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OPTIMIZED ENERGY MANAGEMENT OF A HYBRID ENERGY PLANT BY USING A METHODOLOGY BASED ON DYNAMIC PROGRAMMING

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ABSTRACT

An optimized energy management strategy of hybrid energy plants can lead to a significant reduction in primary energy consumption. This paper documents the development of a methodology based on dynamic programming for the optimization of the energy management strategy of hybrid energy plants, with the aim of minimizing the primary energy consumption. The validity and capability of the optimization methodology presented in this paper is demonstrated by comparing its results to those obtainable by means of commonly used operation strategies. Moreover, a case study consisting of a thirteen-floors building located in the north of Italy is considered to demonstrate the developed methodology. Compared to a thermal-led operation strategy with a different switch-on priority order of plant components, the proposed methodology allows a primary energy saving between up to about 6.57 %.

Keywords: Dynamic programming, Hybrid energy plant, Energy management optimization, Primary energy consumption

NONMENCLATURE

Abbreviations

AB	auxiliary boiler
ABS	absorption chiller
AC	auxiliary chiller
cool	cooling
CHP	combined heat and power
DP	dynamic programming
el	electrical
GSHP	ground source heat pump
HEP	hybrid energy plant
HWS	hot water storage
PV	photovoltaic panel
SOP	switch-on priority
STC	solar thermal collector
th	thermal
TP	traditional plant

Symbols

COP	coefficient of performance
E	energy
F	function
G	solar radiation
k	time variable
N	Last time step
P	power
PE	Primary energy consumption
T	temperature
U	input or control variable
V	volume
X	state
η	efficiency

1. INTRODUCTION

A reduction of primary energy consumption is usually expected to contribute to increased sustainability of buildings. One of the strategies for reducing primary energy consumption is based on the improvement of the efficiency of Hybrid Energy Plants (HEPs). This result may be achieved through the optimal management of the technologies involved in the energy plant. An optimal energy management of the different HEPs helps to optimize the exploitation of fossil and renewable sources. In order to manage such complex issue, methods and guidelines need to be defined to optimize the energy management strategy of the systems.

A variety of methods has been presented in the literature to solve optimization problems [1]. The most

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prominent is linear programming, which can be only used to solve linear problems [2]. Other classes of optimization methods have been developed and proved to be effective in many applications [3]. Despite the advantages of some of these methods, there are still some disadvantages such as (i) long computational time, (ii) high memory usage and (iii) incapability to address the non-linear characteristics of the HEP [4]. Recently, Dynamic Programming (DP) has attracted lots of research in the area of energy systems [5]. In fact, DP has proved its ability to efficiently deal with linear and non-linear objectives and constraints and obtain global optimal solutions in the discrete state space [6]. Several studies used the DP method to solve energy management and optimal control problems of hybrid energy plants [7, 8]. Compared to other optimization methods, DP algorithm proved to be a preferable method for solving the energy management problem of complex HEPs [9]. This paper introduces a DP based methodology for the optimization of the energy management of HEPS.

2. MATERIALS AND METHODS

The energy management problem is solved by minimizing the energy consumed throughout the year and the analysis is carried out on an hourly basis. A model for the simulation of the HEP is implemented in Matlab®. The variability of the performance of the considered systems according to both external air temperature and load is also taken into account. The analysis is carried out on an hourly basis.

2.1 The hybrid energy plant

Figure 1 shows a scheme of plant layout. The HEP is composed of a solar thermal collector (STC), photovoltaic panel (PV), combined heat and power (CHP), ground source heat pump (GSHP), absorption chiller (ABS) and hot water storage (HWS). Moreover, a condensing boiler (AB) and a chiller (AC) are used as auxiliary systems.

As can be seen from Fig 1, the thermal demand for space heating and hot water can be met by the STC, CHP and GSHP, the cooling demand can be fulfilled by the ABS and GSHP, while the electricity energy demand can be met by the PV and CHP. In case the energy demands are not met by these systems, the AB ensure the fulfillment of the thermal demand, the AC ensure the fulfillment of the cooling demand, while the remaining electric energy demand is imported from the grid. Moreover, any excess of electricity, produced from the CHP and PV, is sent to the grid.

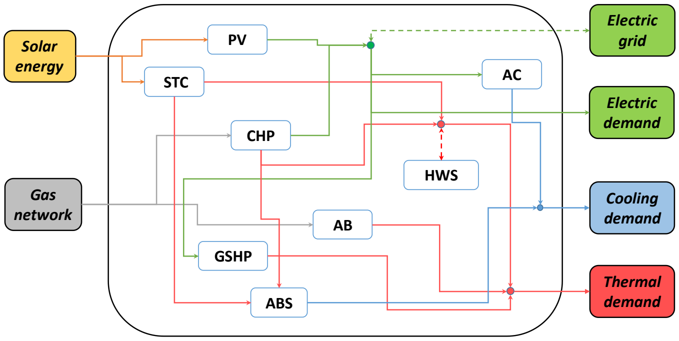

Fig 1 Schematic diagram of the HEP

2.2 Optimization model

In this paper, a solver developed by Sundstrom and Guzzella [10] and implemented in Matlab® is used to solve the optimization problem. The developed solver deals with discrete-time optimal-control problems using Bellman's DP algorithm. The formulation of the optimization problem requires a state-space representation of the model as follows:

$$X_{s,k+1} = F(X_{s,k}, U_{s,k}, k) \qquad (1)$$

$$E_{s,k} = Z(X_{s,k}, U_{s,k}, k) \qquad (2)$$

where *X* represents the state variables, *U* the input variables and *E* the output variables of the technology *s* at time step k.

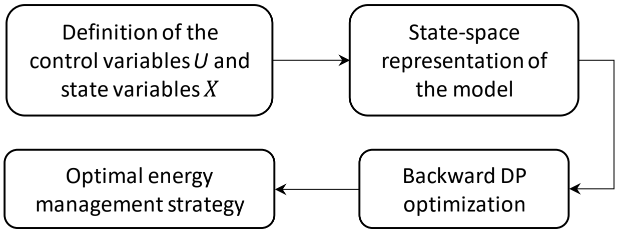

Fig 2 Optimization flowchart of the DP method

As highlighted in Fig. 2, the first step of the optimization method consists of the definition of the control and state variables, then the problem must be formulated in the state-space representation. The optimization problem is solved by constructing a sequence of interrelated decisions called "backward DP optimization". In other words, the DP algorithm divides the original problem into simple sequences of problems and finds the optimal solution to these sub-problems. When the entire problem is solved, the optimal energy management strategy can be found by tracking back the optimal solution which were found for the small problems.

2.3 State-space representation model

In this work, two states are identified, X_{CHP} and X_{HWS}, corresponding to the CHP and HWS, respectively:

$$X_{\mathrm{CHP},k+1} = \begin{cases} 1 & \text{if} \quad U_{\mathrm{CHP},k} \neq 0 \\ 0 & \text{if} \quad U_{\mathrm{CHP},k} = 0 \end{cases} \qquad (3)$$

$$X_{\mathrm{HWS},k+1} = (1 - c_{\mathrm{diss}}) \cdot (X_{\mathrm{HWS},k} + E_{\mathrm{HWS,th,in},k} - E_{\mathrm{HWS,th,out},k}) \qquad (4)$$

Where X_{CHP} represents the on-off condition of the CHP at the beginning of the k-th time step, while X_{HWS} represents the storage state of charge.

In order to control the HEP, four input variables U_{CHP}, U_{GSHP}, U_{ABS} and U_{HWS} are identified. These are defined as the fraction of maximum energy output of the CHP, GSHP, ABS and HWS. The thermal and electrical energy output of the CHP system are calculated as follows:

$$E_{\mathrm{CHP,th},k} = U_{\mathrm{CHP},k} \cdot P_{\mathrm{CHP,th,max},k} \cdot \Delta k \qquad (5)$$

$$E_{\mathrm{CHP,el},k} = \eta_{\mathrm{CHP,el}}(U_{\mathrm{CHP}}, k) \cdot \frac{E_{\mathrm{CHP,th}}(U_{\mathrm{CHP}}, k)}{\eta_{\mathrm{CHP,th}}(U_{\mathrm{CHP}}, T_k, k)} \qquad (6)$$

For the GSHP, the output thermal/cooling energy and the consumed electric energy are represented by the following equations:

$$E_{\mathrm{GSHP,th/cool},k} = U_{\mathrm{GSHP,k}} \cdot P_{\mathrm{GSHP,th/cool,max},k} \cdot \Delta k \qquad (7)$$

$$E_{\mathrm{GSHP,el},k} = \frac{E_{\mathrm{GSHP,th/cool}}(U_{\mathrm{GSHP}}, k)}{COP_{\mathrm{GSHP,th/cool}}(U_{\mathrm{GSHP}}, T_k, k)} \qquad (8)$$

The cooling energy produced by the ABS is calculated as follows:

$$E_{\mathrm{ABS,cool},k} = U_{\mathrm{ABS,k}} \cdot P_{\mathrm{ABS,cool,max},k} \cdot \Delta k \qquad (9)$$

Moreover, the thermal energy taken form the storage is represented as follows:

$$E_{\mathrm{HWS,th,out},k} = U_{\mathrm{HWS},k} \cdot X_{\mathrm{HWS},k} \qquad (10)$$

Finally, the thermal energy and electric energy produced by the STC and the PV systems, are calculated by Eq. (11) and Eq. (12), respectively:

$$E_{\mathrm{STC,th},k} = G_k \cdot A_{\mathrm{STC}} \cdot \eta_{\mathrm{STC},k} \cdot \Delta k \qquad (11)$$

$$E_{\mathrm{PV,th},k} = G_k \cdot A_{\mathrm{PV}} \cdot \eta_{\mathrm{PV},k} \cdot \Delta k \qquad (12)$$

Where G is the solar radiation expressed in [W/m^2].

The primary energy consumed throughout the simulation period is defined as follows:

$$PE = \sum_{k=1}^{N} PE_{\mathrm{fuel,CHP},k} + PE_{\mathrm{fuel,AB},k} + PE_{E_{\mathrm{el,taken}k}} - PE_{E_{\mathrm{el,sent}k}} \qquad (13)$$

2.4 Case study

A thirteen-floor building planned for commercial and office use in the north of Italy is considered as a case study. The thermal and electrical energy demands of a typical winter day and the cooling energy demand of a typical summer day are shown in Fig. 3.

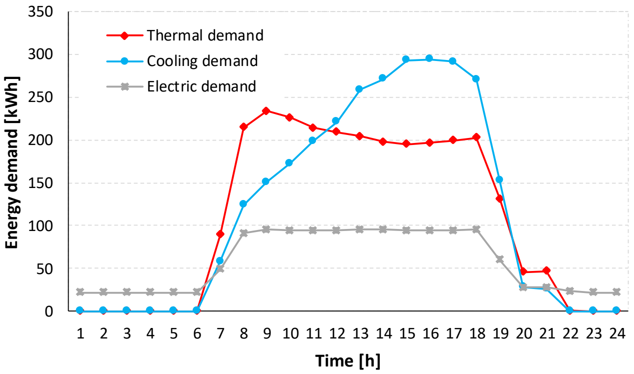

Fig 3 Hourly thermal, cooling and electric enregy demands

It should be mentioned that the sizes of the HEP plant components are obtained from [11]. The air source heat pump considered in [11] is not included in this work because its size is lower than 10 % of the GSHP size. The sizes of the different technologies are summarized in Table 1.

Table 1 Sizes of the HEP components

Component	size	value
PV	A_{PV} [m^2]	209
STC	A_{STC} [m^2]	119
CHP	$P_{\mathrm{el,CHP,nom}}$ [kW$_{\mathrm{e}}$]	100
GSHP	$P_{\mathrm{th/cool,GSHP,nom}}$ [kW$_{\mathrm{th}}$/ kW$_{\mathrm{c}}$]	242/198
ABS	$P_{\mathrm{cool,ABS,nom}}$ [kW$_{\mathrm{c}}$]	109
HWS	V_{HWS} [l]	1180

2.5 Results

In order to demonstrate the effectiveness of the proposed methodology, the results obtained by the DP method are compared to commonly used operation strategies. In particular, six Switch-on priority (SOP) energy management strategies are used as benchmarks [10]:

- SOP 1: STC, HWS, CHP, GSHP;
- SOP 2: STC, HWS, GSHP, CHP;
- SOP 3: STC, GSHP, HWS, CHP.

For SOP 1, 2 and 3, during summer, the ABS is activated first, followed by the reversible GSHP. SOP 4, 5 and 6 are equal to SOP 1, 2 and 3, respectively, but during summer the GSHP is activated first, followed by the ABS.

From the analysis of Table 2 it can be noted that the achievable primary energy saving ranges from about 0.34 % (compared to SOP 4) to 6.57 % (compared to SOP 3).

Table 2 Primary energy consumption for DP and SOP methods

	DP	SOP		
PE [MWh/year]	1091.8	(SOP 1) 1112.6	(SOP 2) 1115.1	(SOP 3) 1168.6
		(SOP 4) 1095.5	(SOP 5) 1098.0	(SOP 6) 1151.5

Therefore, the DP method always allows better results in terms of primary energy saving compared to commonly used energy management strategies. Since the SOP 3 strategy represents the worst case, Figures 4 and 5 highlight the comparison against the DP-optimized strategy. As can be noted from Fig 4, when adopting the SOP 3 strategy, almost the whole thermal energy demand is fulfilled by the GSHP, while the energy available in the storage is unused. Instead, the DP algorithm directly meets the thermal demand by the CHP system storing any excess.

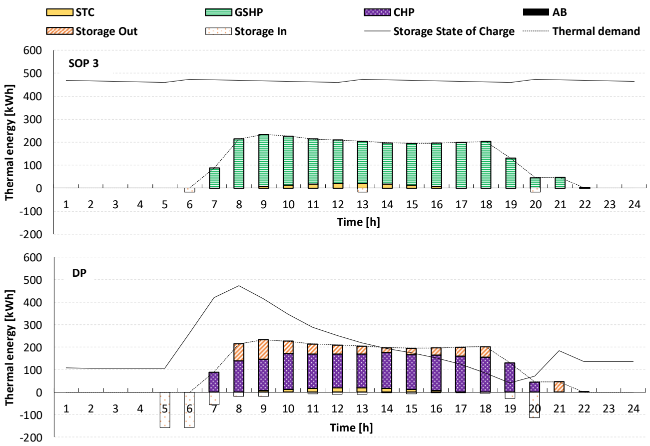

Fig 4 Thermal energy production on a winter day

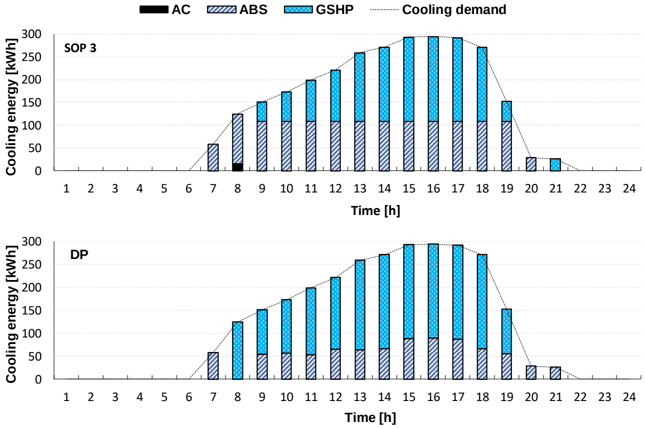

Fig 5 Cooling energy production on a summer day

Moreover, the amount of energy in the storage is always lower than in case of the SOP 3. Indeed, since the thermal energy exchanged with the atmosphere through storage is proportional to the amount of stored energy, the DP method reduces the thermal dissipation by reducing the amount of energy kept in the storage. Regarding the operation during summer (Fig. 5), unlike the SOP 3 strategy, the DP strategy operates the GSHP at nominal loads and consequently at higher performance, while the remaining cooling energy is met by the ABS.

2.6 Conclusions

This study investigated the application of a method based on dynamic programming to optimize the energy management a hybrid energy plant. The results of the methodology were compared to those obtainable by means of other six commonly used energy management strategies. The results showed that, the optimization method developed in this paper allowed primary energy saving between 0.34 and 6.57 %.

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