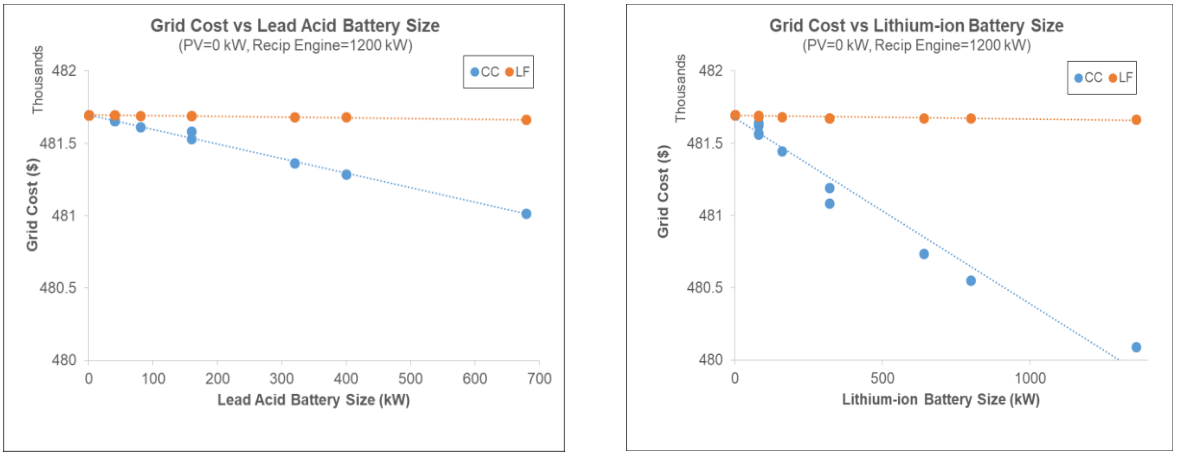


Fig.17 Grid cost vs battery size

Fig.17 shows the correlation between grid cost and battery size. From the figure, it is obvious that the CC (cycle charging) is better than LF (load following). Also, the lithium-ion is better than lead acid on energy savings. This is probably caused by the lower minimum state of charge so that the lithium-ion battery can discharge more power at each charge cycle.

5.1.3.2 Energy cost vs Battery size in Bldg.661

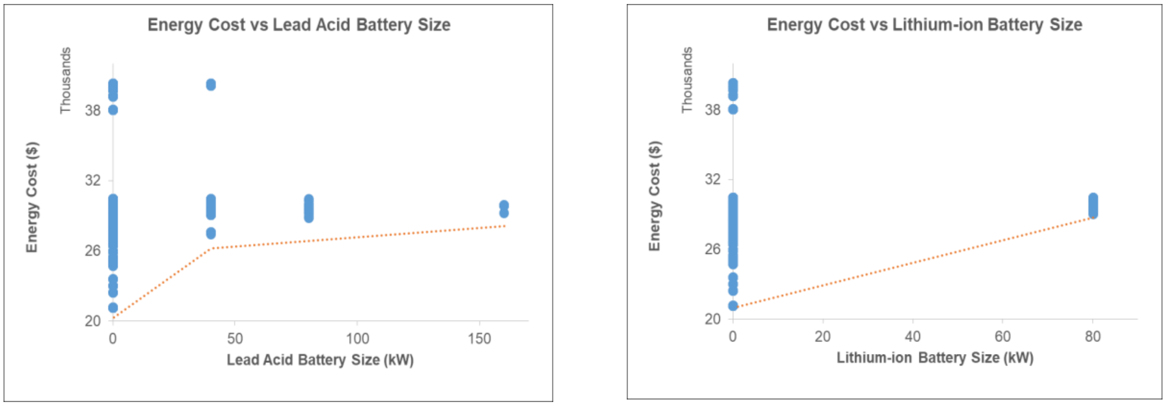


Fig.18 Energy cost vs battery size in Bldg.661

The results shown in Fig.18 have obvious tendency that the system with larger battery size have larger annual energy cost. However, the data shows the total system energy cost, the tendency might be caused by other factors instead of battery size.

According to the Fig.12 about Bldg.661 generator size, the total energy cost above $38000 is due to the system without generator. From the Fig.13, when the PV size is zero, the total annual system energy cost is around $32000. Also, if the PV size is large, the total system energy cost is close to $20000.

Based on this information, it is easier to understand the Fig.18. When the battery size is zero, the total system energy cost is closed to $20000, so that some of the systems with large size PV system. When the battery size is not zero, the total system energy cost is around $32000, which means the system with small size PV system or without PV system. Therefore, the tendency of energy cost is due to the PV size.

But the question is why the system with large PV has small or no battery? It is similar to what the study showed in the hospital case. If the generator supplies the base load, the rest of the load can be supplied by PV, battery, and grid. Once the systems include large capacity size of PV system, batteries have less chance to discharge electricity.

Therefore, the correct way to understand Fig.18 is that the system with large size PV system would not use the battery in the grid-connected case. When the system without or with small size PV system, the battery can have an opportunity.

5.1.4 Conclusions in the grid-connected mode

In the grid-connected mode, the systems with 1300 kW generator in hospital and 20kW in Bldg.661 have the largest energy savings. Therefore, running the generator to supply building base load probably is an effective way to decrease total energy cost.

Because the power generated by PV system is without energy cost, the larger PV system, the larger energy cost savings.

Because solar power sold back to grid can get credit that can offset the purchased fee from the utility in the future, the grid works as a big battery that store the extra solar power. In that case, charging the battery from PV is not a good choice compared with selling it back to grid. Therefore, if ignore the outage of grid, battery is less valuable once the hybrid system equipped with the large size PV system.

If the system without or with small capacity PV system, the battery can have chance to make energy savings by grid arbitrage. The lithium-ion battery is able to have lower minimum state of charge, thereby charging more electricity during one charge cycle. Therefore, the performance of lithium-ion battery is better for the energy cost savings compared with the same size lead-acid battery. Also, because generator runs only as needed to meet the load in the load following strategy, the generator sometimes can supply the electric load more than base load leading to less chance for battery to discharge. Therefore, battery can make more benefits in the cycle charging strategy than that in load following strategy.

In conclusion, the dispatch strategies in grid-connected case are shown as followed.

Generator runs at full load to supply building base load. Because the load profile in hospital is almost constant, the generator runs at all the time in hospital.

In Bldg.661 case, the generator turns off at night due to the low electric rate and small electric demand at night.

Given the benefits from grid with net-metering, PV power sells back to get credit from the utility.

The grid arbitrage is the chance for battery to make energy cost savings. However, in the grid-connected case, the battery has an opportunity to discharge the electricity at daytime once the solar power is low. In this situation, lithium-ion battery is better than lead-acid battery because of the less limitations of minimum state of charge. Also, CC (cycle charging) is better than LF (load following) because more electric demand can be supplied by battery.

5.2 Island Mode

In the island mode, the total energy cost equals to natural gas fuel cost. The PV system, generator, and battery supply the electric demand.

5.2.1 Energy cost vs Generator size

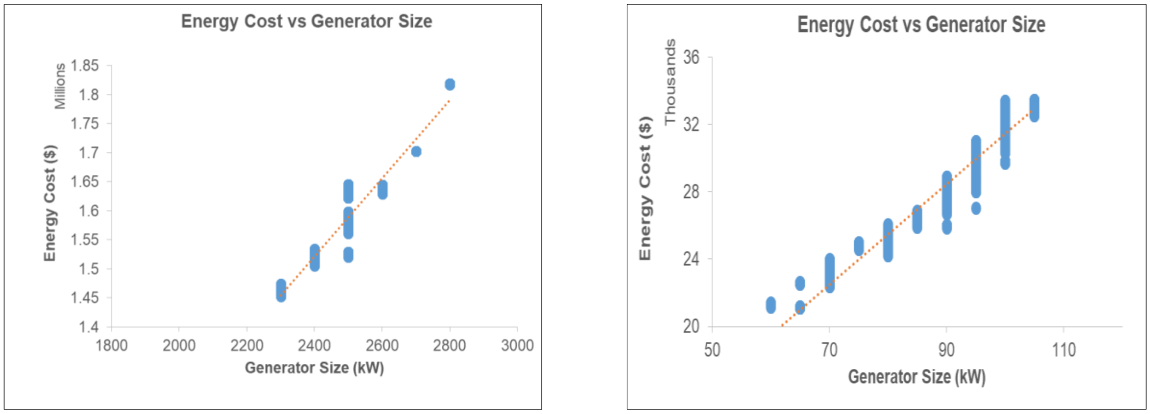


Fig.19 Energy cost vs Generator size (Left: hospital. Right: Bldg.661)

Fig.19 illustrates annual total energy cost of 2000 system configurations based on the generator size. There is an obvious tendency that energy cost increases when the generator size increases. It is easy to understand the results because the total energy cost equals to natural gas fuel cost. Therefore, the larger capacity size of generator, the larger energy cost. However, energy reliability is the most important thing in island mode due to no grid to backup. In that case, generator is a vital component to maintain the reliability so that requires minimum generator capacity size. From Fig.19, the minimum generator size in hospital is 2300kW, and 60kW in Bldg.661.

5.2.2 Energy cost vs PV size

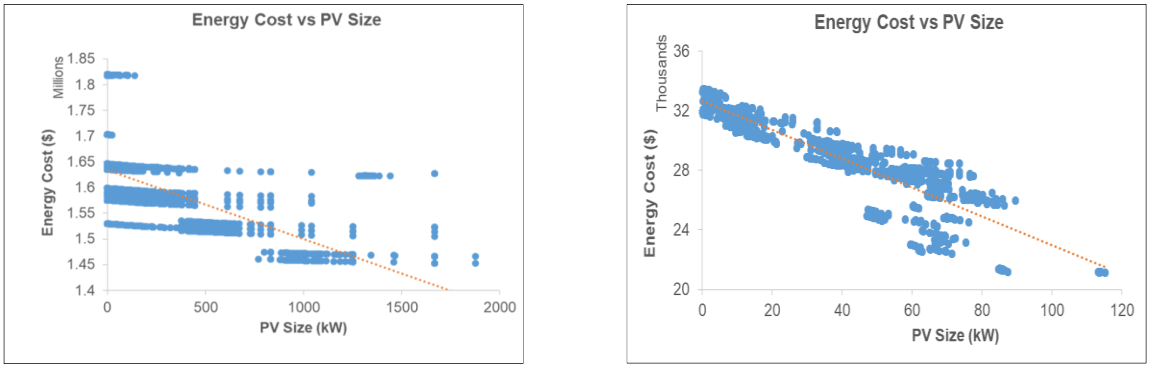


Fig.20 Energy cost vs PV size (Left: hospital. Right: Bldg.661)

Fig.20 shows that annual 2000 system configurations energy cost compared with PV size. Large PV size has significant impact on energy cost savings. The large PV panels generate more free electricity, thereby decreasing the total energy cost. Therefore, the larger PV panel, the larger energy cost savings.

5.2.3 Energy cost vs battery size

In the island mode, the battery has important role to supply the fluctuating electric demand, and store the extra solar power to decrease the energy waste. Because of the differences of building load profile, these parts of study discuss the performance of battery in Bldg.661 and hospital separately.

5.2.3.1 Energy cost vs Battery size in Bldg.661

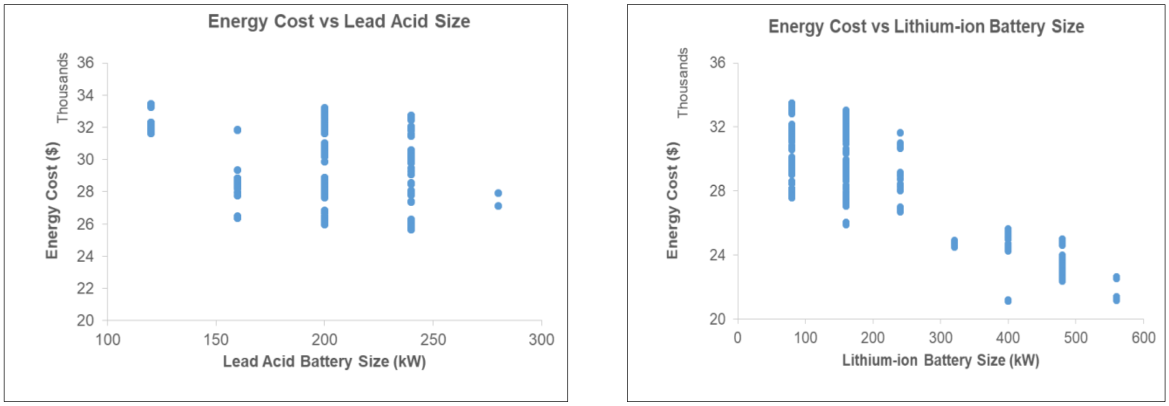


Fig.21 Energy cost vs battery size in Bldg.661

As shown in Fig.21, there is probably a tendency that energy cost decreases when the battery size increases. In the consideration of the influences from PV and generator, it is reasonable to evaluate the performance of battery once the systems selected similar capacity size of other components, like PV and generator.

From the 2000 system configurations, the systems with 40-60kW PV size and 70-90kW generator size are selected. Based on those systems, this study compares the total energy cost with battery size. The details are shown in Fig.22.

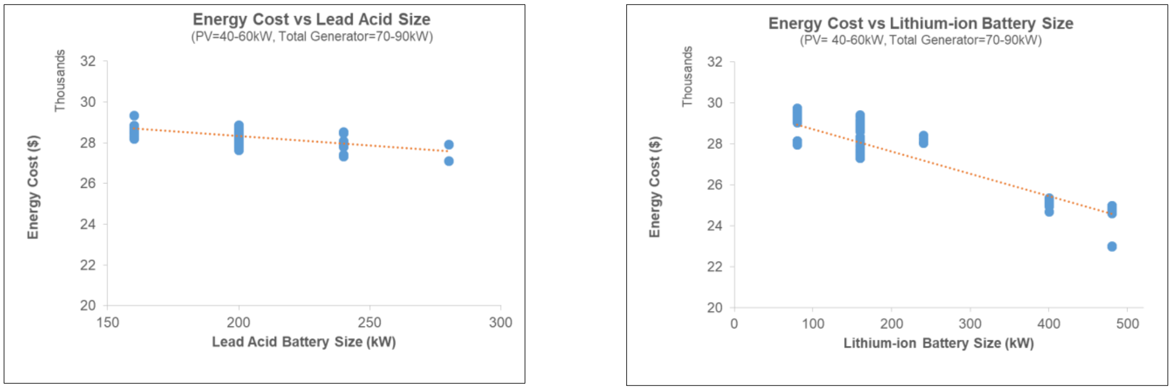
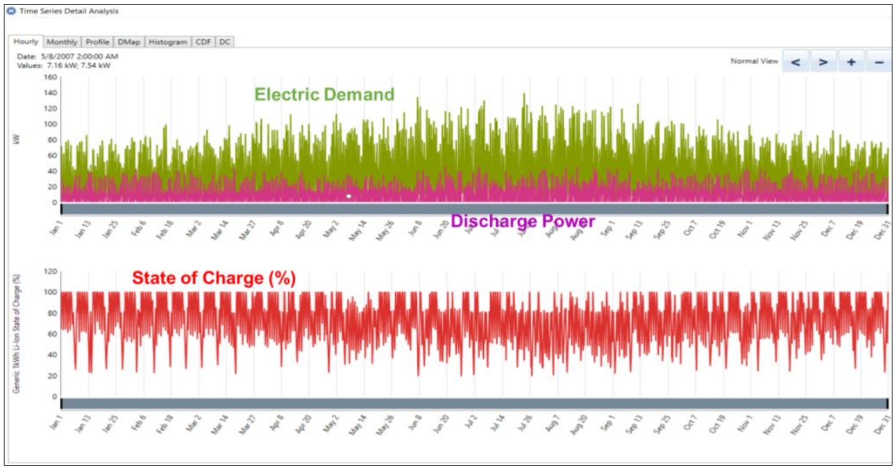


Fig.22 Energy cost vs battery size in Bldg.661

According to Fig.22, there is an obvious tendency that energy cost decreases when the battery size increases. The lithium-ion battery seems to have better performance on energy savings. As mentioned in grid-connected case, this difference is due to minimum state of charge. The lithium-ion battery can charge more electricity in each charge cycle compared with lead-acid battery. The details can be shown in Fig.23 and Fig.24.



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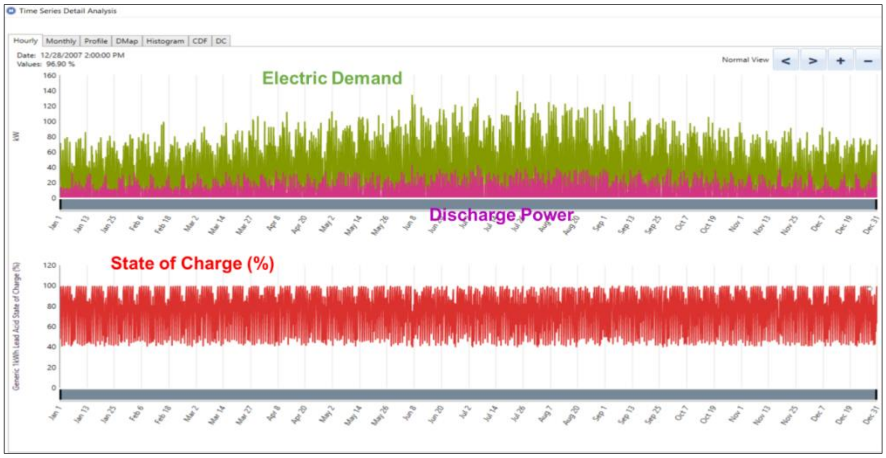
Values: 7.16 kW; 7.54 kW

Fig.23 lithium-ion battery state of charge in Bldg.661



Date: 12/28/2007 2:00:00 PM
Values: 96.90 %

Fig.24 Lead-acid battery state of charge in Bldg.661

5.2.3.2 Energy cost vs Battery size in hospital

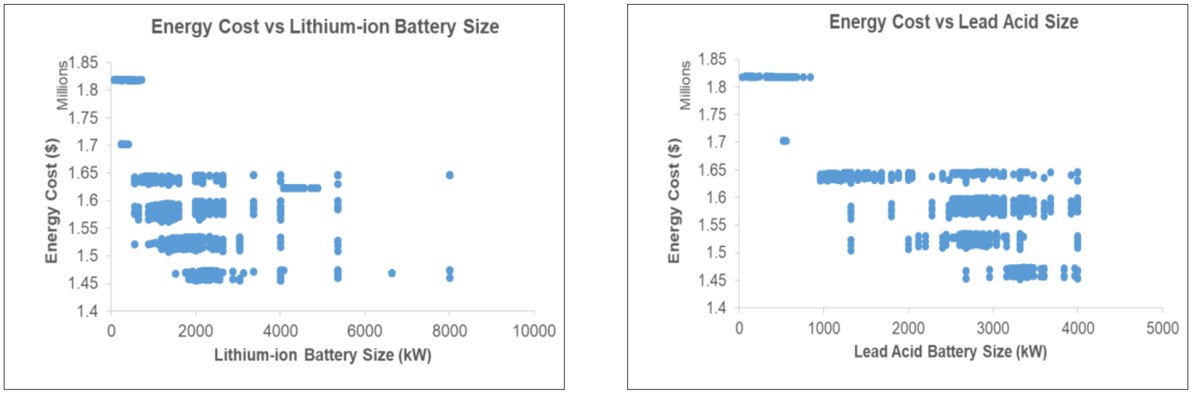


Fig.25 Energy cost vs battery size in hospital

As shown in Fig.25, it is hard to figure out the correlation between energy cost and battery size. In order to decrease the effect from PV and generator, systems with 980-1100kW PV size and 2300kW generator size are selected. According to those systems, this analysis evaluates the relationship between the total energy cost and battery size. The details are shown in Fig.26.

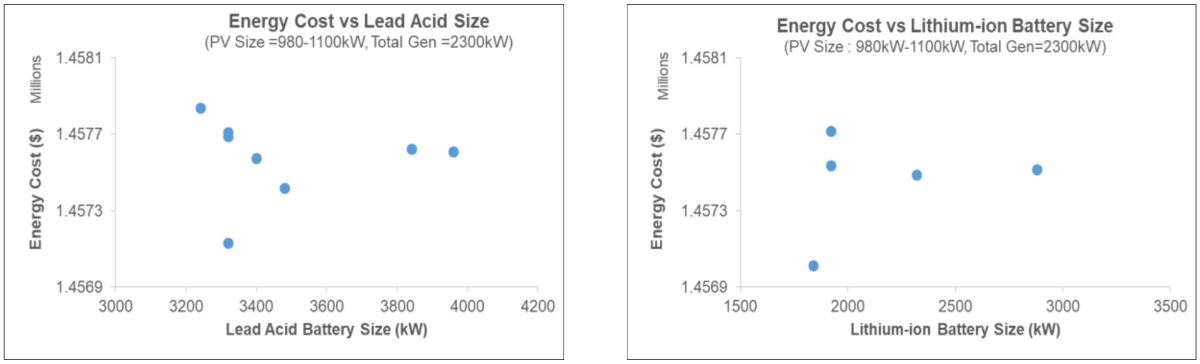


Fig.26 Energy cost vs battery size in hospital

From Fig.26, there is no obvious tendency that battery size has impact on the energy cost. In order to understand the figures above, one of the effective ways is to check the battery's state of charge.

As shown in Fig.27, the battery is only used in summer when the electric demand is high on the annual basis. Fig.28 and Fig.29 illustrate the battery state of charge histogram. According to plots, the battery had stayed at 100% state of charge for more than 95% periods of time within one year. In other words, the systems only use battery for about

438 hours during one year (8760 hours). Therefore, the battery has less impact on energy savings.

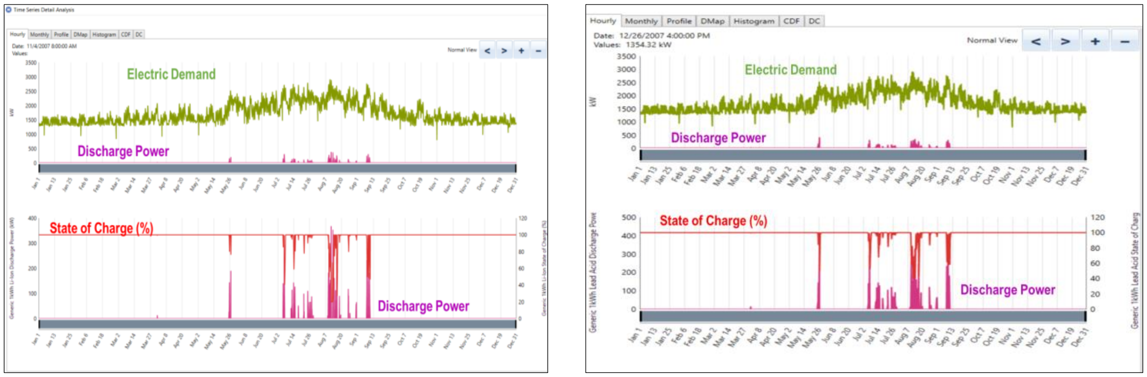


Fig.27 battery state of charge in hospital (Left: lithium-ion battery. Right: Lead-acid battery)

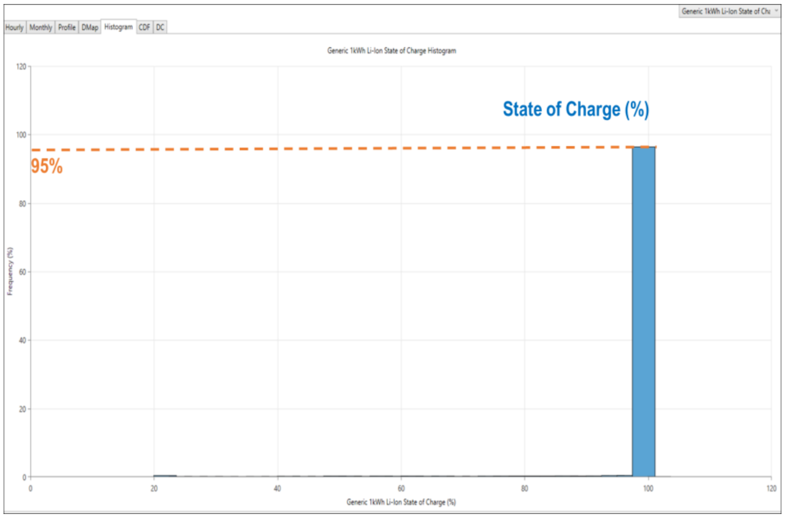


Fig.28 lithium-ion battery state of charge histogram

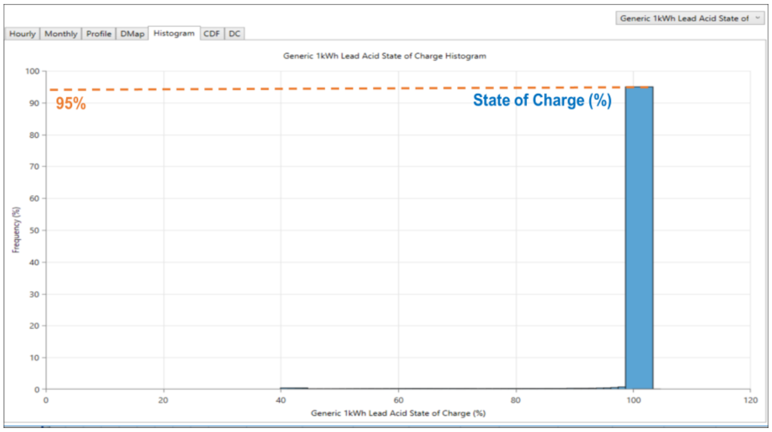


Fig.29 lead-acid battery state of charge histogram

5.2.4 Conclusions in the island mode

In the island mode, the energy cost equals to the cost of natural gas. Therefore, the larger capacity size of generator, the larger energy cost. In order to maintain the energy reliability, the minimum generator capacity size in hospital is 2300kW, and 60kW in Bldg.661.

The large PV panels generate more free electricity, thereby decreasing the total energy

In the Bldg.661case, there is an obvious tendency that the energy cost decreases when the battery size increases. The lithium-ion battery is able to have lower minimum state of charge, thereby charging more electricity during one charge cycle. Therefore, the performance of lithium-ion battery is better for the energy cost savings.

In the hospital case, because the generator runs above the building base load, the battery is only used in several short peak time during the summer, thus the battery has less impact on energy savings. The more important role for battery is to maintain the reliability.

In conclusion, the dispatch strategies in island mode are shown as followed.

Generator runs at full load all the time, while PV system and battery supply the fluctuating demand.

Because hospital demand is relative constant and the generator capacity is larger than the electric demand in winter, the battery has less chance to discharge. Therefore, battery in hospital has less impact on energy savings compared with the case in Bldg.661.

6. Conclusions

The hybrid combined heat and power- PV- battery storage systems have high initial cost, low operating cost and low carbon emissions compared to conventional building system. The high initial cost of hybrid system is one of the major obstacles to be used in wide variety buildings. But the reducing component price and energy price are the opportunities for hybrid combined heat and power- PV- battery storage systems in the future.

In order to investigate the opportunities in the future, the sensitivity analysis simulated the impact of three sensitivity variables: PV price, electric rate, and natural gas price. Lower PV system cost and higher electric rate presented significant effects on the both Bldg.661 and hospital in New Jersey. Lower fuel price is proven as the one of the most important factors in hospital in New Jersey. However, the impacts of the fuel price is less significant in Bldg.661. This is probably due to the low thermal demand in Bldg.661.

In order to explore the effect of dispatch strategies, the study evaluates each component performance on energy savings in four situations: Bldg.661 with grid, hospital with grid, Bldg.661 without grid, and hospital without grid.

In the grid-connected mode, generator runs at full load to supply building base load. In the hospital case, the generator runs at all the time. In the Bldg.661case, the generator turns off at night due to the low electric rate and small electric demand during the period of time. Given the benefits from grid with net-metering, PV power sells back to get credit from the utility. The grid arbitrage is the chance for battery to make energy cost savings. Once the solar power is low, the battery has an opportunity to discharge at daytime to make energy savings. In this situation, lithium-ion battery is better than lead-acid battery because of the less limitations of minimum state of charge. Also, CC (cycle charging) is better than LF (load following).

In the island mode, generator runs at full load all the time, while PV system and battery supply the fluctuating demand. Because of hospital demand profile, the battery has less chance to discharge. Therefore, battery in hospital has less impact on energy savings compared with the case in Bldg.661.

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