SOLAR POWER GENERATION AND SOLAR COOLING TRIGENERATION: A NEW APPROACH OF CONCEPTUAL DESIGN FOR COUNTRIES OF MENA REGION

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ABSTRACT

The rapid increase in population, industrial and agricultural developments in countries of the Middle East and North Africa (MENA) has resulted in proportional increase in demand for electric power. This demand increases sharply during the summer months due to the use of electricity-powered Air Conditioning (AC) systems. The usual response to this problem is to build new, time-consuming and costly power generation plants. Trigeneration or combined heat, power and cooling represents a great opportunity for the Sunbelt countries, especially in the MENAregion. The potential application covers not only the construction industry and the service sector, but also the industry, agribusiness and agriculture sectors. Specifically, we show the possibility to design a basic concept that meets all the requirements and which optimally adapts to all cultural, regulatory and economic considerations according to the studied country and the site of realization in question. We propose in this study the use of the solar thermal for heating, power generation and building cooling. The new developed solar-based technology is capable of producing power via Organic Rankine Cycle (ORC) and absorption or adsorption cooling as a byproduct/cogeneration operated by the rejected heat from the ORC. We consider also the possibility of using ice storage technology which is much cheaper than steam storage. This way, autonomous power generation and cooling (AC) can be installed in locations remote from the electricity grid, resulting in huge savings in both power transmission lines and added power capacity. We present practical results and we describe our conceptual approaches and modeling. The developed parametric model is applied to various design cases, generated from the baseline concept, and then validated by comparison with experimental approaches. We note that our model is also used to predict the future facilities operations. Thereafter, we present our current projects and test stands in two countries in the MENA region.

Keywords: Smart building, predictive model, HVAC, solar-gas trigeneration.

INTRODUCTION

The maturity of solar thermal technology used for producing hot water can be used for satisfying the rapidly increasing demand for cooling through thermal and thermodynamic pathways [2, 3]. However, innovative systems especially those including multi-generation will face a number of challenges including having affordable maintenance, rational use of natural gas as an auxiliary source, coping with the summer high demand for air conditioning, availability of storage facility and a seasonal adjustment of the hot-cold outputs.

Due to their high demand for energy per capita, most countries in the MENA region need a transitional development in the energy generation sector. Such initiatives have already been planned as in Tunisia where 30% contribution from renewable sources is targeted by 2030. Even in oil producing countries such initiatives are taken place as the case with Oman where the government is currently allocating handsome funds for the development of alternative energy producing technologies through research and development. In such efforts, the most challenging tasks will be the development of renewable energy systems that are efficient, reliable, economically feasible and, especially important, compatibility with the climatic characteristics of the location of use.

In this context, we have developed two models of cooling systems: a classic (Type 1) and another innovative (Type 2). The performance of each system has been parametrically evaluated with the aim to identify the limitation of use at nominal conditions. Hence, upon on the availability of solar radiation, it will be possible to propose the most suitable type of installation conforming to the above-mentioned criteria. The performance of the various units is based on widely tested and proven models.

DEVELOPED CONFIGURATIONS

Regional Comparison

The design layout and outputs are to a great extent location-specific. A lucrative technology in one region might be deemed impractical in another place where it may lack compatibility with the renewable resources, availability of subsidized conventional utilities and/or the type of the most utility in demand. Table 1 shows a comparison between Tunisia and Oman which are located far apart within the MENA region.

Criteria	Tunisia	Oman
Solar radiation in urban areas	Medium 1600-1900 kWh /m^2 /year	High 1900-2300 kWh /m^2 /year
Summer daytime peak	Very critical	Critical
Heating utility and hot water	In demand	Low demand
Cooling utility	High demand in summer	In demand most of the year
Investment opportunities in innovative renewable energy technologies	Low to medium	Medium to high
State plans for alternative energy	Established	Evolving
Maturity of the thermal solar energy sector	Commonly used conventional systems	Very low
Importance of electricity production	High	High in remote areas
Electricity rates at peak	high	Medium
Electricity rate in network isolated sites	Very high	Medium

Table 1: Comparison between two countries in MENA region.

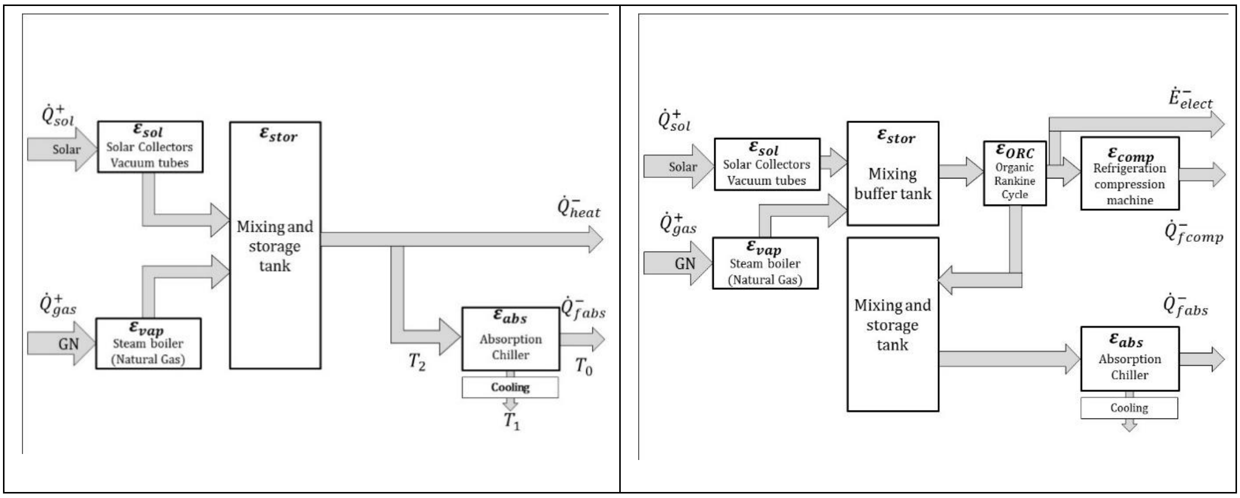

Figure 1: Schematic diagram of the installations Type 1 (Left; Tunisia) and Type 2 (Right; Oman).

PROPOSED CONFIGURATIONS

Modeling the Overall Efficiency for the Proposed Configuration Type 1

In this configuration, the heat gained from the dual input of solar and natural gas are applied directly to an absorption chiller via a storage tank where the injected steam (from a gas boiler) serves as an extra heating source for the water heated by the solar field. In addition to cooling, Type 1 allow direct use of hot water (figure 1).

The solar contribution, (τ_{sol}) is the ratio of the solar gain at the solar collectors to the total heat input of solar gain and the primary heat from natural gas:

$$\tau_{sol} = \frac{\dot{Q}_{sol}^{+}}{\dot{Q}_{sol}^{+} + \dot{Q}_{gaz}^{+}} \quad (1)$$

The ratio of the net heat produced to the sum of the heat and absorption cooling produced is given by:

$$\tau_{heat} = \frac{\dot{Q}_{heat}^{-}}{\dot{Q}_{heat}^{-} + \dot{Q}_{abs}^{+}} \quad (2)$$

The overall efficiency of the given configuration Type 1 is based on two assumptions [6]: **Assumption 1**: The system is considered to produce two equally important outputs, cooling and heating:

$$\varepsilon_{g-abs} = \frac{\dot{Q}_{fabs}^{-} + \dot{Q}_{heat}^{-}}{\dot{Q}_{sol}^{+} + \dot{Q}_{gaz}^{+}} = \varepsilon_{stor}.\left(\varepsilon_{sol}.\tau_{sol} + \varepsilon_{vap}.(1-\tau_{sol})\right).\left(\tau_{heat} + \varepsilon_{abs}.(1-\tau_{heat})\right) \quad (3)$$

Assumption 2: The system produces both cooling and heating with cooling is considered the main product of interest:

$$\varepsilon'_{g-abs} = \frac{\dot{Q}_{fabs}^{-}}{\dot{Q}_{sol}^{+} + \dot{Q}_{gaz}^{+}} = \varepsilon_{stor}.\left(\varepsilon_{sol}.\tau_{sol} + \varepsilon_{vap}.(1-\tau_{sol})\right).\varepsilon_{abs}.(1-\tau_{heat}) \quad (4)$$

The change in internal energy is assumed to be zero. The system is therefore evolving in quasi-stationary operating conditions.

Modeling the Overall Efficiency for Configuration Type 2

In this configuration, the solar energy collected and steam are fed to an ORC via a buffer tank, reducing thermodynamic losses due to mixing compared to configuration Type 1. Cooling is produced by two means: from a compression machine working on the power produced by the ORC and from an absorption machine [6]. Exergy lost by the ORC is either stored or applied to the absorption machine (figure 1).

In this configuration, the solar contribution, (τ_{sol}) is the ratio of the solar gain at the solar collectors to the total heat input of solar gain and the auxiliray fuel and is given by:

$$\tau_{sol} = \frac{\dot{Q}_{sol}^{+}}{\dot{Q}_{sol}^{+} + \dot{Q}_{gaz}^{+}} \quad (5)$$

The ratio of the net electrical power produced to the sum of the net electrical power produced and that consumed by the refregiration-compression system is given by:

$$\tau_{elect} = \frac{\dot{E}_{elect}^{-}}{\dot{E}_{elect}^{+} + \dot{E}_{e.comp}^{+}} \quad (6)$$

The overall efficiency of the given configuration Type 2 is based on two assumptions [6]:

Assumption 1: The system produces two products of equal interest: cooling and electrical power.

$$\varepsilon_{g-trigen} = \frac{\dot{Q}_{fabs}^{-} + \dot{Q}_{fcomp}^{-} + \dot{E}_{elect}^{-}}{\dot{Q}_{sol}^{+} + \dot{Q}_{gaz}^{+}} =$$

$$\varepsilon_{stor}.\left(\varepsilon_{sol}.\tau_{sol} + \varepsilon_{vap}.(1-\tau_{sol})\right).\left(\varepsilon_{abs} + \varepsilon_{ORC}.(\tau_{elect} + \varepsilon_{comp}.(1-\tau_{elect}) - \varepsilon_{abs}\right)\right) \quad (7)$$

Assumption 2: The system produces both cooling and electrical power with only cooling is considered to be the output of interest:

$$\varepsilon'_{g-trigen} = \frac{\dot{Q}^{-}_{fabs} + \dot{Q}^{-}_{fcomp}}{\dot{Q}^{+}_{sol} + \dot{Q}^{+}_{gaz}} =$$

$$= \varepsilon_{stor} \cdot \left(\varepsilon_{sol} \cdot \tau_{sol} + \varepsilon_{vap} \cdot (1 - \tau_{sol})\right) \cdot \left(\varepsilon_{abs} + \varepsilon_{ORC} \cdot (\varepsilon_{comp} \cdot (1 - \tau_{elect}) - \varepsilon_{abs})\right) \quad (8)$$

The feasibility and the optimization of such configuration must be validated at the design phase using process integration methods such as pinch technology [2, 3, 5, 6 ,7].

Modeling the Efficiency of the Absorption System

The absorption refrigerator exchanges heat with three sources given by three levels of temperatures denoted by T_{m0}, T_{m1} and T_{m2}, which are those of the evaporator, the cooling tower and the generator.

In order to address the limitations of usual models, we propose the following empirical model that has been widely validated using both dimensional and dimensionless analysis and it is inspired by the basic expressions of the COP.

$$\varepsilon_{abs} = c_0 \cdot \left(\frac{T_{m0}}{T_{m2}}\right)^{c1} \cdot \left(\frac{T_{m2} - T_{m1}}{T_{m1} - T_{m0}}\right)^{c2} \quad (9)$$

The new empirical model that we have developed has been validated through an experimental study in 2015. The experiments were conducted on the absorption chiller (dual solar-gas) with an output of 175 kW used to cool the industrial premises in an agro-industry in Tunisia.

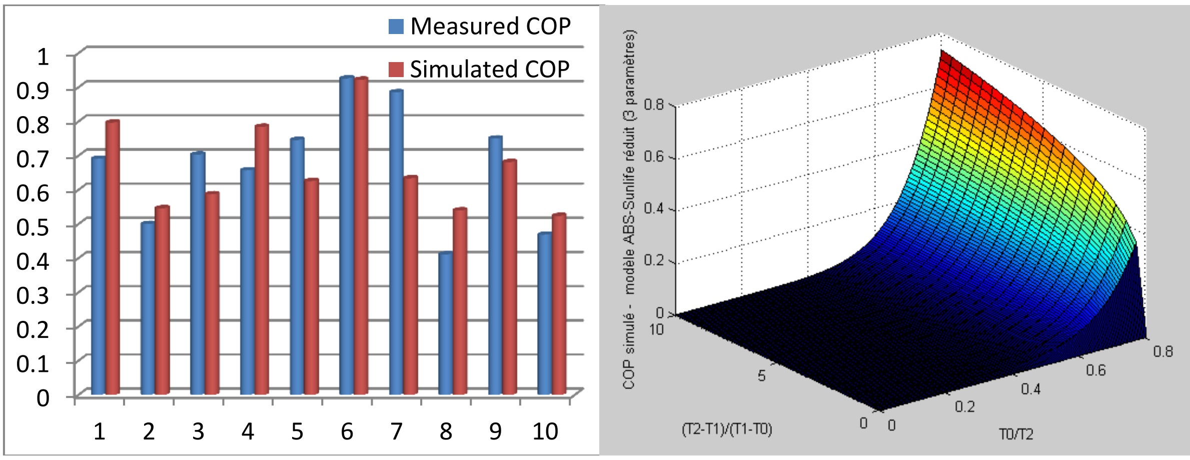

Figure 2: Simulated and measured COP based on the identified parameters.

Modeling the ORC Efficiency

The structure of the cycle has a single volumetric turbine stage using an organic fluid with the high temperature kept constant while the lower temperature is variable.

The condensation of the organic fluid does not take place at ambient temperature but at a temperature higher than that required by the absorption machine [1, 3, 4, 5] and it is also subject to the average ΔT_{pinch}.

The efficiency can be expressed by the following model where parameters d_o and d_1 are determined experimentally.

$$\varepsilon_{ORC} = d_0 \cdot (T_{ORC} - T_{m2})^{d1} \cdot (T_{ORC})^{-1} \quad (10)$$

The Efficiency Model of The Solar Field

After a thorough analysis of the most appropriate solar collectors and the selected temperature ranges, we selected the following model:

$$\varepsilon_{sol} = F'.(\tau\alpha) - \frac{F'.U_{L0}}{E_n}.(T_{m-sol} - T_a) - \frac{F'.U_{L1}}{E_n}.(T_{m-sol} - T_a)^2 \quad (11)$$

This model has been extensively validated in numerous studies involving several experimental works [1, 8].

Figure 3 shows the simulation for both configurations with Type 2 showing higher performance at all generator temperatures.

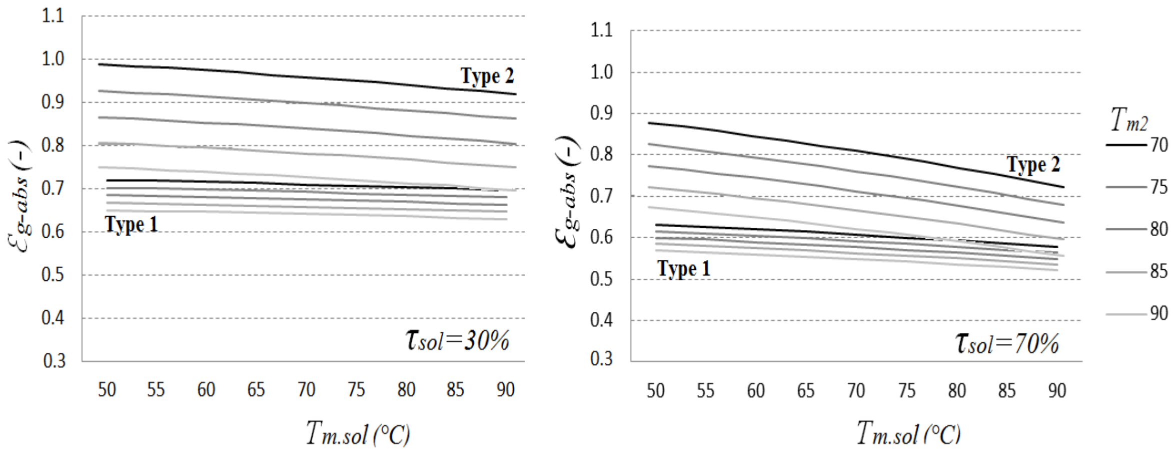

Figure 3: Simulation of Type 1 and Type 2 configurations.

COMPARATIVE STUDY

Type 1 (Tunisia): The system performance (heat and cooling) are very sensitive to the variation in temperature at the solar collectors and the generator of the absorption chiller which is due to the fluctuations in solar radiation. For solar contribution of 30% and 70%, the overall efficiency was 65% and 55%, respectively. Note that cold production is based solely on absorption chillers with the risk of crystallization due to temperature irregularities. The retrofitting in this 2 is possible.

Oman Type 2: The trigeneration performance is sensitive to the choice of the type of solar collectors but they are, in all cases, much higher than those of Type 1. This type is not adequate if the natural gas network will not cover isolated areas. For solar contribution of 30% and 70%, the overall efficiency is 81% and 65% respectively. T_{m-sol}= 140 °C (type 2) and 90°C (Type 1) ; T_{m2} = 80 °C (Type 1 and 2); E_n = 900 W/m^2, T_a = 25 °C

CONCLUSION

We have shown that it is possible to improve the performance of the conventional cooling systems through a combination of solar energy and natural gas that provide significant advantages over the existing systems. The trigeneration systems is mainly based on a cascade transfer of heat so as to give priority to a mechanical work via ORC rather than direct feed of heat to the absorption machine and it significantly improves the energy efficiency of solar cooling system. These systems can ensure maximum availability of energy (heat, cold, electricity) as well as adaptability to local conditions. We also investigated the temperature ranges of operation of the solar collectors and those of various machines (ORC, absorption) that ensure eligible annual level of performance depending on the characteristics of two typical areas considered in MENA.

SYMBOLS

Symbol	Designation	Unit	Symbol	Designation	Unit
$\dot{Q}_{sol}^{+}$	Heat from solar collectors	kW	τ_{sol}	Nominal solar contribution	(-)
$\dot{Q}_{gaz}^{+}$	Primary heat from natural gas fuel	kW	τ_{heat}	Heating utility contribution	(-)
$\dot{Q}_{heat}^{+}$		kW	τ_{elect}	Ratio of net electricity produced	(-)
$\dot{Q}_{abs}^{+}$	Thermal power provided to the absorption machine	kW	ε_{stor}	Storage tank effciency	(-)
$\dot{Q}_{fabs}^{-}$	The cooling load of the absorption machine	kW	ε_{sol}	efficiency of solar collectors	(-)
$\dot{Q}_{fcomp}^{-}$	The cooling load of the refrigeration compression machine	kW	ε_{vap}	efficiency of vapor recovery at heat engine	(-)
$\dot{E}_{e.comp}^{-}$		kW	ε_{ORC}	Effciency of ORC	(-)
$\dot{E}_{elect}^{-}$	Net electrical power produced	kW	ε_{abs}	absorption machine COP	(-)
E_n	Solar radiation	W/m^2	ε_{comp}	Refrigeration compression machine COP	(-)
T_a	Ambient temperature	°C	ε_{g-abs}	Absorober solar cooling overall effciency (Assummption 1)	(-)
T_{m-sol}	Average temperature (solar collectors)	°C	ε'_{g-abs}	Absorober solar cooling overall effciency (Assummption 2)	(-)
T_{m0}	Temperature (evaporator)	°C	$\varepsilon_{g-trigen}$	Trigeneration system overall effciency (Assummption 1)	(-)
T_{m1}	Temperature (cooling tower)	°C	$\varepsilon'_{g-trigen}$	Trigeneration system overall effciency (Assummption 2)	(-)
T_{m2}	Temperature (generator)	°C	$F'.(\tau\alpha)$	Loss factor	(-)
T_{ORC}	High temperature of the ORC	°C	U_{L0}, U_{L1}	Conductivity of solar collectors	W/m^2/°C
T_{e0}, T_{s0}	Inlet, outlet temp. of the evaporator	°C	c_0, c_1, c_2	Absorption machine coffcients	(-)
T_{e2}, T_{s2}	Inlet, outlet temp. of the generator	°C	d_0, d_1	ORC Coeffcients	(-)
$\dot{m}_0, \dot{m}_2$	Mass flow, evaporator & generator	Kg/s	C_{p0}, C_{p2}	Specific heats	J/kg/°C

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