High-rise Building Mini-hydro Pumped-storage Scheme with Shanghai Jinmao Tower as a Case Study

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Abstract—**High-rise buildings are everywhere with heavy electrical loads in metropolis, and their gravity potential energy can be utilized to develop mini-hydro pumped-storage scheme to decrease many negative impacts on the power system, like the large of load peak-valley difference (PVD), the large of fluctuation of load as well as integrated renewable distribution generation(DG). Shanghai Jinmao Tower with 420.5 m high is taken as a case study. China "Load Code for the Design of Building Structure" is introduced for the roof tank design. Shanghai time-of-use electricity pricing mechanism is used for daily benefit calculation. An optimal operation model has been built for parameter selection. The proposal of installed hydro power and pump are 2400 kW and 3600 kW respectively with a global efficiency of 0.6624. Daily income is ¥2800 with annual benefit ¥1 million and 5 yrs return, seems a very attractive investment. The hydro power capacity is about 37% of existed emergence standby generation, and the good compensation of pumped-storage for the large fluctuation of proposed photovoltaic (PV) to meet the sensitive load in isolated micro-grid operation, show the another advantage.**

***Index Terms*—high-rise building; Pumped-storage; time-of-use electricity pricing; load code for the design of building structure; optimization; micro-grid**

I. Introduction

Numbers of high-rise building above 90 m has been counted to 17383, where Hong Kong has more than 3000, New York, Tokyo, Shanghai have more than 500, the top 20 high-rise buildings have their height from 385m to 828m[1,2]. Such record is refreshed each year. All those buildings have very heavy electrical loads [3].

In general, high-rise buildings are built in metropolis where the load peak-valley difference (PVD) is particularly large. It means the investment of power system is in a low usage rate. In Shanghai, for example, the current annual load ratio is about 50% to 60%[4]. With the renewable distribution generation (DG) tied into the bulk power system, PVD will get even worse due to DG's Intermittent, fluctuation and randomness properties.

There are misunderstandings for pumped storage, like it must need certain geographical and geological conditions and make changes to the environment. This view is only suitable for medium and large scale pumped storage station. Theoretically, as long as the potential difference exists, pumped storage technology is applicable. Obviously, there are large amount of potential energy existed between the roof of high-rise building and its deep underground, but this resource has not been utilized yet. Water tank and pump system has been equipped, therefore a mini-hydro pumped-storage micro-grid scheme has been proposed in our previous works [5-6]. For practicability examination, Shanghai Jinmao Tower, present 12th highest building in the world, is taken as a case study in this paper.

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II. Shanghai Jinmao Tower and Electricity Pricing

A. Power Supply System[7-9]

Shanghai Jinmao Tower is 420.5 m high, the cross-section of the main building is 100 m*100 m; The building's electrical distribution system has three voltage levels as 35 kV, 10 kV and 380/220 V. There are two separate circuits with two main transformers each in 35 kV system with total capacity 37.4 MVA. There are thirteen 10 kV/0.4 kV distribution transformers, the maximum load is 26.2 MW. Six sets of 1094 kW fuel generators are installed as the emergency standby power, about 25% of the maximum load.

B. Water Storage and Pump System[10]

The domestic daily water consumption of Shanghai Jinmao Tower is 3400 m^3; which comes from the municipal water supply. Such water firstly enters two underground 30 m^3 fiberglass tanks and becomes domestic water by several steps in pressure filters, and is stored in one 1600 m^3 main underground water tank for both domestic requirement and fire protection. Among this 1600 m^3 storage, domestic usage is limited to 1060 m^3 by special measures to make sure the sufficient water reservation for fire protection. Six 2.4 MPa pumps are used to pump the water from basement to a water storage tank in 51st floors (205 m high). Then six senior 1.6 MPa pumps are used to pump the water from the 51st floor to a roof storage tank in the 91st floor (350 m high). To compensate the lack of water pressure for above 88th floors, additional pressure pumps are equipped in 91st floor.

C. Shanghai Time-of-use Electricity Pricing Mechanism

The current time-of-use electricity pricing mechanism in Shanghai is as followings: the off-peak price is 0.273 ¥/kWh from 22:00pm to 5:00am; the normal price is 0.719 ¥/kWh for several periods as 6:00 to 7:00, 11:00 to 12:00, 15:00 to 17:00 and 21:00 to 22:00; the peak price is 1.202 ¥/kWh for the remaining periods. The price curve is shown in Fig.2(a).

III. Pumped storage optimal operation model

A. Mini-hydro Pumped-storage Scheme Assumption

In this study, for simplification, an independent pumped-storage scheme is assumed at first. Because of the high hydraulic head, impulse turbine is selected and 0.9 is assumed as its efficiency. Generator efficiency is assumed to be 0.92. High efficient pump is selected and its efficiency is 0.80 (it can reach 0.82). Thus the total pump and generation efficiency is 0.6624. It is lower than the general assumptive efficiency value 0.75 for large scale hydro pumped-storage.

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B. Optimal Operation Model

It can be proved that, during the parallel operation tied with the bulk power grid, the optimal operation of pumped-storage system is independent with the load demand, as well as other internal forms of renewable energy generation or standby generation sets. Thus the grid-tied optimal operation of the whole building power system can be simplified as pumped-storage only power system. It operates with the bulk power system to achieve its maximum profit.

Assuming the size of roof water tanks, basement water tanks and the flow are pro-determined. It is also assumed that the turbine generation will never operate in the same time when the pump is in operation mode (to left the water from basement water tank to the roof water tank). The time segment is 15 minutes in Fig.1. The daily optimal operation model is established as (1):

$$\min \sum_{t=1}^{96} \begin{Bmatrix} r_p(t) * P_p(t) - r_s(t) * P_s(t) \\ + r_s(t) * P_w(t) + r_{pn}(t) * P_{pn}(t) \end{Bmatrix} * \Delta t \qquad (1)$$

Where $P_p(t)$, $P_s(t)$ are power purchasing from the grid, power sale to the grid; $P_w(t)$ is the corresponding power (for punishment) calculated from the spilling water when the charge water from the pump is over the limitation of the top tank or the release water for generation is less than the income inflow from the rainfall; $P_{pn}(t)$ is also the punishment power, it happens in two cases, either the determined pump flow is so great that the water in the basement water tank has no sufficient water to support such flow, or the determined turbine flow is so great that the water in the roof water tank will not support such flow, $P_{pn}(t)$ is the shortage of corresponding power. $r_p(t)$, $r_s(t)$ are the price purchasing power from grid and the price selling to grid respectively. In fact, selling power to grid will never happen since the internal generation of such high-rise building will never be larger than the internal load. Therefore, we can assume $r_p(t) = r_s(t)$ as the present price mentioned in Section II. Similarly, we can also assume.$r_{pn}(t) = r_p(t)$. Hence, the operation decision of each time-step is to decide, either to pump the water from basement water tank to the roof tank, or to generate the power by using the water from the roof tank, or to do nothing at all.

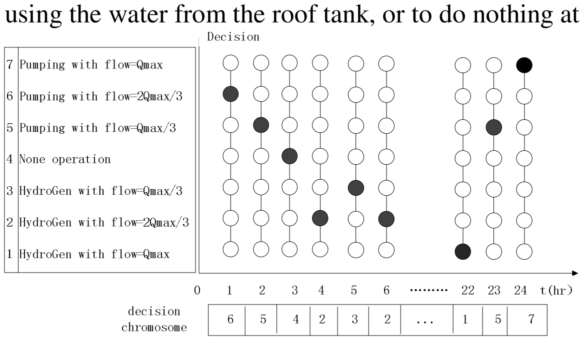


Fig.1 Daily Control Model based on GA

The detailed model including the constraints of roof water tank, basement water tank, hydro power generation, the pump equation, can also be found in paper [6] and omitted in this paper. The water levels of the roof tank and basement tank at the ending of the daily operation should be kept as the initial water levels, to make sure its daily cycle operation. As shown in Fig.1, the flow of pump or turbine is selected as the decision variable, and Genetic Algorithm (GA) [11] is applied to solve that daily optimal operation problem. The objective function (1) is treated as the fitness function in GA method. Since the objective value fluctuates around 0, a large number is needed in the objective function so that it can have a better convergence speed. Also due to the randomness results from GA method, it is necessary to set an acceptable number of iterations to find the optimal solution. In this paper, the iteration number is 10.

IV. Parameter Selection According to Roof Active Load Standards

A. Roof Load Standards for Roof Water Tank

According to China building structure load rule GB 50009-2012 [12] (similar code in USA can be seen from [13]), the range of civil floor uniformly distributed load standard value is from 2.0 to 7.0kN/m^2, which the 7.0kN/m^2 is considered in elevator machine room and other power equipment floors. The uniformly distributed load standard value in roof garden is 3.0 kN / m^2, or 0.31 ton / m^2 accordingly, therefore the building's roof can support the water body up to 0.31 * 100 * 100 tons, which means the total weight and volume of water on the roof are 3100 tons and 3100 m^3. Thus, if the roof tank has 40 m * 40 m bottom area, then the tank pressure will be equally distributed to the roof load-bearing column. The pressure per unit area on tank bottom is 0.31*100*100/40/40 = 1.94 tons/ m^2, in other word, the height of roof water tank is 1.94 meters.

B. Roof Water Tank Design According to Garden Load Code and the Daily Benefit

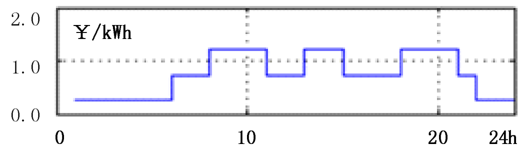
Tab.1 the parameter sets of top water tank under the active load requirement as roof garden purpose

	(1)	(2)	(3)	(4)	(5)	(6)
1	100/10124/124	0.31	2930/3595	8163/11983	68.12	2896
2	80/6554/154	0.48	2382/3597	7966/11982	66.57	2818
3	60/3806/206	0.86	2384/3599	7860/11987	65.57	2811
4	50/2748/248	1.24	2932/3597	7815/11992	65.17	2802
5	40/1910/310	1.94	2388/3599	7783/12002	64.84	2797
6	20/1020/620	7.75	2407/3637	7770/12077	64.34	2796

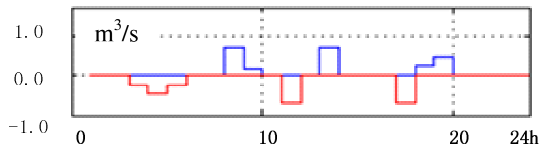
Note: (1) width(m)/bottom area(m^2)/wall surface (m^2); (2) height of tank; (3) hydro power capacity/pump capacity; (4) hydro generating energy/pumping energy; (5) the ratio of generating energy over pumping energy; (6) daily return in ¥

As shown in Tab. 1, it includes six roof tank designs with different bottom area which meet the roof garden standard. Basement water tank is designed 50 m in width, 50 m in length, 2 m in height, so the volume is 5000 m^3.

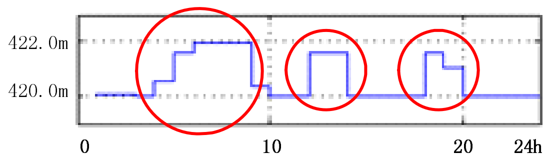
The GA algorithm is applied to calculate all the cases in Tab.1, and the maximum flow as shown in Fig.1 is selected as 0.7 m^3/s. The optimal results of different design are listed in Tab.1, it can be seen that the maximum hydro generation powers are from 2382 kW to 2407 kW and the pumping powers are from 3595 kW to 3637 kW. The ratios of generating energy over pumping energy are from 64.34% to 68.12%; The daily incomes are from ¥2796 to ¥2896.



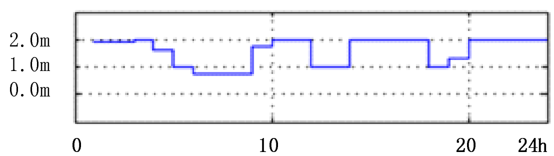
(a) Shanghai Time-of-use Electricity Pricing



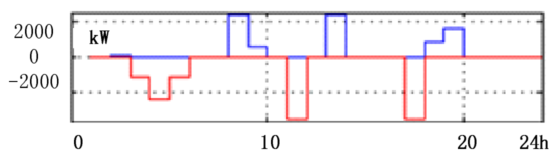
(b) Daily Pump Flow (red) and Turbine Flow (blue) Curves



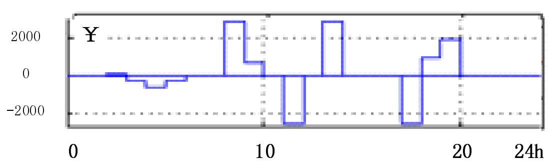
(c) Daily Variation of Water Level of Roof Tank



(d) Daily Variation of Water Level of Basement Tank



(e) Daily Pump (Red) and Turbine (Blue) Power Curve



(f) Daily Receiving or Payment Curve (Net Retn ￥2797)

Fig.2 Roof Tank 40*40*1.94 optimal daily operation

Selecting the design of 40 m * 40 m bottom area, the generating unit is 2400 kW which occupies 37% of standby fuel power capacity and also 12% of the total power capacity in building. Accordingly the capacity of such independent pump system can be selected as 3600 kW. The daily incomes can be ¥2,800 and annual income can be ¥ 1 million. An estimation of investment is also made which shows that the return year of such project is about 5 years. Thus, it seems a worthy investment.

C. The Operation Process

The operation processes are given in Fig.2. The shanghai electricity price curve has three turns from valley to peak or from average to peak. The water level of roof water tank also has three turns from its initial water level (here is dead water level) to nearly full level. The water level of basement water tank has its inverse variation. Accordingly the firstly pumping then following by hydro power generation also take three turns, though the power generation output energy is always less than the assumptive energy of pump in each turn, but the generated energy is always in the costly price period and subsequently the daily income return is positive.

V. THE PARAMETERS SELECTION AND OPERATION RESULTS WITH INCREASING OF THE ROOF ACTIVE LOAD

Building load bearing limit can be exceeded by increasing building weight capacity, which shall change the design of building. The alternative is storing water in multi-layer, which need additional building space to build water tanks. For limitation of the paper, we only consider the first choice to test the variety of height of roof water tank and the different maximum flow of turbine or pump. We only introduce the case of bottom area in 80 m * 80 m. Roof water tank height is varying from 0.5 m to 3.0 m, step is 0.5 m; design maximum flow is varying from 0.1 m^3/ s to 1.0 m^3/ s, step is 0.1 m^3/ s. In the following analysis, it considers the combinations of different tank heights and flows. For each combination, it will get the optimal operation strategy for pumping and generation. Then it draws the result plots for final parameter optimal selection.

A. Daily Income Analysis

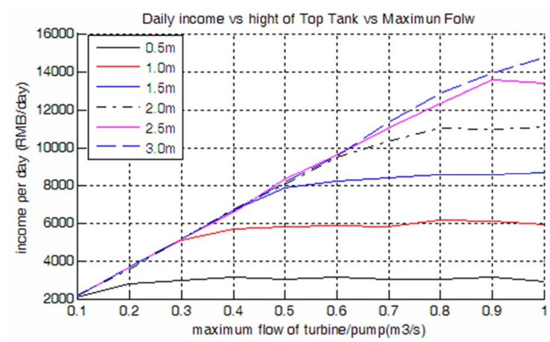


Fig.3 Daily Income vs flow and height of top water tank

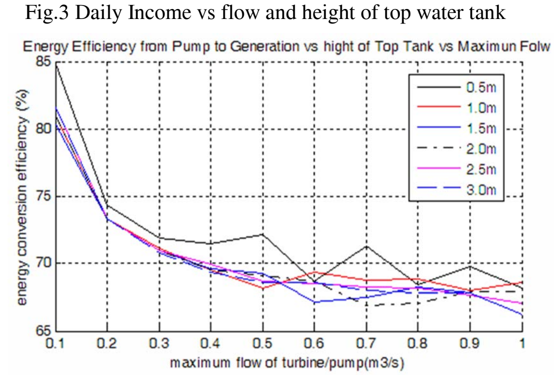


Fig.4 pump and generation efficient vs the flow and height of top water tank

As the bottom area 80 m * 80 m, when the roof tank height is 0.5 m, its daily income is ¥3,000. By increasing every 0.5 m, the income increases varying from ¥2000 to ¥3000; but at the meantime, the entire roof pressure will also linearly increases from 4 kN/m^2 to 24 kN/m^2.

Fig.3 shows that when the flow increases, the income does not necessarily increase, the reason can be seen from

Fig.4. Because that with the flow is increasing, the pumping energy efficiency is decreasing, especially when the tank height is 0.5 m, this decline is particularly evident. The main cause is that the tank capacity is too small. Following the pattern in Fig.1, even choosing the smallest flow $Q_{max}/3$, the tank will also be immediately full of water. The worse is that it will make the roof tank overflow. Therefore, it can be seen from Fig.3, the reasonable flow is in range [0.1,0.6].

B. *Install Capacity Analysis*

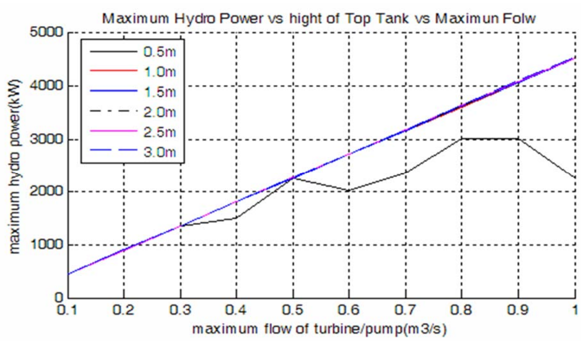


Fig.5 maximum turbine power vs flow and height of top water tank

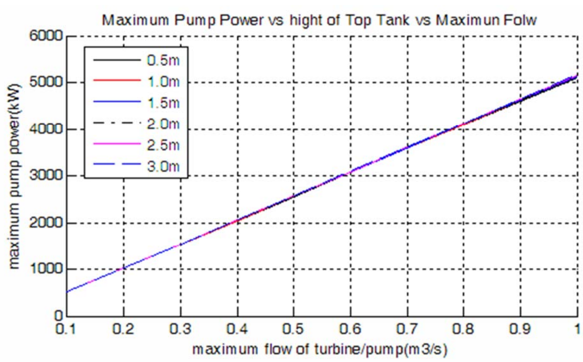


Fig.6 maximum power of pump vs flow and height of top water tank

Fig.5 shows the relationship between hydraulic turbine power output and the roof tank height and flow. Fig.6 shows the relationship between pumping maximum output and the roof tank height and flow.

From Fig.5, it can be observed that when the tank height is varying between 1 m to 3 m, the turbine maximum output is proportional to the flow, it is linear. It indicates that when the tank height is changing, the changing of hydraulic head makes no effort on the turbine power; the only factor to influence the turbine power output is flow. However, such law will be not followed when height of roof water tank is only 0.5 m, when flow is increasing, the output of the turbine will be seriously affected by the changing of roof tank capacity. It means under the condition of hypothetical time varying step (1 hour), even though the roof tank is full of water, the pumping and generation operation can't stand for 1 hour without any power output reducing.

From Fig.6, the maximum pumping power output has a upward trend, in linear with the increasing of the flow. The height of roof water tank has no impact on the pump power since 3 meter is much less than the height of the building.

VI. RESULTS OF DIFFERENT HEIGHT OF THE BUILDINGS

More calculations have been done including the relationship between pump capacity and daily income with building height respectively, under the same assumptive design of roof water tank and basement water tank as the same as in Section IV and using the same optimization algorithm. The curves are shown in Fig.7 and Fig.8, which indicate that when height of building increases 50 m, the hydro power capacity can increase 400 kW approximately, the pump capacity needs to increase 450 kW approximately, the daily return will increase ¥ 700-800.

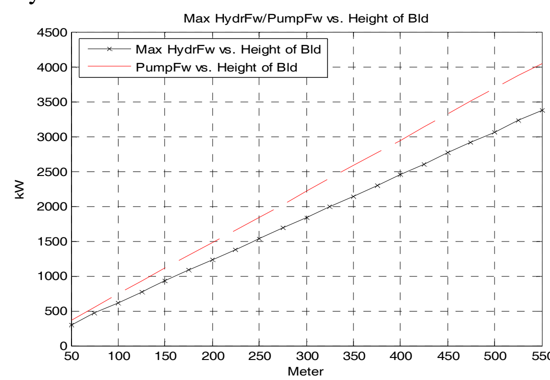


Fig.7 the relationship between install capacity vs building height

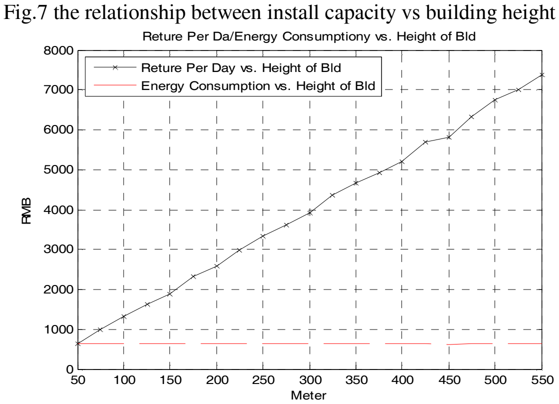


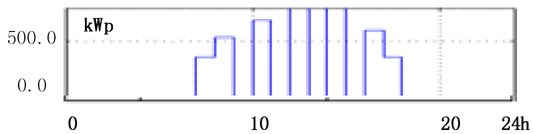
Fig.8 daily income and efficiency vs height of buildings

VII. JOINT OPERATION WITH PV AND PUMPED-STORAGE IN ISOLATED MICRO-GRID

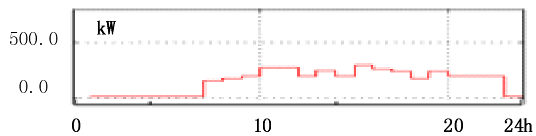
The calculation is also done for the joint operation of PV with the pumped-storage to meet the sensitive load of the Jinmao Building in isolated micro-grid. The result curves are shown in Fig.9. The installed PV capacity is 750 kW, and is taken as the main power supply source of sensitive load. If PV has a very large fluctuation, the function of pumped-storage is arranged proper pumping and hydro generation to regulate the PV output and meet the variation of the sensitive load. From Fig.9, it is observed such regulation is successful.

VIII. CONCLUSION

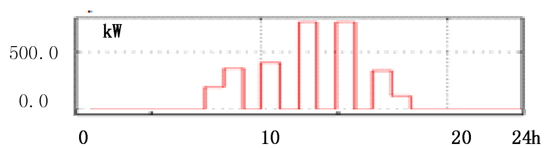
From this study, it can be found that under the load code for the design of building structure, the weight of roof tank can meet such standard as well as to have a profitable pumped-storage scheme in the bulk grid tied operation, to help the load shifting and mitigate the PVD problem. If the pumped-storage is integrated with the renewable DG in a micro-grid, it is also helpful for the smoothing of the fluctuation of DG as well as the power output at the point of common connection (PCC) of micro-grid to the bulk-grid. The pumped-storage will smooth the mismatch between the fluctuation of PV and the sensitive load, which is very important for the isolated operation of the high-rise building if it is break down connection with bulk grid.



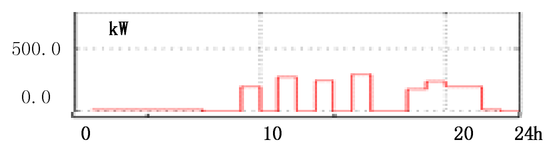
(a) PV Generation Curve with Total 4470 kWh



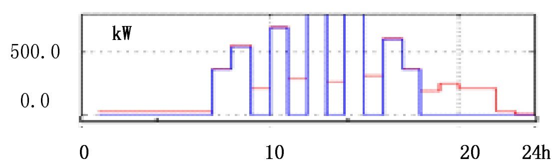
(b) Sensitive Load Curve with Total 3730 kWh



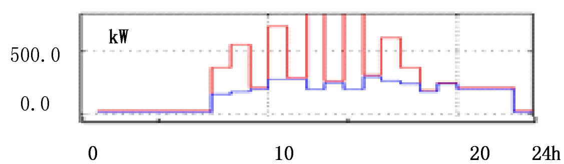
(c) Pump Power Curve with Total 2952 kWh



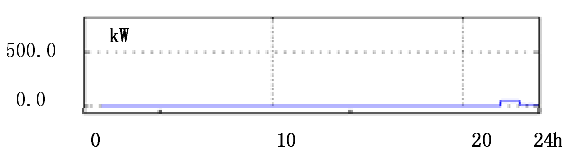
(d) Hydro Power Curve with Total 1988 kWh



(e) PV+ Hydro Power Curve with Total 6458 kWh



(f) Load + Pump Power Curve with Total 6682 kWh



(g) Load Break Curve with Total 223 kWh (5%)

Fig.9. Photovoltaic+ Pumped-Storage + Sensitive Load Isolated Operation Model

Conclusion

The further work is necessary to model the joint operation of existed water tank and pump system to meet the daily domestic water requirement, the water reservation for fire protection, and the daily pumping/hydro power generation to get additional profit by using the time-of-use price mechanism. The joint operation model using the existed emergence standby power is also necessary which can increase the capacity for sensitive load.

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