Analytical and Comparative Study for Solar Thermal Cooling and Photovoltaic Solar Cooling in the MENA Region

by

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Introduction

• In MENA regions, the growing demand for traditional air-conditioning caused a significant increase in peak electric power demand and in primary energy resources demand.

• For example: In Egypt, at least 32% of the electrical energy is consumed by the traditional air-conditioning.

• Although, the MENA regions have a high solar potential

• The solar air-conditioning technology is definitely a solution for this problem in the MENA regions.

• Today, there are two main solar air-conditioning technology options: solar thermal air-conditioning and the solar photovoltaic air-conditioning.

• There are very few research on this technologies under the MENA region climate conditions.

• Which one of the two technologies should be preferred for technical reasons under the MENA regions’ climates?
Objective

- The main objective is to analyze and compare the solar thermal air-conditioning technology and the photovoltaic air-conditioning technology under different thermal load profiles in the MENA region climate conditions.
Step I: Selecting locations and collecting their meteorological data

Step II: Reference building determination

Step III: The building thermal load demands simulation by TRNSYS software

The calculation of solar radiation on tilted surface by TRNSYS software

Step IV: Simulation results and analyses

Step V: Solar air-conditioning scenarios design and simulation by Matlab-Simulink

Analyses of results and comparison
Step I: Selecting locations and collecting their meteorological data

Two countries were selected from the MENA region:

1. Aswan city in Egypt from North Africa (NA)
2. Aqaba city in Jordan from Middle East (ME)

![Map showing the location of Aqaba and Aswan cities](image)

Fig 1: The location of Aqaba and Aswan cities
Step I: Selecting locations and collecting their meteorological data (cont.)

Meteorological data:

1. Aswan city
   • Hourly data
   • From U. S. National Climatic Data Center

2. Aqaba city
   • Measurement data with 15 minute intervals
   • From NERC Centre in Jordan

Fig 1: Annual distribution of horizontal global solar radiation for Aswan and Aqaba cities

Fig 2: Annual distribution of ambient air temperatures for Aqaba and Aswan cities

Fig 3: Annual distribution of ambient air relative humidity in Aswan and Aqaba cities
Step II: Reference building determination

- The building is a Typical Single Family House (TSFH) with a flat roof.

- It represents 72% of the total residential building in Jordan, the number of occupants equal 6 persons.

- A simplification: TSFH in Jordan same that of Egypt’s.

Architecture Design
- **Rectangular** shape and consists of three bedrooms, living room, guest room, and Kitchen.
- Area: **224 m²**.
- Internal height: **2.86 m**.
- **Orientation**: the Guest and living rooms are facing to south.

Wall construction
- External walls: typical stone walls.
- Internal walls: H.C.B
- Windows:

<table>
<thead>
<tr>
<th>A single glazed window</th>
<th>North</th>
<th>South</th>
<th>East, West</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of the wall surface area</td>
<td>10%</td>
<td>30%</td>
<td>20%</td>
</tr>
</tbody>
</table>

Fig 4: Sketch of Typical Single Family House(TSFH).
Step III: The TSFH thermal load demands simulation by TRNSYS software

- **TRANSYS** is a transient system simulation program.
- A very capable tool to simulate the building cooling and heating loads.
- The Multi-zone building model (TYPE 56) is chosen to simulate the heat conduction through the surfaces of the TSFH-envelope.
- The heat balance method is used by TRNSYS as a base for all calculations.

**Simulation steps**

1. TRNBuild program simulation
2. TRNStudio program simulation
Step IV: TRNSYS simulation results and analyses

• The cooling demand follows the outside ambient air temperature and the solar radiation, in both cases.

• The cooling demand >> heating demand, along the year.
• Maximum cooling demands in summer: 13.9 kW for Aswan-TSFH, 15.3 kW for Aqaba-TSFH.

• High cooling demand at night: 8 to 10 kW.

Fig 7: Yearly Cooling and heating demands (kW) for the Aswan-TSFH.

Fig 8: Yearly cooling and heating demands distribution in (kW) for the Aqaba-TSFH.

Fig 9: Weakly Cooling load demand distribution in (kW) for the Aqaba-TSFH and Aswan-TSFH.
Step IV: TRNSYS simulation results and analysis (cont.)

Yearly cooling energy demands:

For Aswan-TSFH: **44,330 kWh/year** which represents **97.5%** of the total annual energy consumption (heating and cooling).

For Aqaba-TSFH is **43,490 kWh/year** which represents **96.3%** of the total annual energy (heating and cooling).

That shows the importance of cooling compared to heating in these locations.

• Monthly cooling demand for Aswan-TSFH is higher than Aqaba-TSFH along the year, except (June, July and Aug.), Due to ventilation where Relative humidity in Aqaba >> Relative humidity in Aswan.
Step V: Solar air-conditioning scenarios design and simulation

Three scenarios are designed and simulated for each building: Aswan-TSFH and Aqaba-TSFH, as:

- Solar photovoltaic air-conditioning without storage.
- Solar photovoltaic air-conditioning with storage.
- Solar thermal air-conditioning with storage (absorption chiller).

The Scenarios design

- Based on the TRNSYS simulation results: the maximum cooling demands in summer: **13.9 kW** for Aswan-TSFH, **15.3 kW** for Aqaba-TSFH.
- Assumption: both cases have the same maximum cooling demand and is equal **15 kW**.

Cooling supply simulation

- Carried out by Matlab-Simulink for each scenario.
- Two time series of input data:
  1. Cooling demand data.
  2. Location meteorological data \((G_{\text{tilt}}, T_{\text{amb}})\).
Step V: Solar air-conditioning scenarios design and simulation (cont.)

- **PV air-conditioning without storage scenario**

**System design**

The polycrystalline solar Module of 0.225 kW has been selected.

**PV-array**
- 27 module =45 m^2
- 14 modules in parallel and two in series
- 44 V-64 V
- Efficiency :13.4%
- On the TSFH -roof
- Tilted angle =location latitude

**Outback Inverter**
- 6 kW
- (44-64) V DC
- 230 V AC/50 Hz
- Efficiency : 95.4 %.

**Fig 12**: Schematic flow diagram for solar PV air-conditioning without storage.
**Step V: Solar air-conditioning scenarios design and simulation (cont.)**

**Simulation and methodology**

\[
P_{el(DC)} = f(G_{tilt}, n_{pv}, A_{pv}) \\
j_{pv} = f(T_c) \\
T_c = f(T_{amb}) \\
P_{el(AC)} = f(P_{el(DC)}, n_{inv}) \\
P_{Cooling} = f(P_{el(AC)}, \text{COP}) \\
\]

*TSFH*

**Fig 13:** Schematic flow diagram for solar PV air-conditioning without storage.
Step V: Solar air-conditioning scenarios design and simulation (cont.)

- **PV air-conditioning with storage scenario**

**System design**

- It is the **same as that of the PV-air conditioning scenario without storage**, we add only the charge controller and battery system.

  **The battery system designed:**
  - Based on the simulation results of the excess cooling and external back-up cooling in the first scenario
  - **The average daily electric DC excess energy** is 6.4 kWh/day.
  - Nominal battery capacity is 392 Ah.
  - The system includes: 8 batteries of 12 V, 85 % eff-, each 4 batteries are connected in series.
Step V: Solar air-conditioning scenarios design and simulation (cont.)

Simulation and methodology

The same calculation of air-conditioning without storage scenario

First scenario results

\[ P_{direct-compensation} \]

\[ P_{cooling} - P_{cooling\ demand} \]

\[ P_{c,\ excess} \]

\[ P_{c,\ back-up} \]

\[ P_{comp-storage} \]

\[ \int P_{c,\ back-up} - \int P_{comp-storage} \]

\[ \int P_{c,\ back-up2} \]

Second scenario results

\[ G_{tilt,\ T_{amb}} \]

\[ P_{charge} < \text{batt-limit} \]

\[ P_{deschage} < \text{limit} \]

Fig 14: Schematic flow diagram for solar PV air-conditioning with storage
Step V: Solar air-conditioning scenarios design and simulation (cont.)

- Solar thermal air-conditioning with storage (absorption chiller)

**System design**

**Flat plate collectors**
- Based on rule of thumb
  \[ A_{\text{coll,spec/m}^2} = \frac{1}{G \cdot \eta_{\text{coll}} \cdot \text{COP}} \]
- \( A_{\text{coll,Spec}} = 3.5 \text{ m}^2 \) for 1kW total area needed=42 m²
- Assumption: area= 45m²
- on the TSFH- roof
- Facing to the south
- The tilt angle equal the location latitude

**Storage tank**
- Stratification
- volume =2m³
- Back-up system
- Electric heater
- Connected with grid

**Absorption chiller**
- LiBr/H₂O
- Cooling capacity = 15 kW
- COP=0.71
- Heating Tem =85 c
- Re-cooling Tem=30c
- Cold Tem=11 c
- Electric demand 30 W
- Assumption, the operation based on the manufacturer data

**Fan coil**
- Working Temp=17/11 C

**Fig 15:** Solar thermal air-conditioning system scenario, Lithium bromide –water absorption chiller.
Step V: Solar air-conditioning scenarios design and simulation (cont.)

Simulation and methodology

\[ P_{\text{coll}} = f(G_{\text{tilt}}, n_0, C_1, C_2, A_{\text{coll}}, T_{\text{coll}}, T_{\text{amb}}) \]

\[ P_{\text{hABCH}} = f(COP, P_{\text{co,demand}}) \]

\[ P_{\text{ST,loss}} = f(A_s U_s, 85\degree C, 20\degree C) \]

\[ \Delta T_S = \frac{P_{\text{coll}} - P_{\text{hABCH}} - P_{\text{ST,loss}}}{\rho_w V_{\text{storage}} C_w} \]

TRNSYS simulation

Results

- \( P_{\text{D,comp}} \)
- \( P_{\text{DCooling}} \)
- \( P_{\text{C,back-up}} \)
- \( P_{\text{C,s}} \)
- \( \int P_{\text{C,back-up}} - \int P_{\text{C,s}} \)

Fig 15: Solar thermal air-conditioning system scenario, Lithium bromide –water absorption chiller.
The influence of a direct cooling supply and demand (yearly)

- **Direct means**: the cooling supply under assumption that the system without storage.
- **In winter (both Thermal and PV)**: High excess and low demand.
- The excess of direct cooling in **(spring, autume and summer)**: thermal higher than PV...
- **Aqaba-TSFH Vs Aswan-TSFH**: in summer due to a higher demand and lower solar radiation in Aqaba.

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**Analyses of results and comparison**

**Fig 16**: PV air-conditioning, direct cooling supply and demand

**Fig 17**: Thermal air-conditioning, direct cooling supply and demand
Analyses of results and comparison (cont.)

The influence of a direct cooling supply and demand (summer week)

• At noon of the day, the direct cooling supply by the thermal air-conditioning higher than PV air-condoning and higher of excess cooling supply

• During evening and night, a high external back-up cooling needed

• The storage system for the thermal air-conditioning scenario is more important than for the PV air-conditioning scenario

• The storage system for Aswan-TSFH is more important than for Aqaba-TSFH epically in summer

Fig18: PV air-conditioning versus solar thermal airconditioning, direct cooling supply and demand in Summer Week.
Analyses of results and comparison (cont.)

The influence of a direct cooling supply and demand (summer day)

• Direct compensation:

  • The performance of daily direct cooling compensation by the PV air-conditioning scenarios is more efficient than in the thermal air-conditioning scenario.

  • But the solar collector efficiency is around 50% and PV module is around 14%.....so how ??!

Due to three reasons:

1. The COP of compressed chiller and Absorption chiller is completely different around (3 for Compressed chiller and 0.7 for absorption chiller).

2. In the morning and evening, in order to prevent that the critical point (the thermal losses are higher than the solar gain from the flat plate collectors (85°C).

3. In the morning and at the evening a higher electric power gain from the PV module due to a high diffuse radiation.

Fig19: PV air-conditioning versus solar thermal air-conditioning, cooling supply and demand performance in Summer day
Analyses of results and comparison (cont.)

**Yearly Cooling energy compensation**

In both cases (Aqaba-TSFH and Aswan-TSFH):

- The **direct compensation** by the PV air-conditioning scenario is **better** than the thermal air-conditioning scenario.
- The **compensation by the storage** in the thermal air-conditioning scenario almost **doubles** that of the PV air-conditioning with storage scenario. **That is due to** an huge excess of power gain from flat collector at noon of the day compared with the PV module.

**Fig21: Yearly cooling energy compensation by the solar PV air-conditioning system with storage scenarios**

**Fig20: Yearly cooling energy compensation by the thermal air-conditioning scenario.**
Analyses of results and comparison (cont.)

Annual cooling compensation energy percentage:

- **The total annual percentage** of cooling energy compensation (direct plus storage) difference between the PV and thermal with storage scenarios **do not exceed 1 %**

  **BUT**

- **The direct** cooling compensation by **PV** air-conditioning scenario is **better than** the thermal air conditioning scenario.

- PV air-conditioning with storage **needs less storage** to cover the same amount of cooling load demand.

- That result is **due to** the same **three reasons** as mentioned earlier:
  - **COP** completely deferent in both scenarios.

  - Thermal **critical point** for the operation of flat plat collectors in morning and at the evening.

  - **Diffused** radiation in the morning and at the evening.

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**Fig22**: Percentage of cooling Energy compensation by the three scenarios.
Analyses of results and comparison (cont.)

Annual cooling compensation energy percentage

Fig 23: Percentage of cooling Energy compensation by the three scenarios.

Exactly the same results which are founded in Aswan-TSFH case, ............

This improved our results
Conclusions

• In both cases, the TSFH cooling demand represents (> 96%) of the total annual energy consumption (heating and cooling). That shows the importance of cooling compared to heating in these locations.

• High night cooling demand in both cases. This shows the importance of the storage system contribution to cover this demand in each technology for these locations.

• The total annual percentage of cooling energy compensation (direct plus storage) difference between the PV and the thermal air-conditioning with storage scenarios do not exceed 1% in both cases.

• The performance of daily direct cooling compensation by the PV air-conditioning scenarios is more efficient than the thermal air-conditioning scenario’s.

• The PV air-conditioning scenario with storage better than the thermal air-conditioning scenario because it needs less storage to cover the same amount of cooling load demand.

• The storage system in the PV air-conditioning scenario is minor and the direct compensation is major. That is vice versa in the thermal air-conditioning scenario.
Thank you

Any?

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