OPTIMAL SIZING OF A HYBRID COOLING SYSTEM

Farah Kojok[a], Rachid Outbib[b], Oussama Ibrahim[c], Rafic Younes[d], Farouk Fardoun[e]

[a],[b] LSIS- Aix-Marseille University - Domaine Universitaire de Saint-Jérôme, Av. Escadrille Normandie-Niemen, 13397 Marseille Cedex 20, France
[c], [d] Department of Mechanical Engineering, Lebanese University, Beirut, Lebanon
[d] LISV Laboratory, Versailles Saint Quentin University, Versailles, France
[e] University Institute of Technology, Department GIM, Lebanese University Campus, P.O. Box 813, Saida, Lebanon

[a] farahkojok2579@hotmail.com, [b] rachid.outbib@lsis.org , [c] oibrahimul@hotmail.com ,
[d] ryounes@ul.edu.lb, [e] fardoun2@yahoo.com

Abstract

The aim of this work is to propose an optimal sizing method for a hybrid cooling system with minimum energy consumption and maximum share of renewable resources. For this purpose, a hybrid cooling system that benefits from renewable energy resources is designed and modeled using Trnsys 17. Then, an optimal sizing method where the problematic is formalized as a mathematical problem under constraints is presented. Finally, the results are obtained and discussed for the two case studies selected, namely Marseilles-France and Beirut-Lebanon.

Keywords: hybrid cooling, optimal sizing, energy management, renewable energy, grid electricity.

1. INTRODUCTION

The demand for cooling is dramatically increasing due to the climate change and the global temperature rise. However, cooling systems are a matter of debate, not only due to the high-energy consumption, but also due to the excessive CO2 emissions as well as the use of synthetic refrigerants that produce greenhouse effect and cause global warming. Therefore, energy efficient cooling systems are key contributors to the reduction of the electrical energy consumption. Solar cooling is one of the energy saving cooling technologies used all over the world. Moreover, and due to the variability of these local energy sources, hybridization in sources and storage systems is to be considered to get new solutions for energy production and hence meet the needs (Poulet and Outbib 2015). Actually, hybrid cooling technology could lead to a great energy saving and COP improvement by more than 50% (Kairouani and Nehdi 2006). However, the improvement achieved by a hybrid cooling system vary widely. It depends on the system design and the way the different types of energy are used. Further, it is found that in some cases, individual cooling systems are more effective than hybrid systems. For instance, in very hot and arid climate, the removal of latent load separately by desiccant system becomes unnecessary, and thus, the comfort level could be reached using an electric or absorption chiller standing alone (Kojok, Fardoun, Younes and Outbib 2016)).

In this work, an optimal sizing method that defines, in a specific region, a hybrid cooling energy system, economically feasible with maximum renewable energy share is presented. The method tends to minimize the dependency of the cooling system on grid electricity and to reduce the nonrenewable energy consumption. Based on the above, a hybrid cooling system, used for a small residential house, is designed and presented in the first section. After that, an optimal sizing method is proposed in section two. The main purpose is to determine, for a given region of the world, a cooling system with minimum energy consumption and maximum share of renewable resources. More precisely, once a hybrid technology is adopted, the main purpose is to define an optimal size taking into consideration a certain number of inherent constraints that could be the energy potential, the financial costs of the system designed and the area available in a building to install the said system. For this purpose, a residential hybrid cooling system that benefits from renewable energy resources is designed and modeled using Trnsys 17. The system,

schematized in figure 1, mainly consists of a solar absorption chiller (AC) , a vapor compression chiller (VCC), a solid desiccant system (DSC), two evacuated tube solar thermal collectors (ET) , two hot water storage tanks (HW) and a chilled water storage tank (CHW), a wind turbine (WT) , a Photovoltaic cell (PV) and batteries with inverter for electric storage the batteries that satisfy the maximum energy output of both WT and PV.
This designed cooling system is used to ensure the cooling need of a standard small house. The total cooling load is separated into its two components ;the sensible load that is related to the dry bulb temperature and the latent load that is related to the wet bulb temperature or the relative humidity. Each load is treated separately by using separate components of the hybrid system. The desiccant dehumidifier component is used to meet the latent load, while chiller components are utilized to meet the sensible load and excess latent load, if found.This strategy of separating both kinds of loads has been proved to be an efficient energy-saving method since it raises the evaporator temperature in the sensible cooling machine (Ling, Kuwabara, Hwang and Radermacher 2013) and (Ling, Kuwabara, Hwang and Radermacher 2011).
In addition, a solid type desiccant is used because it is preferred to a liquid type one, especially for residential applications, due to the simplicity of its structure and its common regeneration by a thermal solar energy source (Ge,Dai and Wang 2014). Concerning the control method of the system, If the solar absorption chiller is not able to meet the chilled water need, then the electric vapor compression chiller starts operating, where its electricity need is secured from the electrical energy renewable energy systems, PV cells, wind turbines and batteries, if stuffiest. Else, grid electricity is utilized. As for the desiccant system, it starts operation when the relative humidity in the house is greater than the relative humidity set point RH_h^{sp} and the desiccant material is regenerated by solar thermal energy stored in the hot water tank water HW2. After being dehumidified in the desiccant wheel, the process air is cooled by the chilled water through a water-to-air heat exchanger (HX) before passing into the house.

2. OPTIMAL SIZING METHOD

This section presents the optimal sizing method applicable to the hybrid cooling system defined in the previous section to define the best configuration from energetic and economic standpoints. At the end of the optimization problem, the number of renewable energy systems and cooling machines for the best configuration hybrid system is defined. Hence, for this hybrid system, the energetic objective aims to minimize the total grid-electrical energy consumption and consequently maximize the renewable energy share. The economic objective aims to obtain a positive net present value (NPV) for the proposed system, which is also greater than that of conventional electric vapor compression chiller over a pre-specified period.

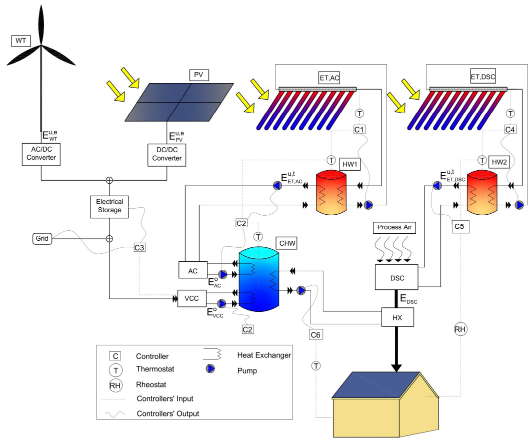

Figure 1: Schematic representation of the proposed residential hybrid cooling system

The optimal sizing method is based on the concept of simulating the proposed hybrid cooling system using small base-units for the renewable energy components, solar and wind systems: PV cell, wind turbine, evacuated tube solar collector connected to hot water storage tank for both absorption chiller and desiccant system. Note that, the evacuated tube solar collector connected to hot water storage tank is considered as one unit. These base units are supposed to produce their maximum possible energy during the studied period of time. Thus, a multiple of a base unit would multiply its maximum energy output for the same climatic and boundary conditions. Results of the sizing problem should then find the appropriate number of individual renewable base units where the number is limited to a maximum value. This method has been first proposed in (Ibrahim, Fardoun, Younes and Louahlia-Gualous 2014). However, in this study, another application is investigated and another formulation and problem solution are presented.

2.1. Objective function

The objective function is determined according to the following demonstration.
The following equations represent the relations between input and output energies (E^i *and* E^o) of each of the absorption chiller, the vapor compression chiller and the desiccant wheel are presented as

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follow, as well as the energy produced by renwable energy systems ($E^{u,t}_{ET,AC}$, $E^{u,t}_{ET,DSC}$, $E^{u,e}_{PV}$, $E^{u,e}_{WT}$) and electrical energy from grid E_{grid}.

$$E^{o}_{AC} = COP_{AC}\, E^{i}_{AC} = COP_{AC}\, N^{AC}_{ET}\, E^{u,t}_{ET,AC} \quad (1)$$

$$E^{o}_{VCC} = COP_{VCC}\, E^{i}_{VCC} = COP_{VCC}\left(N_{PV}E^{u,e}_{PV} + N_{WT}E^{u,e}_{WT} + E_{grid}\right) \quad (2)$$

$$E^{o}_{DSC} = COP_{DSC}\, E^{i}_{DSC} = COP_{DSC}\, N^{DSC}_{ET}\, E^{u,t}_{ET,DSC} \quad (3)$$

Where N and COP are the number and the coefficient of performance of each unit.
The hybrid system should meet the total cooling load (E_L) of the house. Hence, this constraint is presented in equation (4).

$$E^{o}_{AC} + E^{o}_{VCC} + E^{o}_{DSC} \geq E_L \quad (4)$$

Using equations (1) to (4), the following equation is obtained:

$$COP_{VCC}\left(N_{PV}E^{u,e}_{PV} + N_{WT}E^{u,e}_{WT} + E_{grid}\right) + COP_{AC}\, N^{AC}_{ET}\, E^{u,t}_{ET,AC} + COP_{DSC}\, N^{DSC}_{ET}\, E^{u,t}_{ET,DSC} \geq E_L \quad (5)$$

Hence, equation (5) could be reformulated to give equation (6):

$$E_{grid} \geq \frac{E_L}{COP_{VCC}} - \left(\frac{COP_{AC}}{COP_{VCC}} N^{AC}_{ET}\, E^{u,t}_{ET,AC} + \frac{COP_{DSC}}{COP_{VCC}} N^{DSC}_{ET}\, E^{u,t}_{ET,DSC} + N_{PV}E^{u,e}_{PV} + N_{WT}E^{u,e}_{WT}\right) \quad (6)$$

The second term of the right part of equation (6) represents the total renewable energy share of the hybrid system and maximizing this term will minimize the grid electricity consumption as it is obvious from this equation. Therefore, the objective function stated in equation (7).

$$\max f = \frac{COP_{AC}}{COP_{VCC}} N^{AC}_{ET}\, E^{u,t}_{ET,AC} + \frac{COP_{DSC}}{COP_{VCC}} N^{DSC}_{ET}\, E^{u,t}_{ET,DSC} + N_{PV}E^{u,e}_{PV} + N_{WT}E^{u,e}_{WT} = \langle \hat{N}, \beta \rangle \quad (7)$$

With

$$\hat{N} = \begin{pmatrix} N_{PV} \\ N_{WT} \\ N^{AC}_{ET} \\ N^{DSC}_{ET} \end{pmatrix} \text{ and } \beta = \begin{pmatrix} E^{u,e}_{PV} \\ E^{u,e}_{WT} \\ \frac{COP_{AC}}{COP_{VCC}} E^{u,t}_{ET,AC} \\ \frac{COP_{DSC}}{COP_{VCC}} E^{u,t}_{ET,DSC} \end{pmatrix}$$

2.2. Constraints

2.2.1. Energy balance constraints

The maximum cooling energy delivered by the desiccant wheel should not exceed the total latent cooling load as formulated in the following equation:

$$\langle \hat{N}, \rho \rangle \leq E_l \quad (8)$$

$$\text{Where } \rho = \begin{pmatrix} 0 \\ 0 \\ 0 \\ COP_{DSC}\, E^{u,t}_{ET,DSC} \end{pmatrix}$$

2.2.2. Area constraints

Furthermore, given that the hybrid cooling system is applied to a residential with limited roof surface area, it is necessary to impose area constraints related to the number of renewable energy systems installed on the roof. Equation (9) represents this constraint as follows:

$$\langle \hat{N}, \gamma \rangle \leq A_T \quad (9)$$

$$\text{Where } \gamma = \begin{pmatrix} A_{PV} \\ A_{WT} \\ A^{AC}_{ET} \\ A^{DSC}_{ET} \end{pmatrix}$$

where A_X is the surface required for renewable energy system and A_T is the useful total surface area of the house roof.

2.2.3. Economic constraints

From an economic point of view, when comparing two systems, the one with greater Net Present Value (NPV) is the preferred. Thus, in this case, the proposed hybrid cooling system economically compared to a conventional electric vapor compression chiller, this constraint could be translated into the following equation:

$$NPV_{VCC}^{cv} - \mathrm{NPV_{hyb}} \leq 0 \qquad (10)$$

Where $\mathrm{NPV_{VCC}^{cv}}$ and $\mathrm{NPV_{hyb}}$ are the net present values of the conventional vapor compression chiller and the hybrid system, respectively.

Since there is no energy savings considered for the conventional system, then its net present value is simply its capital cost during the studied period. Hence, equation (10) could be written as follows:

$$\left[\left(\sum_{X\epsilon H_1} \mathrm{C}_X^{\mathrm{hyb}} + \sum_{X\epsilon H_2} \mathrm{C}_X^{\mathrm{hyb}}\right) - \mathrm{C_{VCC}^{cv}}\right] - \left[\alpha(\mathrm{N_y})\mathrm{C^e}\left(\mathrm{E_{grid}^{Cv}} - \left(\frac{\mathrm{E_L}}{\mathrm{COP_{VCC}}} - \langle \widehat{\mathrm{N}}, \beta\rangle\right)\right)\right] \leq 0 \qquad (11)$$

Where

- $H_1\ \epsilon\,\{PV;\ WT;\ ET,AC; ET,DSC;\ st^e;\ st^{t1}; st^{t2}\}$
- $H_2\ \ \epsilon\,\{AC;\ \ VCC; DSC\}$
- $\alpha(N_y) = N_y\, DR^{-1}(1 - (1+DR)^{-N_y})$, with N_y being the number of operation years and DR being the discount rate of the considered case study.
- C_X^{hyb} is the cost of each component X in the hybrid system , and C_e is the cost of electrical energy from grid.

The cost of each component $X\epsilon H_1$ and $X\epsilon H_2$ of the hybrid system is calculated using equations (12) and (13), respectively.

$$C_{X\epsilon H_1} = \left(\left[\frac{N_y-1}{N_X^{lt}}\right] + 1\right) C_X^{hyb} = \varphi_{N_y}(N_X^{lt})\, C_X^{hyb} \qquad (12)$$

Where $\mathrm{N_X^{lt}}$ is the life time of the component "X" and $\left[\frac{\mathrm{N_y-1}}{\mathrm{N_X^{lt}}}\right]$ denotes the integer part of $\frac{\mathrm{N_y-1}}{\mathrm{N_X^{lt}}}$. In addition, $N_{st^e} = 0$ if $(N_{PV} + N_{WT}) = 0$; $N_{st^{t1}} = 0$ if $N_{ET}^{AC} = 0$ and $N_{st^{t2}} = 0$ if $N_{ET}^{DSC} = 0$, because storage electrical and thermal systems are used jointly with the corresponding renewable energy system.

$$C_{X\epsilon H_2} = \sigma\,(Z)\varphi_{N_y}(N_X^{lt})\, C_X^{hyb} \qquad (13)$$

Where $\sigma(Z) = \begin{cases} 0\ if\ \ Z \leq 0 \\ 1\ \ if\ \ Z > 0 \end{cases}$

with Z being defined as follows:

$$\mathrm{Z} = \begin{cases} \mathrm{E_L} - (\mathrm{COP_{AC}}\ \mathrm{N_{ET}^{AC}}\ \mathrm{E_{ET,AC}^{u,t}} + \mathrm{COP_{DSC}}\ \mathrm{N_{ET}^{DSC}}\ \ \mathrm{E_{ET,DSC}^{u,t}}) & \text{if } \mathrm{X} \equiv \mathrm{VCC} \\ \mathrm{N_{ET}^{AC}} & \text{if } \mathrm{X} \equiv \mathrm{AC} \\ \mathrm{N_{ET}^{DSC}} & \text{if } \mathrm{X} \equiv \mathrm{DSC} \end{cases}$$

Table 1 illustarets the lietime of each component found in the literature.

Table 1: Lifetime of hybrid cooling system components

Component	Lifetime (years)
Photovoltaic Panel	25
Wind Turbine	20
Evacuated Tube Solar Collector	40
Vapor compression chiller	15
Absorption Chiller	23
Desiccant System	10
Electric Storage	5
Thermal Storage	10

2.3. Optimization problem

Finally, considering the objective function and constraints, the optimal sizing problem can be stated as follows:

the objective function : $Max \langle \hat{N}, \beta \rangle$

$$\begin{cases} \langle \hat{N} \ ,\gamma \rangle \ \leq \ A_T \\ \langle \hat{N} \ ,\rho \rangle \ \leq \ L \\ NPV_{VCC}^{cv} - \mathrm{NPV_{hyb}} \ \leq \ 0 \end{cases}$$

Where *NPV* is predifiened in the previous section.

The problem is stated as a discrete problem with a limited number of cases, namely number of renewable energy systems. Thus, it can be solved by using a straight forward algorithm using Matlab. The optimal solution was found by searching the maximum of the objective function, of all combinations of the vector *N*, in such condition that all constraints are respected.

3. RESULTS AND DISCUSSIONS: CASE STUDIES

The introduced optimal sizing method applied for the proposed hybrid cooling system is investigated in two case studies: Beirut-Lebanon and Marseille- France. The input data concerning the climate of a typical meteorological year and the corresponding cooling load in both regions are obtained using Trnsys. Figures 2 and 3 illustrates the data necessary for energy balance equations and the objective function namely, cooling loads (latent, sensible and total load), thermal energy outputs of evacuated tube solar collectors, electric energy output of photovoltaic panels and the electric energy output of the wind turbine.

Additionally, one constraint of the optimal sizing problem is economic, which needs the price and life-time of each of the various system components as inputs in the way for obtaining the solution. Accordingly, the market prices as well as the life time of hybrid cooling system components in Beirut and Marseille are considered.

The simulations results obtained using Trnsys, the prices from the local market in each city and the lifetime of each system are introduced in the optimization problem. After that, Matlab software is utilized to model the optimal sizing method, where two time periods, 7 and 10 years, are considered for each case. In fact, 7 years represents the minimum number of operating years where the hybrid cooling system become feasible in case of Beirut; and 10 years in case of Marseille. Simulation results yield the optimum number of each energy unit composing the hybrid system. Table 2 illustrates these results for the each considered case all along with the capital cost of the system and the annual operating-cost savings compared with a conventional electric vapor compression chiller. It is shown that for the case of Beirut, the same components-configuration of the hybrid system is obtained for both studied operation periods (7 and 10 years). As for Marseille, the electric vapor compression chiller is preferred to any other hybrid configuration over the 7-years operation period. This is mainly attributed to lower electricity costs in the country compared with that in Beirut and thus, annual operating-cost savings would not be able to meet the economic criterion. On the other hand, for 10-years operation period, the same hybrid system configuration obtained for the case of Beirut is found. Moreover, comparing with the annual savings in both cities, it is clear that they are much higher in Beirut due to higher cooling loads and higher electricity tariff.

Furthermore, although the capital costs of the obtained hybrid system are high in both cities; however, annual cost-savings are also considerable. Hence, if good financial incentives and loans exist, there would be a large spread of such high efficient energy systems.

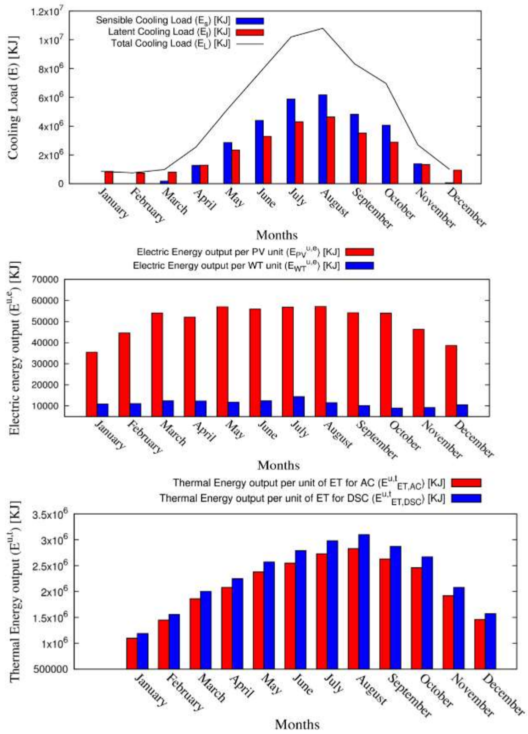

Figure 2: Input data concerning the climate of a typical meteorological year in Beirut-Lebanon

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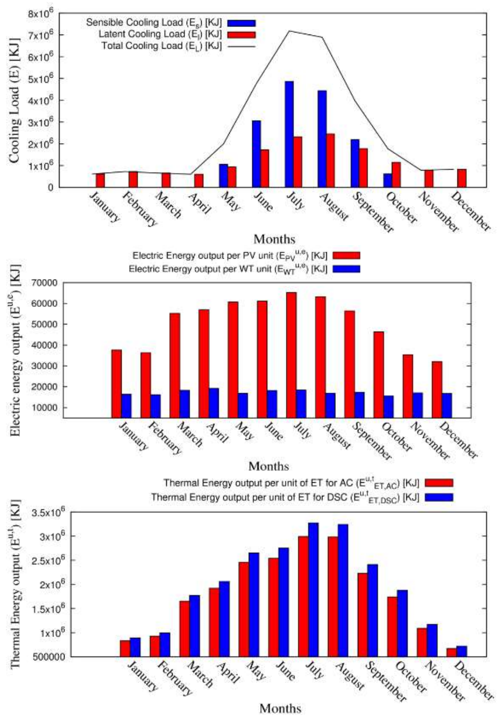

Figure 3: Input data concerning the climate of a typical meteorological year in Marseille-France

4. CONCLUSION

In this work, the optimal sizing of a hybrid cooling system is studied. For this purpose, a hybrid cooling system based on renewable energy system was defined. Then, an optimal sizing method was presented in order to obtain the best configuration of the hybrid cooling system in term of maximum renewable energy share and minimum grid contribution. The optimization problem was applied for two cases study namely, Beirut-Lebanon and Marseille-France. It was shown that the grid electricity cost has a significant role in determining the optimal size of a hybrid cooling system. For instance, at lower electricity cost in Marseille-France, a conventional cooling system could be more feasible than hybrid systems especially at short operation period. On the other hand, at high electricity cost, a hybrid cooling system could be more economical than conventional one, even if the prices of renewable energy systems are high.

Finally, this method need to be improved, and an optimal strategy for energy management and control - according to the cooling demand, energy input, costs, etc. -should be implemented. Hence, it allows the components of the system to operate at its maximal performance.

Table 2: Results for the optimal number for each system component as well as the capital cost and annual saving for both case studies.

Case Study	Beirut, Lebanon		Marseille, France	
Number of operation years (N_y) [years]	7	10	7	10
Number of PV [unit]	10	10	0	10
Number of WT [unit]	2	2	0	2
Number of ET, AC [unit]	2	2	0	2
Number of ET,DSC [unit]	1	1	0	1
Number of AC [unit]	1	1	0	1
Number of VCC [unit]	1	1	1	1
Number of DSC [unit]	1	1	0	1
Total Capital Cost [USD $]	32130	32130	1087	22242
Annual Saving [USD $/year]	795	795	0	253

NOMENCLATURE

Variables

A	*Area [m2]*
C	*Cost [$]*
COP	*Coefficient of Performance [-]*
N	*Number of Units/years [Units/years]*
RH	*Relative Humidity [%]*
T	*Temperature [°]*

Abbreviations

AC	*Absorption Chiller*
CHW	*Chilled Water tank*
COP	*Coefficient of performance*
DR	*Discount Rate*

DSC	*Desiccant System*
ET,AC	*Evacuated tube solar collector for Absorption chiller*
ET,DSC	*Evacuated tube solar collector for Desiccant system*
HW	*Hot Water tank*
Hyb	*Hybrid*
NPV	*Net Present Value*
PV	*Photovoltaic*
VCC	*Vapor Compression Chiller*
WT	*Wind Turbine*

Subscripts

chw	*Chilled water*
cv	*Conventional*
e	*Electric*
gen	*Generator*
i	*Input*
l	*Latent*
l	*load*
lt	*Lifetime*
max	*Maximum*
min	*Minimum*
o	*Output*
s	*Sensible*
sp	*Set point*
st	*Storage*
t	*Thermal*
u	*Unit*
y	*Years*

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