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Abstract: This paper presents a tool for managing a system of multi-sources with a reduced cost and a low CO_2 emission and to facilitate to integrate renewable energy. Two scenarios for the hybrid PV-wind system in "Perpignan Méditerranée" with four strategies of back-up electricity power are studied. The objective is dial to a technical – economical and environmental analysis with satisfying the electricity demand.

Keywords: Energy management, renewable energy, back-up power, virtual power plant.

1. Introduction

Nowadays in France, the nuclear energy includes the 78.3% of electricity generation, far above the EU-27 average (31%). In 2004, the 59 installed nuclear power plants produced more than 115 Mtoe of nuclear energy, about 43% higher than in 1990. The share of renewable sources, mainly hydro generation, in electricity slightly is around 10%. Electricity generation in France increased by 36% over the 1990-2004 period [1]. In the energy policy, two major objectives are promoting both energy savings and renewable energy. Mankind's traditional uses of wind, water, and solar energy are widespread in some countries, but the mass production of electricity using renewable energy sources, allowing reducing gas emissions, has become more commonplace recently, reflecting the major threats of climate change and fossil fuels exhaustion.

The present work takes place in a global development of robust and reliable tools for managing energy sources, reducing energy consumption and promoting renewable energy.

This paper starts by showing the forecasting data of hourly electric load, solar irradiance and wind speed for one day ahead. The electricity price on the PowerNext market [2] is used for two days from June 27th-28th, 2006. Let us note that June 28, 2006 was a typical day about energy consumption, that is why the present paper focuses on managing energy sources for the "Perpignan Méditerranée" agglomeration community on this day. The mathematical model of the components, followed by the description of the objective functions, the basic concepts and the collection of data for the model parameters. Finally, the results of four strategies to satisfy the electricity demand are shown.

The proposed tool is dedicated to the management of the existing and future energy production systems of the "Perpignan Méditerranée" agglomeration community. The city of Perpignan is located in southern France, near the border with Spain, and enjoys a typical Mediterranean climate. The agglomeration community is about 250000 inhabitants.

2. Database

Perpignan's hourly average wind speed, solar irradiance and electric load during years 1997 to 2006 allowed developing forecasting tools, based on artificial neural networks and wavelet-based multi-resolution analysis [3,4,5]. Data used for the present study were provided by the just-mentioned tools. Electricity price given by PowerNext for June 27 and June 28, 2006 were used. Both electricity price and forecasted data are shown in tables A1 and A2 (Apendix), respectively.

3. Scenarios & strategies

We propose two scenarios: an actual scenario and a future scenario (Table 1). The only difference between the two scenarios deals with the sizing of the considered energy production systems. The nominal powers of wind turbines are 7.4 MW and 127 MW respectively. 5400 m^2 and 120ha of PV solar panels are installed, respectively. The "Grenelle 2015" [6] plans the construction of about 120 MW of wind turbines and more than

100ha of PV solar panels for the "Perpignan Méditerranée" agglomeration community.

Table 1. Scenarios about wind/PV installations.

Scenario	*Actual*		*Future*	
	Wind turbine	*PV*	*Wind turbine*	*PV*
P_{ins} (S_{ins})	7.4×10^3 kW	5.4×10^3 m^2	1.27×10^5 kW	1.2×10^5 m^2
η_g	21%	14.1%	21%	14.1%
η_c	95%	95%	95%	95%

where P_{ins} is the total power (kW) for wind turbines, S_{ins} is the total area of PV solar panels, η_g is the efficiency of the generator and η_c the efficiency of the inverter. Let us note that 80% and 40% of the daily energy consumed is provided by nuclear plants for the actual and future scenarios respectively. Four strategies are proposed:

- *Strategy 1:* buying energy tomorrow, to meet tomorrow's back-up requirements, according to the hourly price given by PowerNext Spot Auction,
- *Strategy 2:* using diesel generators tomorrow to meet tomorrow's back-up requirements,
- *Strategy 3:* buying energy today at the lowest price, according to the hourly price given by PowerNext Spot Auction, to meet tomorrow's back-up requirements and stocking energy in battery tanks,
- *Strategy 4:* buying energy today at the lowest price, according to the hourly price given by PowerNext Spot Auction, to meet tomorrow's back-up requirements, electrolyzing and stocking H_2, using H_2 fuel cells.

4. Mathematical models

4.1 Wind turbines

The energy production of a wind generator is expressed in terms of wind speed. These are many mathematical models used in wind power studies. The average power produced by a wind generator given in [7], as:

$$Pw = \int_{V_{in}}^{V_{out}} P(v) f(v) dv \quad (1)$$

with: V_{in} the wind speed when the electricity production starts [m/s], V_{out} the wind speed when the electricity production ends [m/s], P(v) the wind generator's power curve (given by the manufacturer) and f(v) the weibull probability density function.

In this paper, a Nordex wind generator is used. Many wind generators of this type are installed at the city of Rivesaltes, about 10 km from Perpignan. The characteristics of those generators (power production according to wind speed) are supplied by the manufacturer, considering wind generator of type N60/1300 (Nordex) [8]. So, the average power [W] produced by a wind generator is:

$$P_w = \begin{cases} (A) 0.0538v^4 - 3.5973v^3 + 73.4533v^2 \\ -443.4775v + 853.5148, if\ 4 \le v \le 17 \\ (B) 0, if\ v < 4 \\ (C) 0.2031v^4 - 17.4593v^3 + 560.2264v^2 \\ -7956.5v + 43533, if\ 17 < v \le 25 \\ (D) 0, if\ v > 25 \end{cases} \quad (2)$$

where v is the average wind speed [m/s].

4.2 PV generators

The PV modules which are composed of many solar cells are integrated to form solar array. The hourly energy generated (E_{pv}, kWh) from the PV system is calculated using the equation [9]:

$$E_{pv} = S \eta_m P_f \eta_{pc} I \quad (3)$$

with: S is the array area in m^2, η_m is the module conversion efficiency ($\eta_m = 0.141$), Pf is the packing factor ($Pf = 0.9$), η_{pc} is the power conditioning efficiency ($\eta_{pc} = 0.95$) and I is the hourly irradiance (kWh/m^2). The PV modules NU185E1 (Sharp) are used for this calculation. The details related to this module parameters are provided in [10].

4.3. Hydrogen production & storage

Depending mainly on the production capability of the plant and of the country where the alkaline electrolysis is implemented, the estimation of the cost of the hydrogen produced will vary between 1.6 €/kgH_2 and 5 €/kgH_2 [11]. A study carried out by the French CEA (Commissariat à l'Energie Atomique) deals with the cost of producing hydrogen by alkaline electrolysis in four countries (Iceland, France, Norway and USA). So, the production cost of 1 kg of hydrogen (including compression and storage) is [11]:

$$C_{H2} = 0.3H^{-0.23} + 0.37H^{-0.025} + 52.2C_P \quad (4)$$

where C_{H2} is the average hydrogen generation cost [€/kg.H_2], H is the production capacity of the plant [kg/s] and C_P is the electricity price [€/kWh]. The first part of the equation is maintenance cost, second part is capital cost and the last is electricity cost. The equation is valid for a production rate between 0.1 kgH_2/s and 1.2kgH_2/s. For the present study, we use equation (4) for the actual scenario. The cost of hydrogen production will be reduced in the future, so the cost for producing 1kg of hydrogen for the future scenario is 0.4xC_{H2}. Let us note that one way to produce hydrogen without CO_2 emissions is to electrolyze water. Indeed, if the electricity source used to power the electrolyzer does not generate CO_2, then the entire cycle of energy production and consumption can be free of greenhouse gas generation.

4.4. Hydrogen fuel cells

Acquisition, Operation and Maintenance (O&M) costs of fuel cells depend on the technology used, the manufacturer, and functioning conditions. According to [12], for the different technological types of stationary fuel cell, acquisition costs vary between 1300 and 1500 $/kW, and fixed O&M costs can be from 8 to 30 $/kW/year, while variable O&M costs are between 1.4 and 2.5 $/MWh. Taking into account about 1000 h/year of working at full capacity, O&M costs for each electrical power kWh would be between 0.0094 and 0.0325 $/kWh. Useful lifetime for stationary units is about 40.000 h.

For this study, the capital cost of fuel cell is so 1300€/kW for the actual scenario and 350€/kW for the future scenario [12]. The O&M cost is 0.012 €/kWh, lifetime station units is about 40.000 h while the maximum efficiency rate is 0.45 for both scenarios. The hydrogen consumed by fuel cells, F_{H2} (kg/h), is modeled as dependent on the output power [13]:

$$if\ P/P_{N\_FC} \le P_{max\_ef}: \quad (5)$$
$$F_{H_2} = B_{FC} \cdot P_{N\_FC} + A_{FC} \cdot P_{FC}$$
$$if\ P/P_{N\_FC} > P_{max\_ef}: \quad (6)$$
$$F_{H_2} = B_{FC} \cdot P_{N\_FC} + A_{FC} \cdot P_{FC} \cdot \left(1 + F_{ef}\left(\frac{P}{P_{N\_FC}} - P_{\max\_ef}\right)\right)$$

where P_{FC} is the output power of the fuel cell (kW), P_{N_FC} (kW) is the nominal output power of the fuel cell, A_{FC} and B_{FC} are the coefficients of the consumption curve (kg/kWh), P_{max_ef} (% of P_{N_FC}) is the fuel cell output power that has the maximum efficiency and F_{ef} is the fuel cell consumption factor to consider the high consumption above P_{max_ef}. The efficiency of the Low Heating Value of hydrogen LHV_{H2} is calculated using equation 7:

$$\eta_{FC\%} = \frac{100P}{F_{H2} LHV_{H2}} \quad (7)$$

where LHV_{H2} = 33.3 kWh/kg, A_{FC} = 0.05 kg/kWh, B_{FC} = 0.004 kg/kWh, P_{max_ef} = 0.2 and F_{ef} = 1.

4.5. Diesel generators

The use of diesel generator is common in many hybrid combinations to ensure supply continuity. For an interval, the rate of fuel (F), consumed by the diesel generator delivering a power (P), is expressed as follows [14]:

$$F = a.P^2 + b.P + c \quad (8)$$

where a, b, c are the coefficients of the diesel generator, obtained from the manufacturers' data. The considered values are: a = 12.202×10^{-6} l/kWh, b = 0.223 l/kWh, c = 40.706 l/kWh.

The heavy fuel oil price is 0.11€/l (150$US/ton [15]) for the actual scenario and 0.20€/l for the future scenario. CO_2 emissions are 3.09 kgCO_2/l. The capital cost of a diesel generator is 300€/kW while O&M cost is 0.0025 €/kWh. The running hour is about 7000 hours per years and lifecycles are 20 years for both scenarios.

4.6. Battery bank

The simple battery model used for the hybrid model is expressed by [16]. In this model, the hourly state, at hour t, of a battery unit is depicted as a function of its precedent state, at hour (t-1), of the charge and of the renewable energy produced at hour (t). In case of batteries charge, the state can be calculated as follows:

$$E_{bat}(t) = E_{bat}(t-1) + \left(E_G(t) - \frac{E_L(t)}{\eta_r}\right)\eta_{bat,ch} \quad (9)$$

In case of batteries discharge, the state can be calculated as follows:

$$E_{bat}(t) = E_{bat}(t-1) + \left(\frac{E_L(t)}{\eta_r} - E_G(t)\right)\eta_{bat,dch} \quad (10)$$

where η_r is efficiency of rectifier (0.90), $\eta_{bat,ch}$ is the charge efficiency of batteries (0.80), $\eta_{bat,dch}$ is the discharge efficiency of batteries (0.85), $E_L(t)$ is the demand energy of charge (consumption) at an hour t, $E_{bat}(t)$ and $E_{bat}(t-1)$ are the energy storage in the bank of batteries at an hour t and at an hour t-1, respectively, E_G(t) is the total energy supply at hour t. The self-discharge factor of battery is equal 0. In case of dimension, the capacitor of battery bank is equal to 1.2xE_{max_bat}, where E_{max_bat} is the maximum of E_{bat}.

A lead-acid battery power plant has currently the lowest battery cost at around $150/kWh because it has been the longest and most fully developed battery technology. The battery cost is projected to reduce to \$100/kWh in the future [17]. In this study, the capital cost of battery is 100€/kWh for the actual scenario and 60€/kWh for the future scenario. The O&M cost is 0.0012 €/kWh. Lifecycle of a battery is about 20 years or 8000 cycles of charge/discharge for both scenarios.

4.7 Inverters & Rectifiers

The inverter cost is 250€/kW nominal power (commercial data). The lifespan is 10 years; the efficiency depends on the output power. O&M cost is included in each system.

There is no inverter added for both strategies 1 and 2 but there is one for strategies 3 and 4. The efficiency depends on the output power:

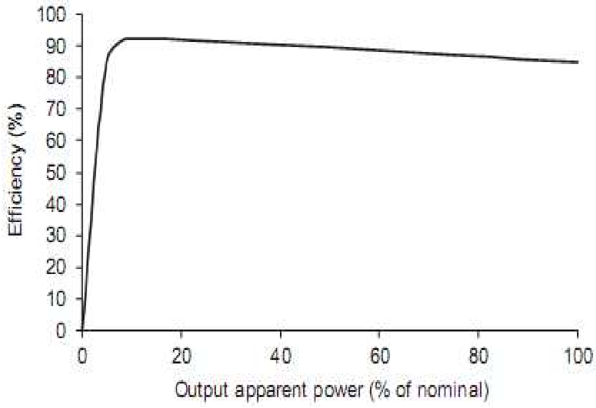

Fig. 1. Inverter efficiency curve.

The rectifier is selected for strategies 3 and 4. For strategies 1 and 2, there is no rectifier added. The cost of the rectifiers is 120€/kW, the lifetime is 10 years, and the efficiency is 0.9. O&M cost is included in the system. For the actual scenario, the price of inverter and rectifier are as just-mentioned. For the future scenario, prices are half.

5. Results and discussion

5.1. Actual scenario

Fig. 2 shows the hourly electric load and supply during the next day (24h). Power is supplied by three energy sources: nuclear energy (80% of the daily load), wind energy and PV solar energy. In this scenario, the supplied power does not satisfy the load. Fig. 3 shows both hourly excess and unmet powers during June 28, 2006. Excess power will be sold on the PowerNext market.

Table 2 shows, considering the four previously-defined strategies, the total cost for back-up power and CO_2 emissions for June 28, 2006. Considering the actual scenario, applying the first strategy leads to the lowest energy cost and there are no CO_2 emissions (let us note that CO_2 emissions are only related to both the backup and production systems of the "Perpignan Méditerranée" agglomeration community; when electricity is bought, no emissions are considered). In the other hand, applying the second strategy leads to very high CO_2 emissions while applying the third strategy leads to the biggest energy cost.

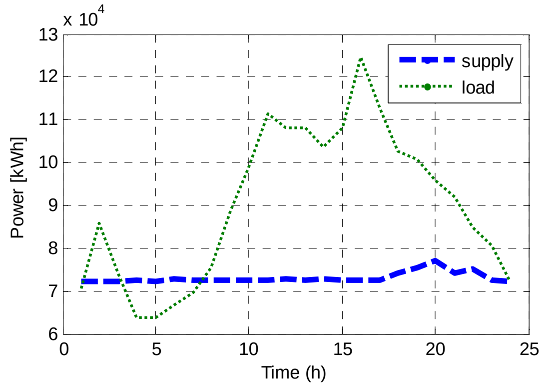

Fig. 2. Hourly electric load and supply in the next day.

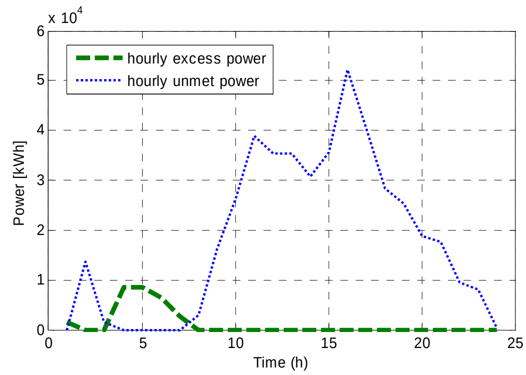

Fig. 3. Hourly overall and unmet power in the next day.

Table. 2. Costs & CO_2 emissions (actual scenario).

Strategy	*Cost (€)*	*CO_2 (kg)*
Strategy 1	*23302.86*	*0*
Strategy 2	*31616.44*	*1.35×10^6*
Strategy 3	*64026.79*	*0*
Strategy 4	*37525.95*	*0*

5.2. Future scenario

Fig. 4. shows the hourly electric load and supply during the next day (24h). Considering this scenario, the supplied power is higher than it was for the actual scenario, due to a higher both number of wind turbines and PV area, even if the nuclear power is decreased (only 40% of the daily energy consumed is provided by nuclear plants for this scenario).

Fig. 5 shows both hourly excess and unmet powers during June 28, 2006. Excess power will be sold on the PowerNext market. Table 3 shows, considering the four previously-defined strategies, the total cost for back-up power and CO_2 emissions for the just-mentioned day.

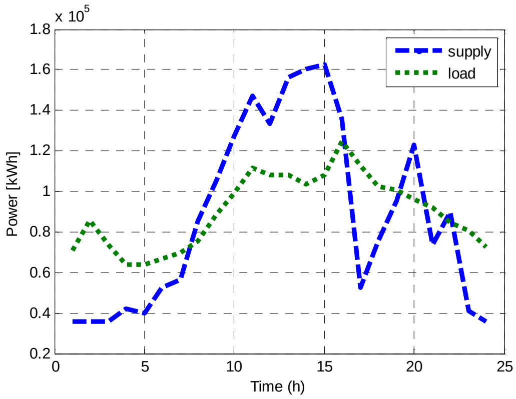

Fig. 4. Hourly electric load and supply in the next day.

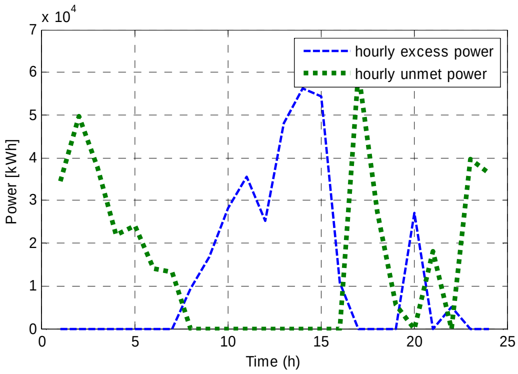

Fig. 5. Hourly overall and unmet power in the next day.

Table. 3. Costs & CO_2 emissions (future scenario).

Strategy	*Cost (€)*	*CO_2 (kg)*
Strategy 1	*13097.86*	*0*
Strategy 2	*53362.18*	*1.18×10^6*
Strategy 3	*32571.43*	*0*
Strategy 4	*11413.04*	*0*

Considering the future scenario, applying the fourth strategy leads to the lowest energy cost, because of a reduction of the capital cost of fuel cells and of hydrogen production, and there are no CO_2 emissions. In the other hand, applying the second strategy leads to both the biggest energy cost and very high CO_2 emissions because of fossil energy cost will increase in the future. Considering both actual future scenarios, the total electricity sold is about 449 € and 18.0 M€ respectively.

6. Conclusion

The present paper deals with several strategies to manage energy resources as well as production and backup systems in a Mediterranean area (the "Perpignan Méditerranée" agglomeration community, south of France). These strategies mainly focus on energy cost and CO_2 emissions. The main conclusion of the work is that, thanks to a good energy strategy, one can implement and manage efficiently renewable energy production and backup systems. As a consequence, one can meet energy demand and limit CO_2 emissions while producing a not too expensive energy. Complementary work deals with the combination of the proposed strategies and the sizing of both the production and backup systems, with the aim of optimizing the energy management. That is why a virtual power plant, including forecast modules about meteorological parameters and electric load, is currently under development.

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Appendix

Table. A1. Hourly electricity price for June 27 and 28, 2006 on PowerNext EpexSpot auction [€/MWh] (France)

Date	Hour1	Hour2	Hour3	Hour4	Hour5	Hour6	Hour7	Hour8	Hour9	Hour10	Hour11	Hour12
28/06/2006	34,00	31,00	27,00	22,00	9,00	29,00	31,00	48,99	51,00	67,91	71,00	79,19
27/06/2006	32,00	27,99	22,01	10,00	10,00	23,10	31,31	42,00	49,74	53,01	60,99	66,58

Date	Hour13	Hour14	Hour15	Hour16	Hour17	Hour18	Hour19	Hour20	Hour21	Hour22	Hour23	Hour24
28/06/2006	74,00	74,00	73,00	70,00	61,00	55,00	54,00	49,00	48,99	46,99	50,01	41,18
27/06/2006	58,00	61,00	59,99	53,78	53,00	48,00	47,99	41,07	41,65	40,39	44,01	36,21

Table. A2. Hourly meteorological parameters and electric load forecasting for June 28, 2006 (Perpignan)

hour	Electric load (MWh)			Solar irradiance (J/cm^2)			Wind speed (m/s)		
	actual	forecast	ab.error	actual	forecast	ab.error	actual	forecast	ab.error
1	71,00	70,60	0,40	0,00	0,00	0,00	2,00	1,95	0,05
2	85,00	85,68	0,68	0,00	0,00	0,00	2,00	1,82	0,18
3	73,00	73,62	0,62	0,00	0,00	0,00	3,00	2,99	0,01
4	64,00	63,85	0,15	0,00	0,00	0,00	5,00	5,05	0,05
5	63,00	63,70	0,70	0,00	0,00	0,00	4,00	4,04	0,04
6	66,00	66,55	0,55	5,00	5,20	0,20	6,00	6,18	0,18
7	69,00	69,62	0,62	41,00	41,19	0,19	4,00	4,02	0,02
8	76,00	75,50	0,50	107,00	106,04	0,96	5,00	5,16	0,16
9	87,00	88,52	1,52	171,00	172,28	1,28	4,00	3,84	0,16
10	97,00	98,80	1,80	230,00	226,66	3,34	3,00	3,12	0,12
11	103,00	111,48	8,48	277,00	276,11	0,89	2,00	2,02	0,02
12	107,00	108,04	1,04	232,00	232,60	0,60	4,00	4,12	0,12
13	109,00	108,04	0,96	299,00	299,03	0,03	4,00	3,89	0,11
14	107,00	103,70	3,30	297,00	294,54	2,46	5,00	5,03	0,03
15	107,00	108,15	1,15	313,00	315,02	2,02	3,00	3,11	0,11
16	123,00	124,77	1,77	250,00	247,75	2,25	3,00	3,03	0,03
17	112,00	112,57	0,57	30,00	31,92	1,92	4,00	4,04	0,04
18	103,00	102,50	0,50	7,00	5,95	1,05	8,00	7,93	0,07
19	100,00	100,60	0,60	5,00	5,01	0,01	9,00	9,26	0,26
20	96,00	95,80	0,20	3,00	2,57	0,43	11,00	11,10	0,10
21	89,00	91,81	2,81	1,00	1,02	0,02	8,00	7,98	0,02
22	84,00	84,70	0,70	0,00	0,00	0,00	9,00	9,04	0,04
23	81,00	80,44	0,56	0,00	0,00	0,00	5,00	4,80	0,20
24	72,00	72,30	0,30	0,00	0,00	0,00	2,00	2,04	0,04

Nota: "ab.error" is the absolute error.