Feasibility and Simulation Study of High-rise Building Micro-grid with PV and Mini-hydro Pumping

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Abstract—**Electrical load is centralized in city, especial in high-rise building which not only has PV generation resource but also has a gravity potential. The height in range of 30-400 meters, are everywhere in city. Water is also a necessary resource that city should have; water storage in the roof, or water body in waist, and a water tank underground of a building or a building group, is not a very difficult to build them, in fact, water system including pumping system has already been implemented in those buildings for water drink, sanitation, swim pool, fire control, water drain, etc. The hydro pumping generation will only added some new space, weight-bearing, new mini hydro pumping system, etc. A micro-grid development scheme of PV and mini-hydro pumping is presented and the focus is on the daily and short-term operation simulation and parameters selection of such scheme.**

***Index Terms*—High-rise building, Photovoltaic on roof, hydro power, pumping storage, micro-grid, joint operation, feasibility study, simulation, Simulink**

I. INTRODUCTION

Urbanization has become a worldwide trend, especially with the rapid growth of electricity consumption in metropolis's area, which should be paid much more attention. Presently, PV (Photovoltaic) on roof-mount or wall-hung has been utilized in this regarding. However, a seriously ignored potential power resource is the potential power resource which is existed with tall buildings and its utilization form is hydro power with pumping storage. In fact, all city high-rise buildings have a water loop system where both roof and bottom of buildings are equipped with water tanks together with pumping system for drinking, sanitation, swim pool, fire control, water drain, etc.

Joint operation of PV power and hydropower with pumped storage can better solve a lot of problems and shares a lot of advantages [1-3], ref. [1] gives a great proposal for European power grid. Water tower model [4] and pumped storage hydroelectricity [5] never come together before, but it seems reasonable to happen together in high-rise buildings [6]. By using buildings' 30 to 400 meters potential energy in form of hydro power with pumping storage, together with the PV generation and form a micro-grid, to coordinate with local load as well as the connected bulk power grid. Such scheme can make the fitness between PV, hydro, local load, pumping storage as well as the bulk power, to address the sunny, cloudy or rainy weather condition, and to shift the peak and redeem the off-peak of grid. This paper will address such proposal for high-rise building and focus on the daily and short-term operation simulation, and some arguments.

II. A MICRO-GRID SCHEME WITH PV AND PUMPING STORAGE FOR HIGH-RISE BUILDING AND ITS OPERATION MODE

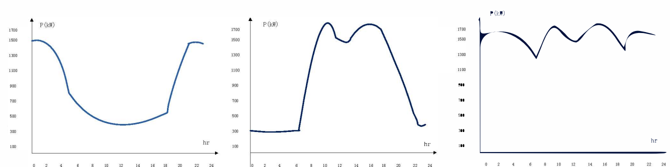
A. *The typical load forms*

The typical load curves (Fig.1) of the building will seriously depend on the property of the building:

(1) Residential: most of the families use electricity in evening and night, the load come down in the day time for most of the people will go to work.

(2) Official/ Commercial: the load will be increased in day time and decreased in the evening and night.

(3) Mixed load. Mixed of residential with official and/or commercial load will make more flat of the load curve.



(a)Residential (b) Official/Commercial (c)Mixed

Fig.1 three typical building load curve

B. *PV and pumped storage micro-grid of high-rise building*

Fig.2 gives a proposed micro-grid scheme of PV and pumped storage for high-rise building.

C. *The Operational model of the building micro-grid*

(1) Complete isolation operation mode of micro-grid

There is no such case if there is no own electrical power source of the building, but when equipped with PV plus pumped storage of mini-hydro, naturally such micro-grid can be operated by cutting from the bulk in emergence which highly increased the reliability of the power supply of the buildings. In such case, the micro-grid should keep the safety and stable operation regardless the variation of the PV and load, which need automatic control system to maintain such operation mode.

(2) Bulk grid only supply with no absorb mode

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If there is shortage of power supply by the building's own power source, than the bulk grid will make the supplement supply, but if there is extra electrical power from the building's micro-grid, then bulk grid will not absorb such extra power.

(3) Bulk grid supply the shortage and absorb the extra power of building's micro-grid.

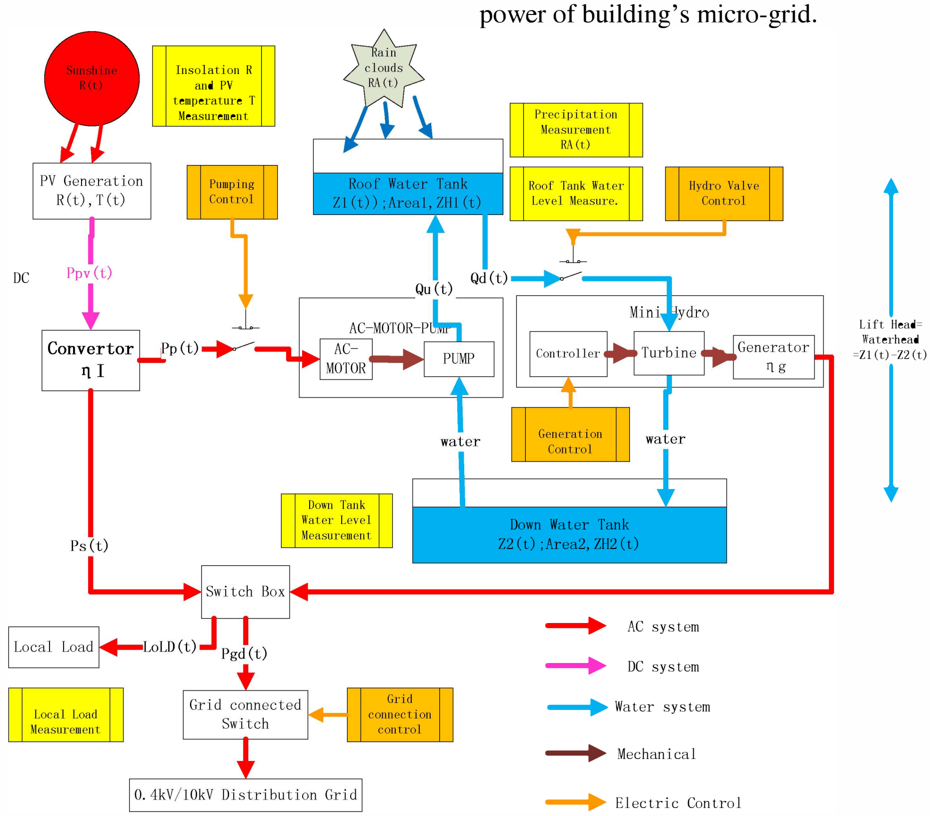


Fig.2 PV and Mini-hydro Pumping based Micro-grid for High-rise Building in City

III. MICRO-GRID OPERATION MODE STRATEGIES

A. Best choice for residential building micro-grid

See Fig.3, it looks a very attractive for such scheme for residential building:

(1) During sunny or cloudy when PV power is available, then we have following sequence strategies:

(a) At mid-night, use the cheap electricity from bulk grid to feed water to the roof tank till its full, as ① in Fig.3(a).

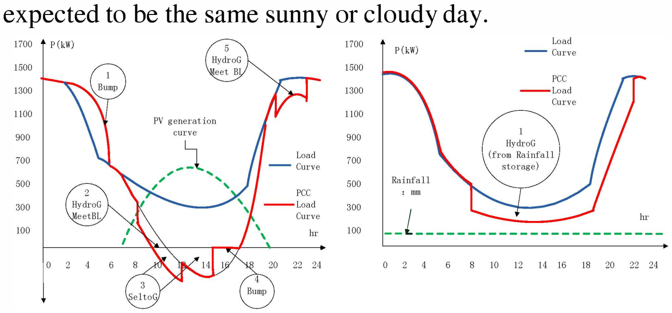
(b) As soon as the coming of peak hour of bulk grid, the hydropower will produce the power to meet the building's load till the roof tank becomes empty, as ② in Fig.3(a).

(c) If the sum of PV power and hydropower is exceed the building's load, then the surplus power will send to bulk power grid in peak power sale price, as ③ in Fig.3(a).

(d) As soon as the roof tank becomes empty, the bump will start pumping again to feed the roof tank by the exceeding power of PV power minus of building's load. Such decision may not economic because it wastes much more energy and get less money than its alternative to sell those amount of electricity to bulk grid, but it will return a more reliability or credit when we have the water on the roof if bulk grid failed in coming hours, as ④ in Fig.3(a).

(e) The roof water will also again to generate the peak power to decrease the building's load which will decrease the peak power from the bulk grid before the end of daily peak hours, as ⑤ in Fig.3(a).

Above circle will go on in next day if tomorrow is expected to be the same sunny or cloudy day.



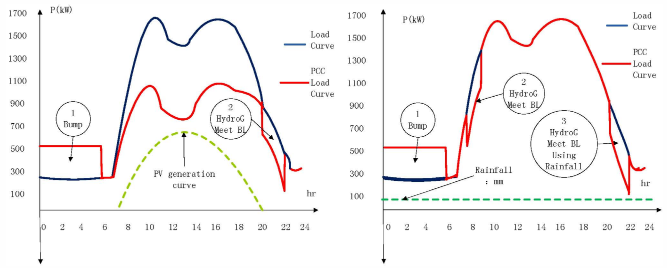
(a) sunny or cloudy (b) rainy day

Fig.3 operation curve of residential building

(2) During rainy day, the PV will stop. Assume the rainfall starts from mid-night, but it is much more economic to store the rainfall till the peak hour coming, for example, start to generate power from morning 8 clock, which will decrease the most costly peak time purchasing the power from the bulk grid, see Fig.3 (b).

In such development, the off-peak load of building micro-grid get increased and peak load decreased even sending peak power to bulk grid, which is very welcomed by bulk grid. In meantime, from building's customer side, the payment of peak load gets decreased greatly decreased. If the ratio of price of peak and off-peak is about 2-4 times, such scheme will have a good economic benefit from long-term operation.

B. Best choice for official/commercial building micro-grid



(a) sunny or cloudy (b) rainy day

Fig.4 operation curve of official/commercial building

(1) During sunny or cloudy when PV power is available, then we have following sequence strategies:

(a) At mid-night, use the cheap electricity from bulk grid to charge the roof tank.

(b) Using PV power in day-hour to meet the building's load.

(c) Arrange the roof water to be empty by power generation before the closing of night peak-hours.

Above circle will go on to next day, if tomorrow is expected to be the same sunny or cloudy day. See Fig.4 (a).

(2) During rainy day, the PV will stop. See Fig.4(b), the building's load curve still make us to bump the roof water tank full in the night off-peak hours, and using those water(also including accumulated water from rainfall) to generate peak power just after day-time peak-hours. Before the closing the night peak-hours, again to empty the roof water tank by generating the peak-power.

C. PV fluctuation control

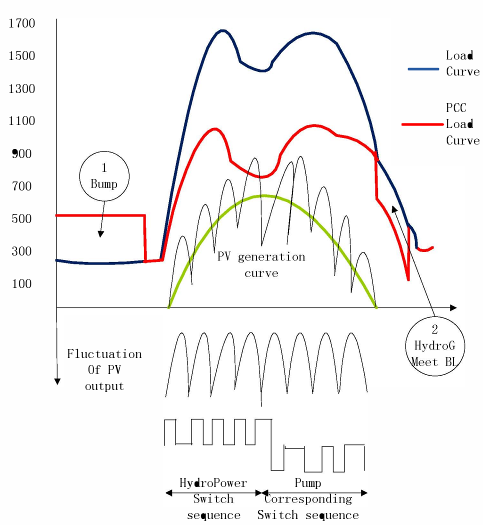


Fig.5 PV fluctuation control by hydropower and pump

We can observe that the PV will have an unexpected fluctuation as shown in Fig.5, however we still have fluctuation decreasing measures by switch operation of hydro-turbine and bump as shown in Fig.5.

IV. Near Constant Load of Micro-Grid Operation Mode

A. PCC near constant load control strategies

As per bulk is concerned, maintain the Point of Common Coupling (PCC) as a predictable or near constant load is very important.

B. Charging the roof water tank in excess power over the building's load

See Fig.3(a), during the day hours, if PV excesses the building's load, then it will at firstly to pump the water from down water tank to charging the roof water tank till it reaches the maximum volume. If there is still the excess power and the bulk grid can absorb, then such electricity will sell to bulk grid, normally the sell price is high because it is the peak time of the bulk grid.

C. The usage of roof tank's water

Also following strategies:

(1) It will be the emergence power in any cases in absent of bulk power as well as the PV power.

(2) It is better to be used in peak hours, normally in sunny or cloudy day, such peak hours is in evening when the PV power is not available during night or in rainy day.

(3) In case of there is the rainfall or any overflow of the roof tank, the water will be generated into power in its capability.

V. Matlab/Simulink Simulation

See Fig.6. Following we will give more detailed model.

VI. PV Plant Model

A. PV module model

Boroway's PV module model [7,8] is used.

B. PV plant model

Assuming photovoltaic array consists of m string PV modules in parallel, each string consists of n PV modules in series which are with same type of cell, and the total output current is I_{tl}, terminal voltage is U_{tl}, total power is P_{tl} [6,8] , so:

$$I_{tl} = mI \tag{1}$$

$$U_{tl} = nV \tag{2}$$

$$P = IV \tag{3}$$

$$P_{tl} = \eta_R I_{tl} U_{tl} = \eta_R mnIV = \eta_R mnP \tag{4}$$

VII. Hydropower with Pumping Storage Model

A. Roof water tank model

When t+1 time of the water tank water level between minimum and maximum level between roof water tank limit, i.e., $Z_{uHPMIN} \le Z_{uHP}(t+1) \le Z_{uHPMAX}$, then

$$Z_{uHP}(t+1) = \frac{\left(Q_{udN}(t) + R_{rain}(t) * S_{rain} - Q_{uOUT}(t) - Q_{uOF}(t)\right) * \Delta t}{a_1 * b_1} + Z_{uHP}(t) \tag{5}$$

when t+1 time of the roof water tank water is greater than the maximum roof water tank water level in the water tank water level, $Z_{uHP}(t+1) \ge Z_{uHPMAX}$ then

$$Z_{uHP}(t+1) = Z_{uHPMAX} \tag{6}$$

When t+1 time of the water level on the roof water tank under minimum water level $Z_{uHP}(t+1) \le Z_{uHPMIN}$ then

$$Z_{uHP}(t+1) = Z_{uHPMIN} \tag{7}$$

The water tank water level less than death, the water no longer drop, no outflow.

$Z_{uHP}(t), Z_{uHP}(t+1)$ are water level at t moment and t+1 of the roof tank respectively; $Q_{uIN}(t)$ is water into the roof water tank at time t(m^3/s); $Q_{u\bullet UT}(t)$ is water out of the roof water tank at time t(m^3/s); $R_{rain}(t)$ is the rainfall at time t in mm/s; S_{rain} is the roof rainfall collection area; $Q_{u\bullet F}(t)$ is the overflow of the roof water tank at time t(m^3/s); a_1, b_1 are width and length of the roof water tank respectively. Z_{uMAX}, Z_{uMIN} are the maximum limit and minimum limit of the roof water tank respectively.

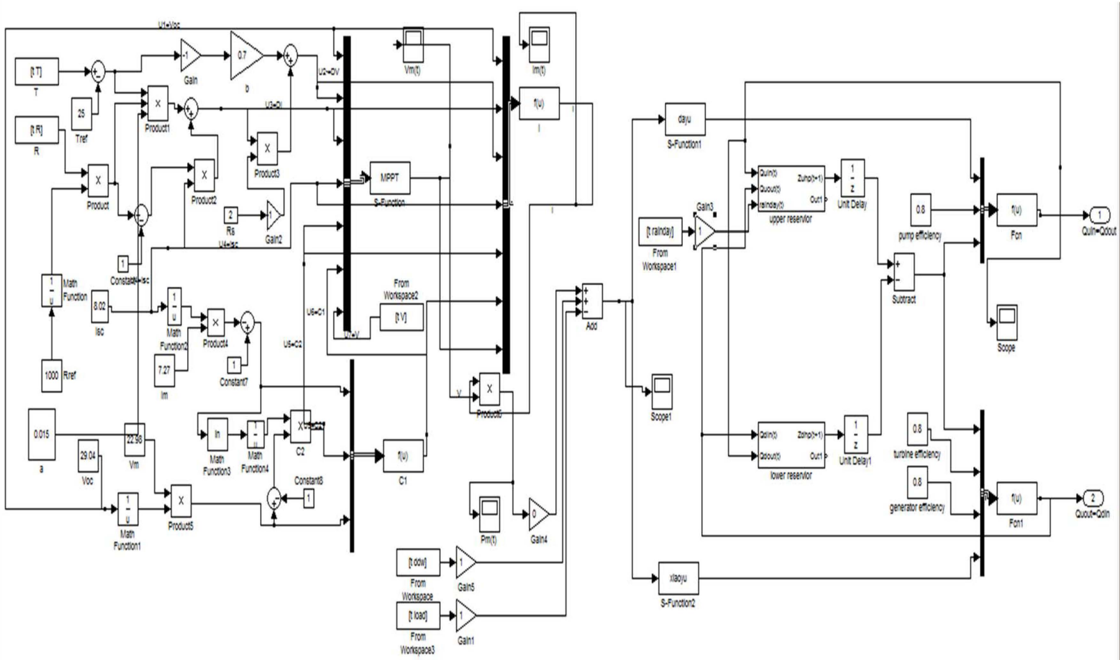


Fig.6 MATLAB / SIMULINK simulation diagram

B. Down water tank model

When t+1 time of the water tank water level between minimum and maximum level between roof water tank limit, $Z_{dHPMIN} \le Z_{dHP}(t+1) \le Z_{dHPMAX}$ then

$$Z_{dHP}(t+1) = \frac{(Q_{dIN}(t) - Q_{dOUT}(t)) * \Delta t}{a_2 * b_2} + z_{dHP}(t) \tag{8}$$

when t+1 time of the lower water tank water is greater than the maximum lower water tank water level in the water tank water level, $Z_{dHP}(t+1) \ge Z_{dHPMAX}$ then

$$Z_{dHP}(t+1) = Z_{dHPMAX} \tag{9}$$

Exceed the maximum water tank water level roof limit on the water will flow $Q_{d\bullet F}(t)$ overflow tank.

When t+1 time of the water level on the roof water tank under minimum water level $Z_{dHP}(t+1) \le Z_{dMIN}$ then

$$Z_{dHP}(t+1) = Z_{dHPMIN} \tag{10}$$

When the water level is below the water tank dead water level, water level does not change and no overflow.

$Z_{dHP}(t), Z_{dHP}(t+1)$ are water levels of the lower water tank at t moment and t+1 respectively; $Q_{dIN}(t)$ is water into the lower water tank at time t(m^3/s); $Q_{dOUT}(t)$ is water out of the lower water tank at time t(m^3/s); $Q_{dOF}(t)$ The overflow of the lower water tank at time t(m^3/s); a_2, b_2 Respectively for the lower water tank of the long , width(m); Z_{dHPMAX}, Z_{dHPMIN} Respectively on the maximum limit of the lower water tank water level and minimum water level(m).

C. Pump model

$$P_{HP}(t) = \frac{9.8 * Q_{dOUT}(t) * (Z_{uHP}(t) - Z_{dHP}(t))}{\eta_P} \tag{11}$$

η_P is pump efficiency. $Z_{uHP}(t)$ and $Z_{dHP}(t)$ are the roof water tank's water level and lower one at time t (m) respectively. In general, pump is working at a constant discharge or rated discharge Q_{rp}。

D. Turbine power generation model

$$P_{HP}(t) = 9.8 * \eta_T * \eta_G * Q_{uOUT}(t) * (Z_{uHP}(t) - Z_{dHP}(t)) \tag{12}$$

η_T is turbine efficiency , η_G is generator efficiency. In general, turbine is working at a constant discharge or rated discharge Q_{rt}.

E. Water system model

We assume that the bump and turbine never work in same time, so we have:

(1) When bump is working, then turbine will stop:

$$\begin{cases} Q_{dOUT}(t) = Q_{uIN}(t) = Q_{rp} \\ Q_{uOUT}(t) = 0 \\ Q_{dIN}(t) = 0 \end{cases} \tag{13}$$

(2)when turbine is working, then bump will stop:

$$\begin{cases} Q_{uOUT}(t) = Q_{dIN}(t) = Q_{rt} \\ Q_{dOUT}(t) = 0 \\ Q_{uIN}(t) = 0 \end{cases} \tag{14}$$

VIII. MICRO-GRID WITH BULK GRID

Assume the load is $L_d(t)$, then the power required from bulk grid $P_g(t)$ can be calculated as :

$$P_g(t) = L_d(t) + P_{BP}(t) - P_{PV}(t) - P_{HP}(t) \qquad (15)$$

IX. CASE STUDY AND RESULT ANALYSIS

A. Case study parameters

Tab.1 Study Cases Parameters

Items	parameters	Case 1*	Case 2*	Case 3*
Building parameters	height(m)/floors	80/24	420/88	240/80
	width(m)	15	50	100
	length(m)	105	50	
	usable floor area	37500		200
roof rainfall collection	roof water collection area(m2)	1820	2500	25000
Build Load	Residential area(m2)	37500	60000	5000
	Residential load(kW)	1875	3000	
	office area		60000	
	office load		6000	
	commercial area			
	commercial load			
	left load		3200	6500
Upper water tank	width(m)	10	30	80
	length(m)	60	30	150
	height(m)	2	3	4
	bottom level(m)	80	420	240
	weight(T)	1200	2700	48000
	Average Pressure(T/m2)*	2/0.76	3/1.08	4/2.4
	full charge or realise hour	1.67		
down water tank	width(m)	10	30	80
	length(m)	60	30	150
	height(m)	2	3	4
	bottom level(m)	-5	-5	-5
PV installation	roof area (m2)**	1365	2500	18000
	south wall area (m2)**	3360	16000	15000
	rate power(kW)	600	2000	4000
	sunny max power(kW)	600	2000	4000
	cloudy max power(kW)	360	1200	2400
	rainy power(kW)	0	0	0
Hydro turbine generator	rate power(kW)	150	850	500
	rate flow(m3/s)	0.2	0.2	0.2
	turbine efficiency	0.9	0.9	0.9
	generator efficiency	0.9	0.9	0.9
	full power rainfall(mm/hr)	396	288	
Pump	rate power(kW)	250	1500	800
	rate flow(m3/s)	0.2	0.2	0.2
	pump efficiency	0.5	0.5	0.5

Tab.1 gives 3 typical buildings for simulation study, case1 simulates "Baiyin" residential building in Hangzhou; case2 simulates the highest building in Shanghai "Jinmao Tower" (residential+hotel). Last one simulates Zhejiang Electric Power Corporation buildings. All buildings are assumed in a cubic size. The design notes are: (1) The PV install capacity is 1kW per 8 m2 horizon surface. (2) The wall PV area is 40% of total south wall surface area. (3) The weight limit for residential building is 0.2T/m^2. (4) Residential load density is 50W/ m2, official & commercial load density is 100 W/ m2. (5) roof water collection area = (Width+2)*(Length+2); (6) roof water tank, full charge or release hours T_{wc} is calculated as:

$$T_{wc} = \frac{W_{ud} * W_{ld} * H_{ud}}{q_t * 60 * 60} \qquad (16)$$

B. Generation assuming and result analysis

A typical PV daily power output curve is assumed, and 3 weather conditions are considered as (1) sunny day with full power output of PV plant; (2) cloudy day with 60% of the full power output; (3) none power generated from PV but a typical rainfall curve is given in this study.

From the simulation, it is observed that the expected operation results are obtained which shown in Fig.3 and Fig.4.and Fig.5, because all the operation strategies are pre-designed.

X. ARGUMENTS AND FURTHER STUDY

This study is a pre-designed operation simulation, and only concern about the daily generation and load matching and compensation. Though it is a rough study, but it might be a big solution for future city smart &micro grid.

Many others are not considered, so there are many arguments as following:

(1) The proposal is not a general means of hydropower project, but a storage scheme. So what is result to compare with the other solution like battery?

(2) Underground power house will isolate the noisy of hydro turbine and pump system with many measures.

(3) The efficiency of small pump is not high, but some researches present that efficiency of pump can be improved by using power electronics technology and cascade pumping.

(4) Larger capacity of roof tank can regulate more PV power and more peak\off-peak regulation capability for the bulk grid. But the increasing of roof burden may also increase supporting architecture of the whole building. In this study, see Tab.1, direct average pressure is selected from 2T to 4T, and the roof average pressure is from 0.76T to 2.4 T which needs further feasibility study.

(5) The roof water tank will add additional cost, so how to calculate it?

(6) The dynamics of the system is not considered.

XI. REFERENCES

[1] Matthias Popp, Speicherbedarf bei einer Stromversorgung mit erneuerbaren Energien, 1. Auflage, 2010, 159 S. 24 Abb. in Farbe., Geb.ISBN: 978-3-642-01926-5

[2] R. Aihara， A. Yokoyama， F. Nomiyama and N. Kosugi， "Impact of Operational Scheduling of Pumped Storage Power Plant Considering Excess Energy and Reduction of Fuel Cost on Power Supply Reliability in a Power System with a Large Penetration of Photovoltaic Generations"， in Proc. 2010 International Conference on Power System Technology， Hangzhou， China， Oct. 2010.

[3] D Manolakosa, G Papadakisa, D Papantonisb, S Kyritsis，"A stand-alone photovoltaic power system for remote villages using pumped water energy storage". Energy, Jan., 2004, 29(1): 57－69

[4] http://en.wikipedia.org/wiki/Water_tower

[5] http://en.wikipedia.org/wiki/Pumped-storage_hydroelectricity

[6] Qianzi Zhang. (Guided by Jianmin Zhang) "A Feasibility and Simulation Study of High-rise Building in City with PV and Mini-hydro Pumping：Might be a Big Solution for Future City Smart & Micro Grid"(in Chinese/ English),Graduation Thesis, Shandong Univ. of Sci.& Tech., June, 2012, Zibo, Shandong, China

[7] Borowy BS, Salameh ZM. "Methodology for optimally sizing the combination of a battery bank and PV array in a Wind/PV hybrid system". IEEE Transactions on Energy Conversion 1996;11:367－75.

[8] Qianzhi Zhang, Jianmin Zhang. "Photovoltaic Plant Metering Monitoring Model and its Calibration and Parameter Assessment", PES General Meeting IEEE, San Diego, U.S.A, 22 – 26 July 2012