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Abstract

This paper presents an energy management strategy for a commercial building in supermarket application. Some objectives are established as load shedding, to reduce the electricity bill and the CO_2 emissions of commercial building, using photovoltaic (PV) and storage systems. An energy management supervision strategy based on the rules of the electricity bill will be presented. This paper focuses on the supervision strategy with the help of fuzzy logic and a graphical methodology to build it. It is shown, with the help of simulations and some economic and ecological indicators that the energy bill cost and the CO_2 emissions can be reduced by using the proposed solution.

Keywords: Photovoltaic (PV) systems, fuzzy logic, storage system, energy management, commercial building, supermarket

I. Introduction

In recent years, the Energy European legislations seek to lower the CO_2 emissions and the fossil energy consumption by the development of renewable energy [1,2,3]. One of the priority is the building performance requirements and very low energy buildings (passive houses) because the largest cost-effective savings potential lies in the residential (households) and commercial buildings sector (tertiary sector), where the full potential is now estimated to be around 27% and 30% of energy use, respectively [1]. It is indicated in [1]: In residential buildings, retrofitted wall and roof insulation offer the greatest opportunities, while in commercial buildings, improved energy management systems are very important.

Several research works propose solutions for building energy management, from design to control, with the help of implicit or explicit methods and with or without renewable energies: control loop, design methods, genetic algorithms with fuzzy controllers, economic model predictive control, building automation systems [4-19].

A general methodology to design a supervision system has been developed in [20]. The objective of this paper is to design an energy management system for a commercial building by applying this general methodology. A supermarket connected to the power network and associated to photovoltaic and storage systems are considered in this paper.

Thanks for this methodology, some energy management strategies, developed with the help of fuzzy logic, for the storage system, are developed. It is shown in this paper that the storage system can adjust the power supplied by grid in the peak period and off-peak period in order to reduce the electricity bill and the CO_2 emissions.

In section II, the connection configuration of the supermarket is defined. The objective, the constraints and means of action of this supervision are also introduced in this section. The principles of the electricity bill are presented in section III. The principles of energy management supervision strategy are presented in section IV. Then, the fuzzy logic based supervisor is developed in section V. Simulation results are shown in section VI and the comparisons of different topologies (with or without PV and storage system) with the help of economic and ecological indicators are shown in section VII. The conclusion is given in section VIII.

II. Models, configuration and objectives

Fig.1 shows the electrical configuration of a commercial building in supermarket application studied in this paper. There are a PV system [21] and a storage system installed in parallel with the supermarket load [22]. All these equipments are installed behind the electric meter. The PV production should be consumed by the load in priority.

A general model of the storage system is used [20]. It is not based on a priori defined technology. It is only characterized by a maximum power of charge, a maximum power of discharge, a charging and discharging efficiency, a maximum and minimum level of stored energy and a time constant of charge and discharge. The PV system and supermarket load are modeled respectively by a production and a load profile shown in Fig. 2.

In a supermarket, there are several types of electric load: food refrigeration equipments, lighting systems, air handling systems, computer and cash management systems etc…

In order to design a generalized supervision strategy, the actual energy consumption data of several supermarkets are analyzed. The ratio of consumption/surface has been determined to create a fictive supermarket. Fig. 2.a shows the total consumption power profiles of this fictive supermarket for one week in winter. It can be noted that in Sunday (day 7) and in the night of everyday when the supermarket is closed, the power consumption is much lower than when it is open during the daytime.

PV system is modeled by a production profile based on the irradiance data supplied by Photovoltaic Geographical Information System (PVGIS) [23]. It is the average value of the month January in north of France (Lille). Neither the weather influence, nor daily difference of the sunrise and sunset moments of each day in the week are taken into account. This profile is shown in Fig. 2.b.

As mentioned in [20], the first step of the methodology of supervisor design is to determine the work specification of the system and to identify the characteristics and the objectives of the system. The objectives, the constraints and means action of the energy management system are then:

- Objectives:
  . To reduce the electricity bill;
  . To balance between the power of peak and off-peak periods to reduce the CO_2 emissions;
  . To ensure the energy availability.
- Constraints:
  . The electricity price of different periods;
  . The limit of the subscribed power;
  . The limit of the storage capacity.
- Means of action:
  . Reference power of the storage system.

The electricity prices are different at each pricing periods, these price variation are used to establish energy management strategies to reduce the electricity bill and the CO_2 emissions by balancing the consumption of peak and off-peak periods. The storage system is used to achieve the power balancing.

The subscribed power is another constraint. The subscribed power is a limitation of the consumption power. The load should not pass over this limitation; otherwise, it will be invoiced penalty by a much higher price.

III. Rules of the electricity bill

The electricity bill is composed by three parts: the annual premium, the active consumption and the reactive consumption. The active consumption is composed by two costs: consumption cost (cost by kWh) and punishment cost if it is applicable (when the supplied power exceeds the subscribed power). Fig. 3 shows the method to calculate the electricity bill.

As mentioned above, the annual premium is calculated from the subscribed power P_s. This power is calculated according to the subscribed power defined in each pricing period P_i.

Equation (1) shows how to calculate the annual premium where P_p is the total annual premium (€), P_{kW} is the price by power (€/kW), k_i is a period coefficient given by the electrical power company and P_i is the subscribed power (kW) according to the pricing period.

(1)

For example, prices for three different pricing periods (for i from 1 to 3) in winter [24] are as follows:

- Peak period in winter (PPW) : $k_1 = 1$ and P_{kWh} *(€/kWh)* = 0.1151;
- Shoulder period in winter (SPW) : $k_2 = 0.77$ and P_{kWh} *(€/kWh)* = 0.07662;
- Off-peak period in winter (OPW) : $k_3 = 0.38$ and P_{kWh} *(€/kWh)* = 0.04641;
- In the three periods, P_{kW}, the price by power (€/kW) is equal to 66.12.

The pricing period will be presented in section V.

IV. Objectives of the energy management supervision strategies

According to objectives and constraints mentioned in section II, the principles of the energy management supervision are listed as follow:

1. Don't exceed the subscribed power.
2. During the peak period, to reduce the power supplied by the grid in order to reduce the electricity bill.
3. To ensure the availability of the storage system for the next pricing period. To charge the storage system during the off-peak period or the shoulder period only if it is really necessary.
4. The PV production should be consumed by loads or stored by the storage system in priority. If there is still exceeded power, it will then be sent to the grid if the purchase agreement allows the supplied power to be negative.

The architecture of the supervision system is shown in Fig. 1. The subscribed power P_s, the absorbed power P_a (power supplied by grid), *SOC* (State Of Charge) and the time t will be the inputs of the supervision according to the principles mentioned above.

V. Fuzzy logic based energy management supervision strategies

As mentioned above, there are several objectives faced by the supervision system. Fuzzy logic is an adapted tool to solve this kind of problem. Because it can take into account several objectives and constraint to find a compromise according to the actual situation [20,25,26,27,28].

In section IV, the principles of the energy management strategy have been listed. These principles can be translated into several rules according to the different pricing periods.

As shown in Fig. 1, the architecture of the supervision system is in accordance with the objectives mentioned in section II. There are four inputs: P_a, absorbed active power (the power supplied by grid); P_s, the subscribed power according to the pricing period; SOC, the State Of Charge and t, the time. There is only one output which corresponds to the means of action noted in section II.

According to the different pricing periods, the objectives of the supervision strategy will be different. The pricing periods are split in 6 operating modes. The different pricing periods and operating modes are as follows:

- For the pricing period PPW, i.e. from 9h to 11h and from 18h to 20h, from Monday to Friday, the operating modes are:
  . PPW1: from 9h to 11h when the PV production is great;
  . PPW2: from 18h to 20h when there's no more PV production.
- For the pricing period SPW, i.e. from 7h to 9h, from 11h to 18h and from 20h to 1h, from Monday to Friday, the operating modes are:
  . SPW1: from 7h to 9h and from 11h to 18h which is followed by a PPW period;
  . SPW2: from 20h to 1h which is followed by an off – peak period.
- For the pricing period OPW, i.e. form 1h to 7h, from Monday to Friday and all of the weekend and the day off, the operating modes are :
  . OPW1: from 1h to 7h, from Monday to Friday and all the day of Saturday when the supermarket is opened;
  . OPW2: Sunday or the days off when the supermarket is closed.

The supervision strategies will be established separately according to the one of operating modes described above. Fig. 4 shows a chart representation of this fuzzy logic supervision. This graphical tool was presented in [20,29] and helps us to design the supervision strategies for different operating modes. The operating modes listed above are represented with rounded rectangles and the states of the system are represented by transitions. The three pricing periods are shown in N1.1, N1.2 and N1.3. In each pricing period, there are different operating modes whose the transition condition is shown in this section. Fig. 5, Fig. 6 and Fig. 7 present respectively the details of the operating modes of peak period (PPW), shoulder period (SPW) and off-peak period (OPW). Different objectives of each operating mode are shown in the bloc from N1.1.1 to N1.3.2. The order of the items shows the priority of the objectives.

All these 6 operating modes will be explained in the next parts.

V.1 Operating mode PPW1

During this period, the PV production will be important and the electricity price is expensive. The objectives of the supervision strategy N1.3.1 are shown in Fig. 5.

Equation (2) shows the convention of the power difference ΔP where P_i is the subscribed power of each pricing period as mentioned in (1) and P_a is the absorbed active power as shown in Fig. 3.

$$\Delta P=(P_i-P_a)/P_i \qquad (2)$$

A fuzzy logic strategy includes three classical parts [30]: fuzzification, inference, and defuzzification.

V.1.1 Fuzzification

Both input variable membership functions are shown in Fig. 8. As mentioned above in section IV, one of the principles of energy management is to ensure that the grid power doesn't pass over the subscribed power. So, the membership function of ΔP is not symmetrical around 0.

V.1.2 Inference

The fuzzy rules are expressed as follow:
IF ΔP is Small Positive **AND** *SOC* is Medium, **THEN** P_{ref} of storage system is Negative Medium.
IF ΔP is Negative **AND** *SOC* is Medium, **THEN** P_{ref} of storage system is Negative Great.
Etc…

These rules are defined according to the objectives of N1.3.1 shown in the Fig. 5.

Thanks to these rules, according to the actual situation (the electricity price, the consumption, the subscribed power, the state of charge of the storage system etc.), the supervision system behaves in an adapted ways to achieve the objectives.

Table 1 shows the corresponding fuzzy rules for the PPW1 strategy (S=Small, M=Medium, B=Big, Z=Zero, P=Positive, N=Negative)

V.1.3 Defuzzification

The membership function of the output variable is shown in Fig. 9. Fig. 10 shows the variation of P_{ref} vs. the SOC and ΔP. It shows the nonlinear relationship between input and output variables obtained with fuzzy logic.

It can be noted, that in most cases, the storage system is discharged. When ΔP is closed to 1 (power supplied is close to 0), the storage system will be charged to ensure the "consumer" characteristic of the supermarket.

V.2 Operating mode PPW2

This period is between 18h~20h in winter. During this period, there is no more PV production. In order to reduce the electricity bill during this expensive period, the storage system should be discharged.

The objectives N1.3.2 are shown in Fig. 5. The membership function of inputs and output are the same as shown in Fig. 8 and Fig. 9, but the fuzzy rules are different because of the different objectives. The fuzzy rules for the PPW2 strategy are shown in Table 2.

The relation between the inputs and output is then different than in PPW1 as shown in Fig. 11.

It can be noted that the difference between the period PPW2 and PPW1 appears mainly when ΔP is close to 1.

V.3 Operating mode SPW1

This period is between 7h~9h and 11h~18h from Monday to Friday. In this period, the PV production is important (day time), but it fluctuates a lot and is not predictable (passing of cloud, overcast sky, etc…). So the strategy should be more flexible.

According to the objectives N1.2.1 shown in Fig. 6, the fuzzy rules of this period are shown in the Table 3.

The generated surface is shown in Fig. 12.

The comparison of Fig. 10 and Fig. 12 shows that both strategies are similar: when ΔP is close to 1, the storage is charged. This similarity can be found in the fuzzy rules of PPW1 and SPW1 strategies. The difference is that the volume surrounded by the surface and the axes in SPW1 is greater than in PPW1. Which means that in SPW1 period, the storage system will be charged more when the consumption level is low (ΔP is close to 1), and be discharged less when the consumption level is high (ΔP is close to 0). This is due to an electricity price in SPW period cheaper than in PPW period, and to one of the objectives of SPW1 which is to ensure the energy availability of the storage system.

V.4 Operating mode SPW2

This period is between 20h~1h, in this period, there is no more PV production. But this period is followed by an off-peak period. During the off-peak period, the storage system will be charged and the subscribed power will be defined greater than the consumption. So, in SPW2, the availability of the storage system is less important.

According to the objectives N 1.2.2 shown in Fig. 6, the fuzzy rules of this period are defined in Table 4.

The Fig. 13 shows the generated surface of SPW2 strategy.

It can be noted that in SPW2 strategy, in comparison with the SPW1 strategy (Fig. 12), the storage system is less charged. It is charged only when *SOC* is low (less than 50% for example), because ensuring the storage availability is not the major requirement to meet thanks to the following off-peak period.

V.5 Operating mode OPW1

OPW1 is one of the off-peak periods between 1h to 7h from Monday to Friday. In this period, the annual premium and the electricity price are cheaper than in the other periods. The storage system can be charged in this period thanks to the low electricity price. According to the objectives N 1.1.1 shown in Fig. 7, the fuzzy rules of this period are defined as in Table 5.

Fig. 14 shows the generated surface of OPW1 strategy.

It can be noted that in most of the cases when ΔP is positive, the storage system is charged in maximum except when ΔP is close to 0 (the power supplied by the grid P_a is close to the subscribed power P_s), because the major objective of this period is to charge the storage system to ensure energy availability for the next period.

V.6 Operating mode OPW2

This period is particular. It is the Sunday or the days off when the supermarket is closed. In these periods, the consumption level of the supermarket is low. The PV production in the daytime will be probably greater than the consumption. In this case, if the storage system is full, the exceeded power will be sent to the grid. As noted in IV, the PV production should be consumed by loads or stored in priority. So if the storage system is full, it should be discharged before the sunrise. The storage system will then have enough availability to store during the daytime. At the end of the daytime, if the storage system is not charged till full, it can be charged in the night by the grid for the next working day.

In this period, the *SOC* is no more the variable to take into account. According to the objectives N 1.1.2 shown in Fig. 7, a simple one input one output relationship is used to express this strategy. This relation is shown in Fig. 15.

In this strategy, most of the time, the storage system is discharged. Only when ΔP is close to 100% (the PV production is close to the consumption), it will be charged. At this moment, it should charge the storage system in order to avoid sending the PV production to the grid (absorbed or stored in priority).

VI. Simulation results

In this simulation, a supermarket of 13058m^2 is considered with a peak power rating of the PV system at 1.16MW. Capacity of the storage system is 1700kWh, maximum power of the storage system is 400kW.

Fig. 16 shows the simulation results for a supermarket during one week with the help of Matlab Simulink. In the first row, the solid line is the subscribed power; the dashed line is the supplied power by the grid. In the second row, the solid line presents the load power and the dashed line presents the PV production. And in the third row, the solid line is the SOC of the storage system.

The Fuzzy logic explained above is implemented with the help of the Fuzzy logic toolbox of Matlab. This paper shows the results simulated for January when the price period is the most complex; the other seasons have been simulated as well with different PV production and consumption.

It may be noticed that in Fig. 16, the supplied power doesn't pass over the subscribed power even when the load power of the supermarket passed over it, because the storage system is used to adapt these thresholds.

Fig. 17 shows a zoom of the simulation results for two open days. It may be noticed that:

- During 7h~9h and 16h~18h, the storage system is slowly discharged to ensure that the consumption power doesn't pass through the subscribed power.
- During 9h~11h, the peak period, thanks to the PV production during this period the storage system is lightly discharged.
- During 11h~13h, the shoulder period, owing to the PV production and the storage capacity, the PV production is consumed by load or stored by storage in priority. The energy availability is then ensured.
- During 18h~20h, there's no more PV production during the peak period, the storage system is discharged at its maximum power (the slope of SOC is sharper) because the electricity price is the most expensive during this period.
- During 20~21h, the storage is lightly discharged to ensure that the consumption power doesn't pass over the subscribed power.
- During 22h~1h, the storage is lightly charged because ΔP is big and SOC is small.
- During 1h~6h, the storage system is charged at its maximum power because the electricity price is the cheapest during this period.

Fig. 18 shows a zoom of the simulation results for two off-peak days including one off day. It can be noted that:

- During 0h~3h of Saturday, the storage is charged. Then during the daytime, the storage is not used.
- During 0h~7h of Sunday, the storage is fully discharged ensuring the availability to store during the daytime.
- During 9h~15h, when the PV production is greater than the consumption (dashed line is upper than the solid one), the storage system begins to store the exceeding production energy until the production is lower than the consumption (dashed line is lower than the solid one).
- From 17h, after the sunset, the OPW1 strategy is applied. The storage start to be charged until it is filled.

VII. Analyze of the simulation results

This section shows the comparison of the simulation results according to some economic and ecological criteria. The economic criteria are the annual premium (P_p in Fig. 3) and the electricity consumption cost for one week (Cost by kWh in Fig. 3). The ecological criterion is the CO_2 emission. The calculation is based on the data of realized production of the French Transmission System Operator (RTE France). These two types of indicator are also useful in the optimization problem 0.

Table 6 shows different indications deduced from the simulation results for different electrical configurations.

Case 1 represents the configuration without storage and PV system, the subscribed power is chosen 1200kW for all the pricing periods.

Case 2 represent the configuration with storage and PV system and the associated supervision system. The subscribed power is chosen as follow:

OPW:1000kW, SPW: 800kW, PPW: 600kW

As shown in Table 6, thanks to the PV and the storage system, the electricity bill and the CO_2 emissions can significantly be reduced in case 2 in comparison with case 1. The annual premium can be reduced of 21594€ (31%) for one year and the electricity bill can be reduced of 2716€ (30.93%) for one week. The CO_2 emissions can be reduced of 3.063T (26.04%) for one week.

This estimation of the CO_2 emissions is based on the realized production of the French Transmission System Operator (RTE France) 0 and the CO_2 emissions estimation for every type of production 0. Fig. 19 shows the comparison of CO_2 emissions for a period of one week. The dashed line shows the CO_2 emissions in case 1 and the solid line shows the CO_2 emissions in case 2.

It can be noted that during the daytime, the solid line is lower than the dashed one. At this moment, the PV production reduces the power supplied by the grid and the CO_2 emissions due to the pollutant electricity production. In midnight, the solid line is higher than the dashed one. At this moment, the storage system is charged by the grid, so the CO_2 emissions are greater because of the increasing use of classical productions. But this increase is lower than the reduction of CO_2 emission during the day time.

Because the CO_2 emissions fluctuates a lot according to the seasons, the consumption and the type of production, one year's CO_2 emission data has been used to evaluate the impact of the proposed energy management strategy. One year results of CO_2 emissions with or without PV and storage system are:

- Case 1: 260 T of CO_2 emissions;
- Case 2: 123.8 T of CO_2 emissions.

It can be noted that the CO_2 emission is reduced significant in case 2. Reduction of 136.2T (52.38%) of CO_2 emissions can be realized thanks to the PV production, storage system and the associated energy management strategies.

It should be highlighted that these CO_2 emissions calculation is based on data in France. In France, there are a lot of nuclear and hydraulic productions that have no CO_2 emissions. Thus, the unit CO_2 emission per MW is relatively lower than other countries or of the European level. The CO_2 emissions gain should then be greater if the data are based on Europe or other countries.

VIII. Conclusion

The energy management of a commercial building is a complex problem because of the PV production, the storage system, the variation of electricity price, the different kind of consumptions, the purchase agreement, etc. The energy management should consider these constraints and achieves several objectives at the same time. The storage system can be achieved with the help of different storage equipments such as battery, the cold room, etc. The power reference issued from the supervision system can not only control the storage system but also be a reference to control the load shedding.

The fuzzy logic supervision strategy has been proven to be an adapted tool to solve this kind of problem. This paper proposed a fuzzy logic strategy to control the system in order to satisfy economic and ecological objectives.

A graphical methodology is used to design the supervision strategy. This supervision strategy is evaluated by some economic and ecological indicators. The energy bill cost and CO_2 emissions are reduced thanks to the proposed solution.

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Tables with captions

Table 1 Fuzzy rules: Power reference of storage system in PPW1 strategy

		ΔP				
SOC	P_{ref}	BP	SP	Z	SN	BN
	B	SP	BN	BN	BN	BN
	M	MP	MN	MN	BN	BN
	S	BP	SN	MN	BN	BN

Table 2 Fuzzy rules: Power reference of storage system in PPW2 strategy

		ΔP				
SOC	P_{ref}	BP	SP	Z	SN	BN
	B	BN	BN	BN	BN	BN
	M	MN	MN	MN	BN	BN
	S	SN	SN	SN	BN	BN

Table 3 Fuzzy rules: Power reference of storage system in SPW1 strategy

		ΔP				
SOC	P_{ref}	BP	SP	Z	SN	BN
	B	SP	Z	MN	BN	BN
	M	MP	SP	MN	BN	BN
	S	BP	SP	Z	MN	BN

Table 4 Fuzzy rules: Power reference of storage system in SPW2 strategy

		ΔP				
SOC	P_{ref}	BP	SP	Z	SN	BN
	B	Z	Z	Z	MN	BN
	M	Z	Z	Z	MN	BN
	S	SP	SP	Z	MN	BN

Table 5 Fuzzy rules: Power reference of storage system in OPW1 strategy

		ΔP				
SOC	P_{ref}	BP	SP	Z	SN	BN
	B	BP	BP	Z	BN	BN
	M	BP	BP	MP	MN	BN
	S	BP	BP	BP	MN	BN

Table 6 Comparison of the result with or without storage and PV systems associated with the supervision system

	Annual premium (€)	Consumption for one week (€)	CO_2 emissions for one week (T)
Case 1	79344	8782	11.604
Case 2	54747	6066	8.541
Difference	-24597 (-31.00%)	-2716 (-30.93%)	-3.063 (-26.40%)

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Figure(s)

Figures

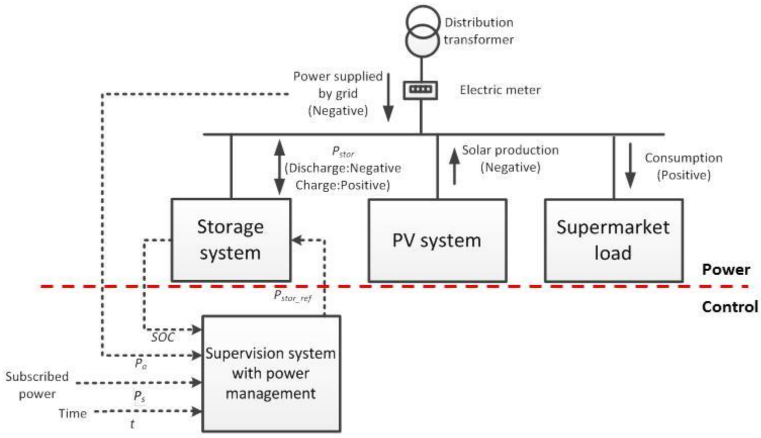
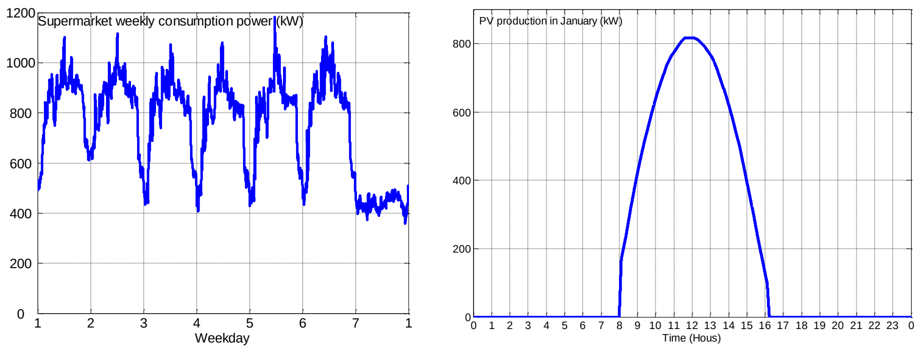


Fig. 1 Electrical configuration of a commercial building and architecture of the supervision system



a) Weekly consumption power profile *b) Daily PV production profile*

Fig. 2 Consumption and production profile of a fictive supermarket

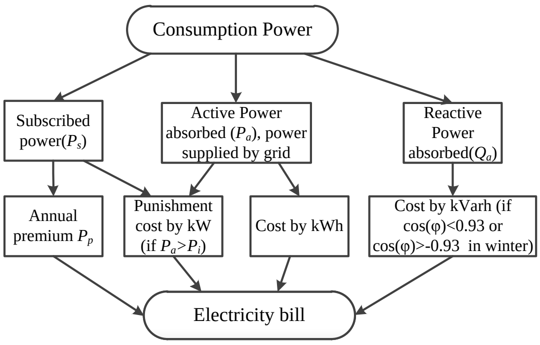


Fig. 3 Composition of an electricity bill

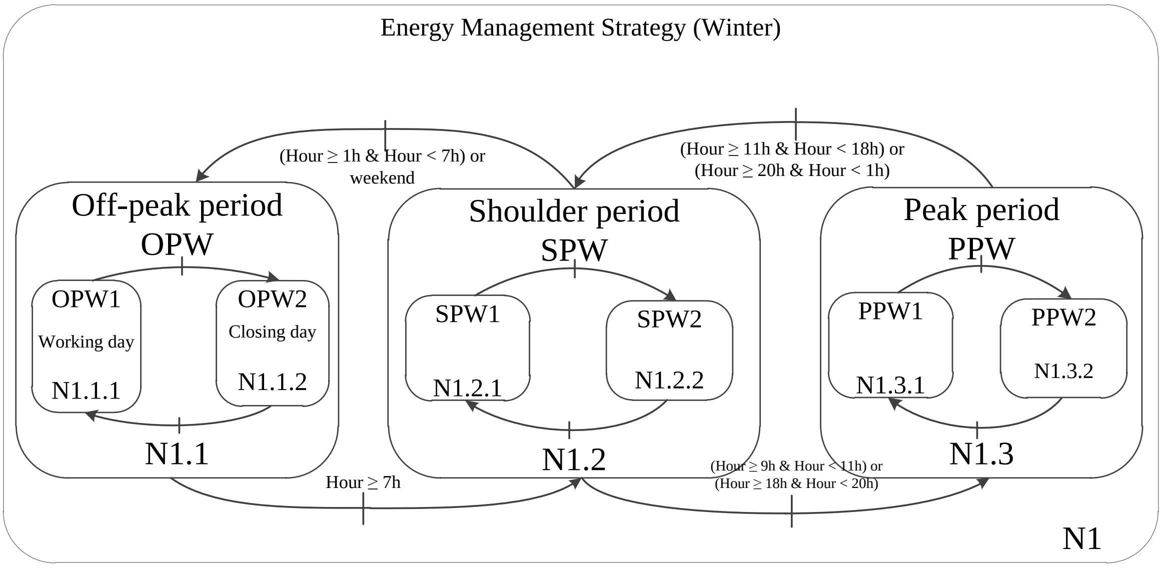


Fig. 4 Chart representation of the fuzzy logic supervision strategies

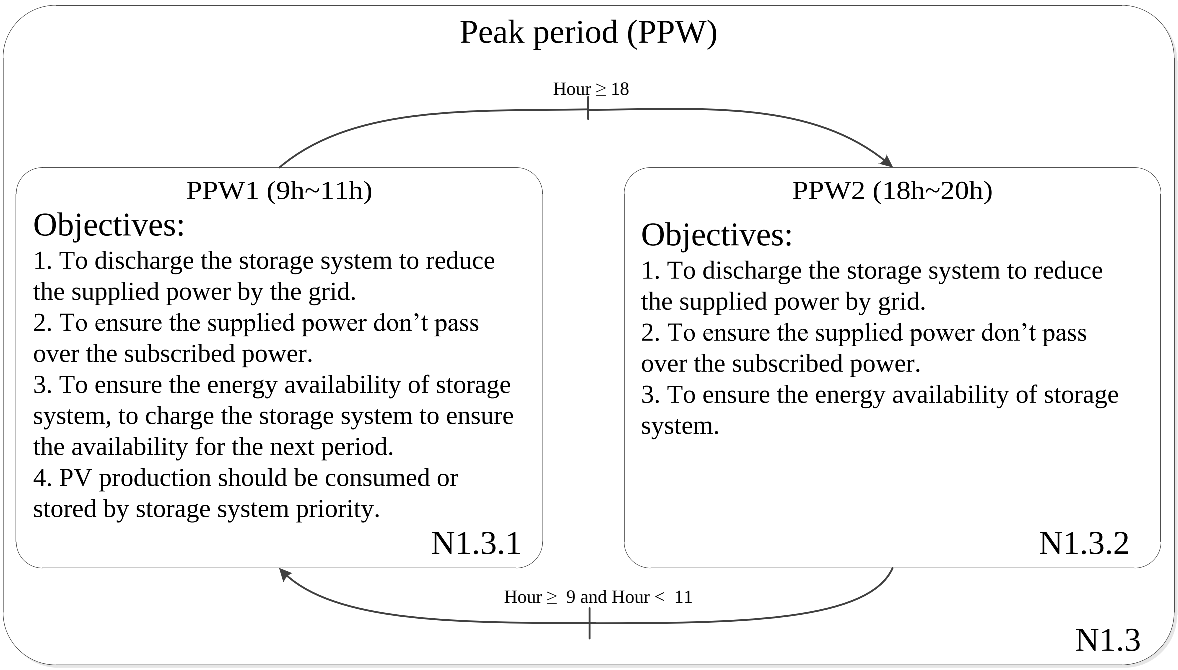


Fig. 5 Detail of the peak period in winter

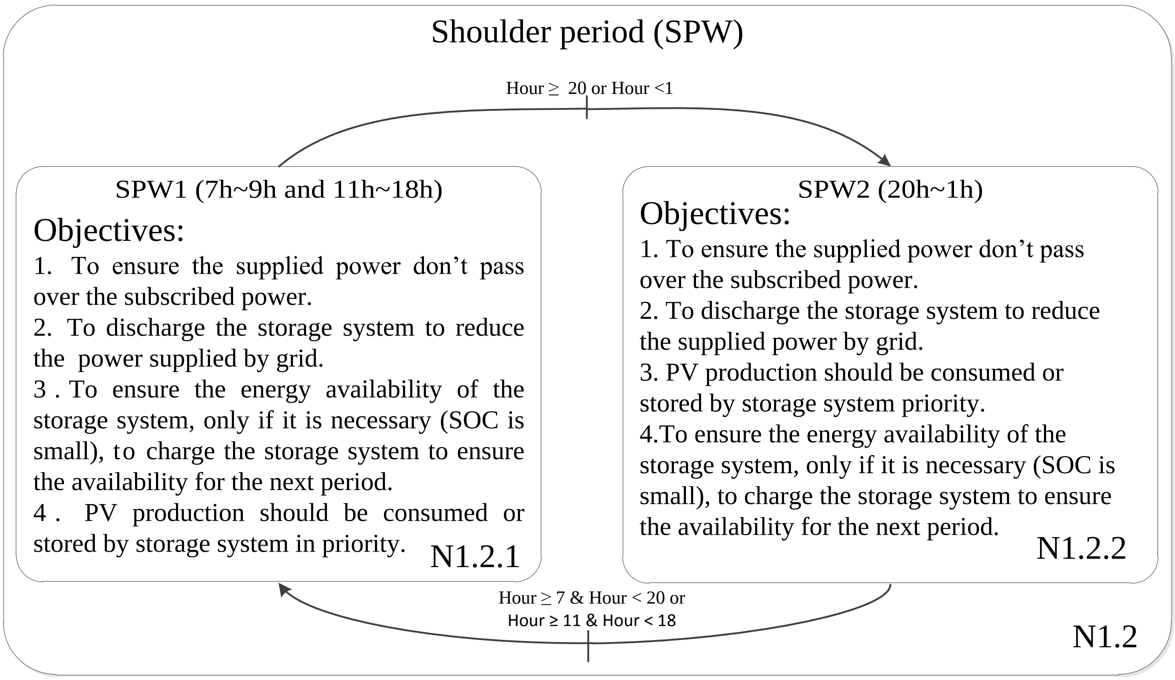


Fig. 6 Detail of the shoulder period in winter

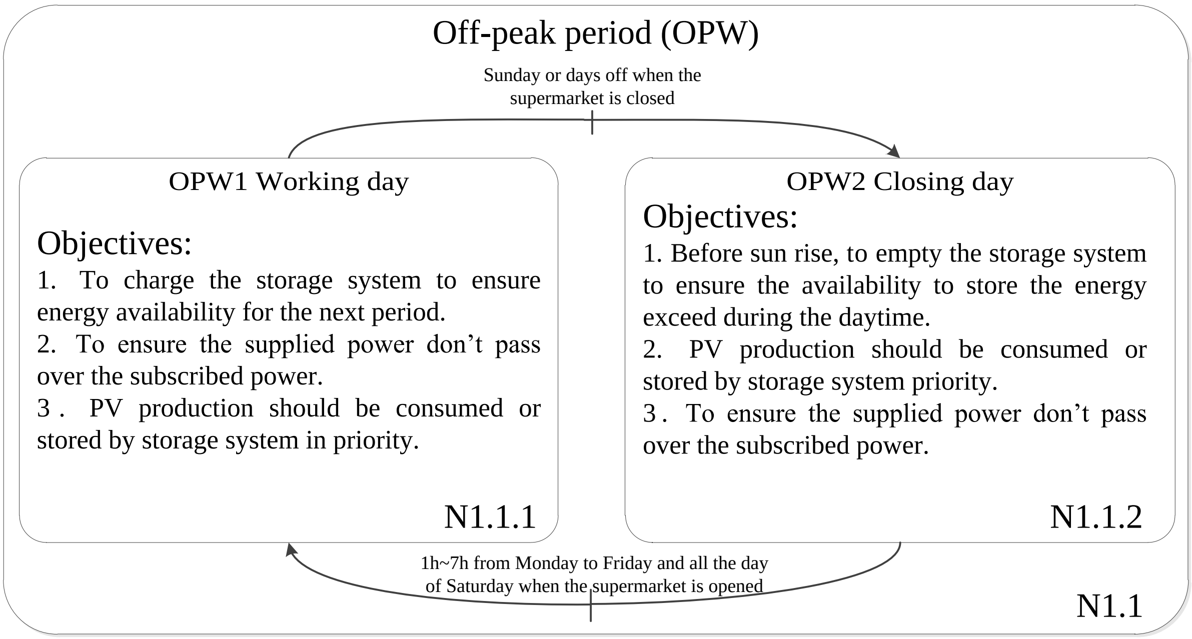
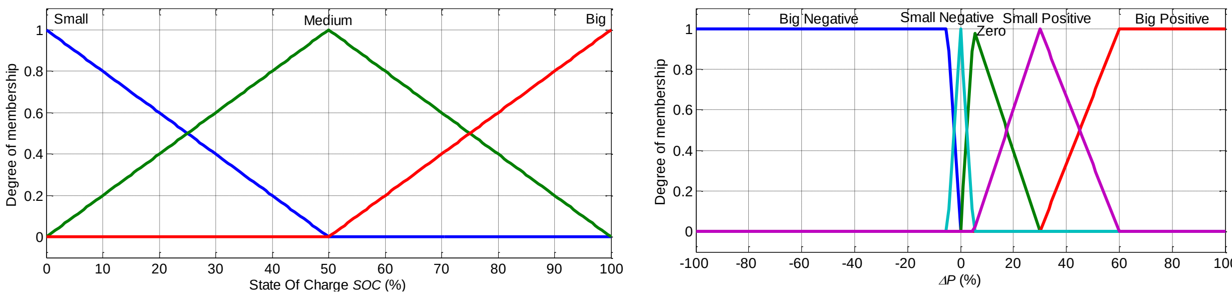


Fig. 7 Detail of the off-peak period in winter



a)SOC of the storage system

b)Power difference between the subscribed power and the supplied power

Fig. 8 Membership functions of input variable for fuzzy energy management strategy

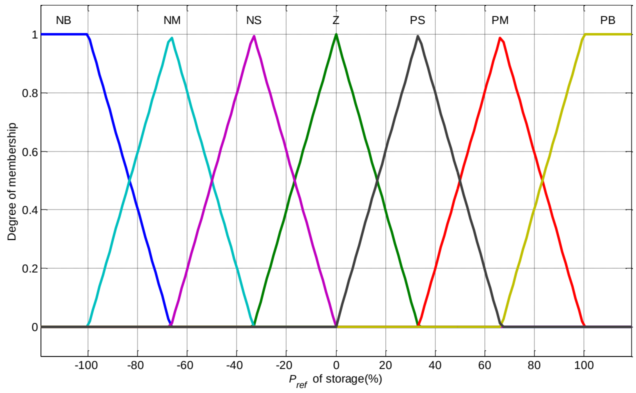


Fig. 9 Membership functions of output variable for the fuzzy energy management strategy

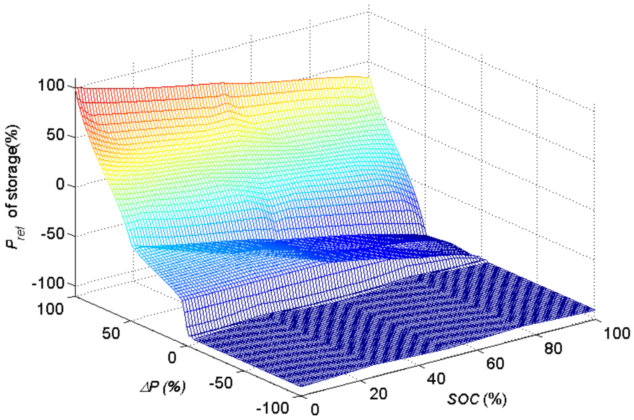


Fig. 10 Generated surface of PPW1 strategy

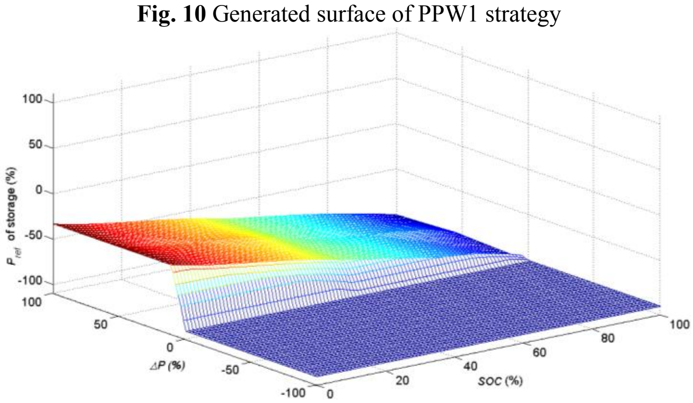


Fig. 11 Generated surface of PPW2 strategy

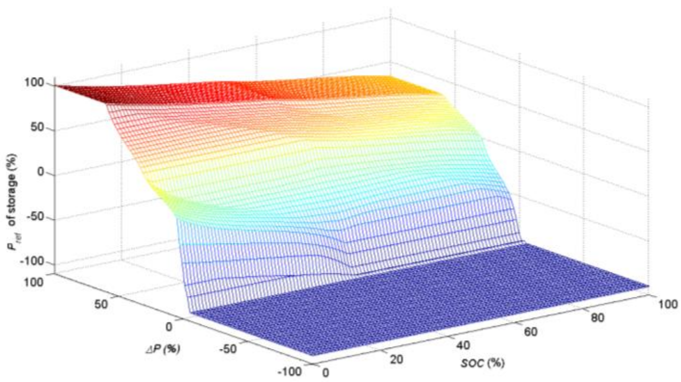


Fig. 12 Generated surface of SPW1 strategy

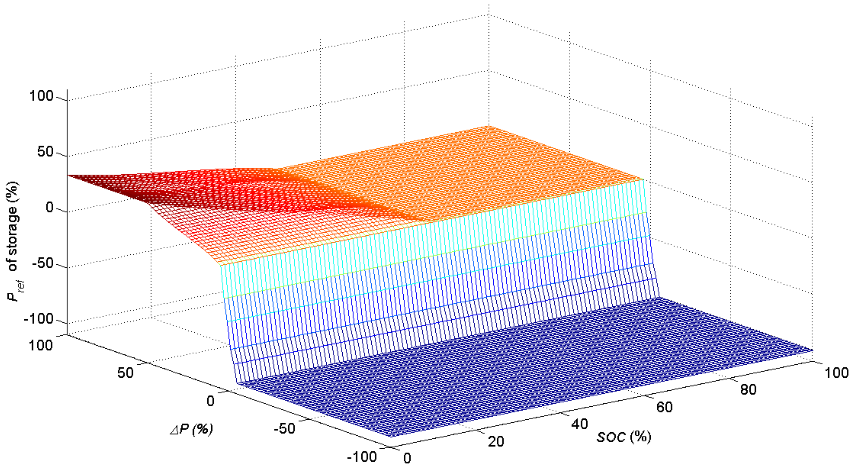


Fig. 13 Generated surface of SPW2 strategy

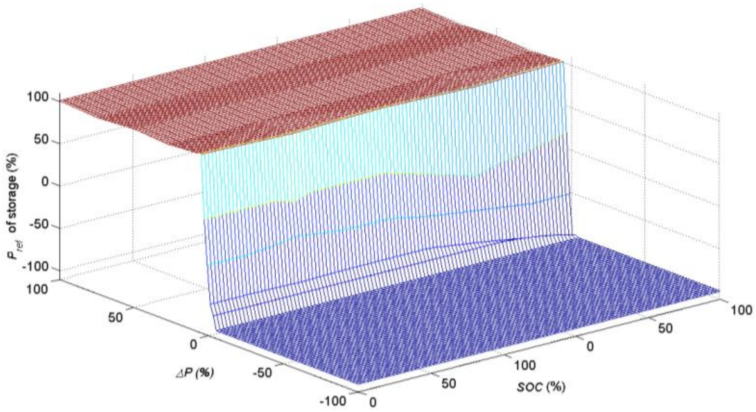


Fig. 14 Generated surface of OPW1 strategy

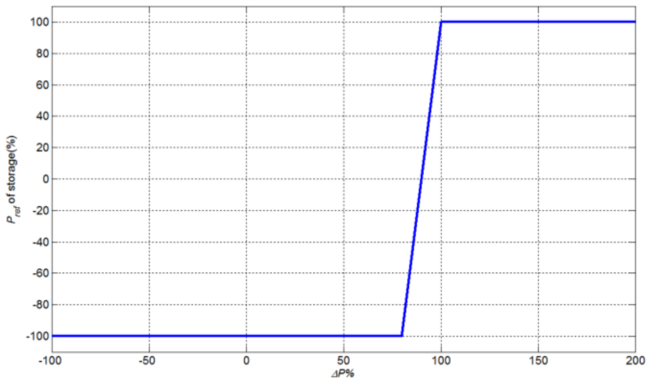


Fig. 15 Curve of OPW2 strategy

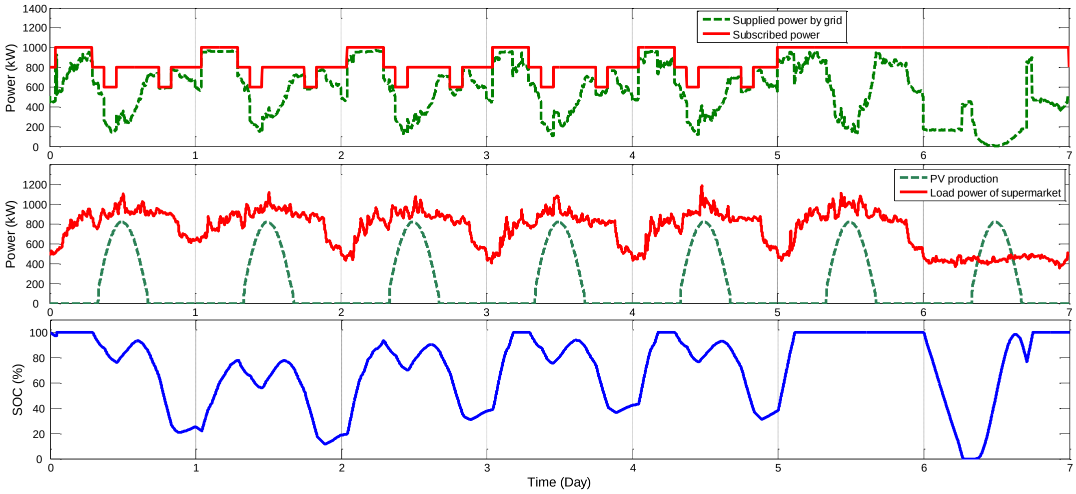


Fig. 16 Simulation results for one week

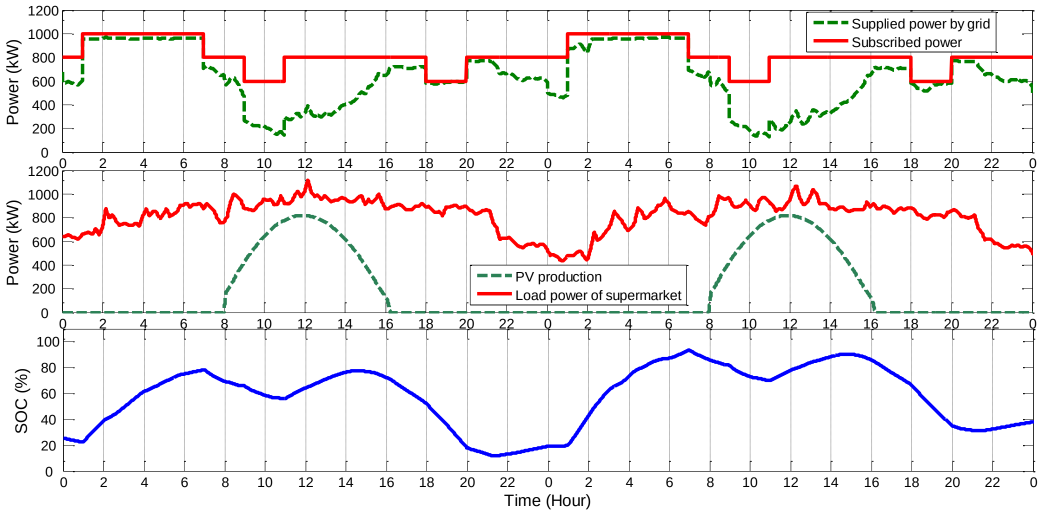


Fig. 17 Zoom of the simulation results for two open days (day 2 and day 3)

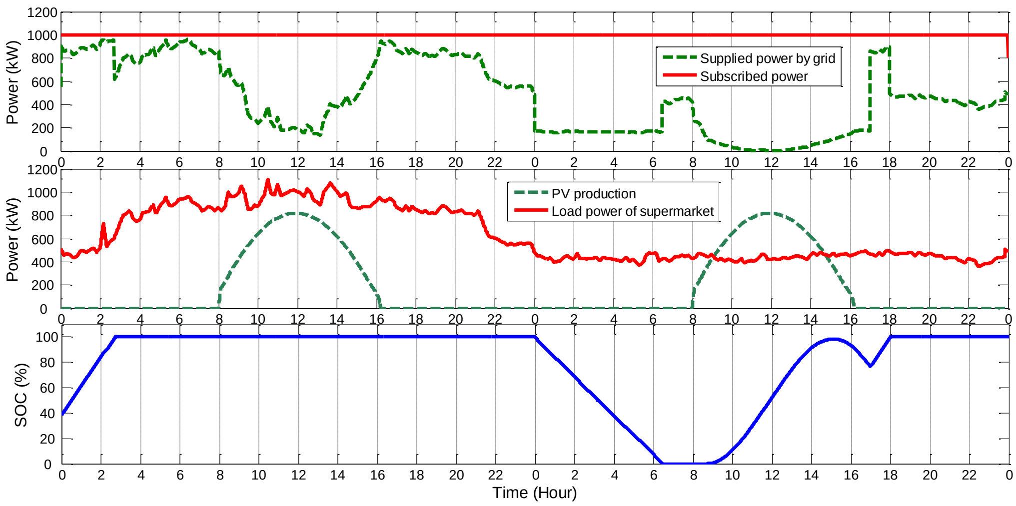


Fig. 18 Zoom of the simulation results for two off-peak days (day 6 and day 7)

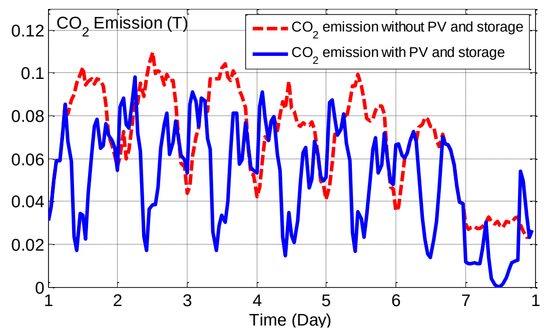


Fig. 19 Comparison of CO_2 emissions