LIFE CYCLE ENERGY PERFORMANCES AND ENVIRONMENTAL ANALYSIS OF SOLAR DEC FREESCOO UNITS

Authors: Marco Beccali a, Pietro Finocchiaro, b, Sonia Longo a, Luigi Randazzo a

a DEIM – University of Palermo, ITALY
b SOLARINVENT srl, ITALY

marco.beccali@unipa.it
Freescoo (from FREE Solar COOling) is an innovative patented solar DEC air conditioning concept based on fixed and cooled adsorption beds and efficient evaporative cooling process.

- It is a project lead by the startup company SOLARINVENT SRL.
- In the framework of a Research Project funded by the Italian Ministry of Economic Development, a second generation of Freescoo prototypes were installed and tested in summer 2004 at the University of Palermo (UNIPA) and at the ENEA Research Center Casaccia (Rome, Italy).
- UNIPA has been committed to test the prototypes “2.0”
INNOVATIVE FIXED AND COOLED ADSORPTION BED

- The main component for dehumidification is a **fin and tube heat exchanger** commonly used in the air conditioning sector, wherein the spaces between the fins are filled with silica gel grains.
- The developed component allows a simultaneous **mass transfer** between the moist air and the adsorbent media and **heat exchange** between the air and the water flowing into the heat exchanger tubes;
- **Cooling of the desiccant** material during the adsorption process allows high dehumidification performances of the bed and in better overall energy performances of the system;
Water temperatures for cooling the bed can be easily achieved with a cooling tower;

Higher amount of silica gel can be used than in rotor;

Adsorption and desorption processes happen in different times in a couple of beds;

Solar energy can be efficiently stored in the desiccant in terms of adsorption capacity which can be used later when regeneration heat is not available, strongly reducing the necessity for thermal storage;
COMPARISON OF THE ADSORPTION PROCESSES

Dehumidification by desiccant rotor
- Adsorption process realized by means of desiccant rotors is a quasi–isoenthalpic transformation
- It presents the disadvantage of causing a temperature increase of the desiccant material
- No enthalpy difference between in and out

Dehumidification by cooled desiccant bed
- Condensation heat can be rejected
- The thermodynamic process causes an enthalpy difference between inlet and outlet air conditions
- In general, the temperature of air exiting the adsorption bed can be lower than the one of incoming air
- Downstream indirect evaporative cooling process can be operated at lower temperature
MAIN SYSTEM FEATURES

- Designed for small scale applications with air ventilation, dehumidification and cooling needs
- Based on fixed and cooled adsorption beds and high efficient evaporative cooling concepts
- Use of solar PVT air collector
- Minimization of parasitic energy consumption
- Nearly Solar autonomous, no use of auxiliary energy source for cold production but only for auxiliaries
- Compact, all in one, reliable, and easy to install
DESIGN CONCEPT OF THE NEW DEC CYCLE

- Adsorption bed: Dehumidification + 1\textsuperscript{st} step cooling
- Wet heat exchanger: 2\textsuperscript{nd} step cooling
- Outside air
- Return air
- Internal Cooling Tower
- Exhaust air
The new compact system developed is based on the use of two fixed packed desiccant beds of silica gel operating in a batch process and cooled by cooling tower, and two wet heat exchangers connected in series.

- Adsorption bed designed to be operated in “low flow” mode (air velocity = 0.16 m/s)
- A portion of the primary air flow rate exiting the wet heat exchanger is drown into the secondary side.

International PCT pending
MONITORING OF TWO SYSTEMS

Location:

Palermo

- Solar air collector area: 2.4 m²
- Two desiccant beds, with 13 kg of silica gel each
- Nominal flow rate: 500 m³/h
- Max power absorbed: 150W
- Max cooling power: 2.7 kW
  \((T_{out} = 35°C, RH_{out} = 50%, T_{bui} = 27°C, RH_{bui} = 50%)\)
- Total weight ≈ 230 kg
- Area of conditioned space = 46 m²
- Volume of conditioned space = 190 m³
- Occupation pattern = small office
- Auxiliary device installed: Split system
- About 3 weeks of monitoring carried out this summer
- Selection of one day

Rome

- Solar air collector area: 4.8 m²
- Two desiccant beds, with 25 kg of silica gel each
- Nominal flow rate: 1000 m³/h
- Max power absorbed: 250W
- Max cooling power: 5.5 kW
  \((T_{out} = 35°C, RH_{out} = 50%, T_{bui} = 27°C, RH_{bui} = 50%)\)
- Total weight ≈ 400 kg
- Area of conditioned space = 46.5 m²
- Volume of conditioned space = 125 m³
- Occupation pattern = seminar room
- Auxiliary device installed: 5 x 2.5 kW fan coil
- About 1.5 months of monitoring carried out this summer
- Selection of 15 days continuous operation

marco.beccali@unipa.it
MAIN PERFORMANCE INDICATORS USED

\[ MR = \frac{\dot{m}_{\text{outside}}}{(\dot{m}_{\text{supply}} + \dot{m}_{\text{outside}})} \]

\[ \text{Cooling energy}_{\text{ADS BED}} = \dot{m}_{\text{outside}} (h_1 - h_2) \]

\[ \text{Cooling energy}_{\text{WET HX}} = (\dot{m}_{\text{outside}} + \dot{m}_{\text{supply}})(h_3 - h_4) \]

\[ \text{Total cooling energy delivered} = \left[ \dot{m}_{\text{outside}} (h_1 - h_2) + (\dot{m}_{\text{outside}} + \dot{m}_{\text{supply}})(h_2 - h_4) \right] (1 - MR) \]

\[ EER = \frac{\text{Total cooling energy delivered}}{\text{Total electricity consumed}} \]

\[ \text{COP}_{\text{th}} = \frac{\text{Total cooling energy delivered}}{\text{Solar Heat delivered}} \]
INSTANTANEOUS ENERGY PERFORMANCES

Results of freescoo prototype installed at University of Palermo

Dehumidification

System operated for 5 h from 16:00 to 21:00

Flow rates of the system

Temperature profiles in the machine

Temperature profiles - solar collector

marco.beccali@unipa.it
INSTANTANEOUS ENERGY PERFORMANCES

Results of freescoo prototype installed at University of Palermo

Cooling after the sunset
Daily energy performances

Results of freescoo prototype installed at University of Palermo

Electricity distribution among the components

- Main fan: 71%
- Solar fan: 15%
- Other: 1.8%
- HX pump: 0.2%
- Cooling tower pump: 12%

- Daily EER = 8.8 NOT taking into account the PV production
- Daily EER_{grid} = 17.1 taking into account only the electricity taken from the grid
- Daily thermal COP_{coll} = 0.88 if ΔT=T_{coll out}-T_{coll in} is considered
- 51% of electricity taken from the grid
- 49% of electricity produced by PV

marco.beccali@unipa.it
- Two weeks of operation without any interruption of the monitoring
- Out Temperature raised up to 35°C
- Humidity ratio raised up to 20 g/kg
- About 15 kWh of cooling energy/day

Results of ENEA freescoo prototype
Average EER = 8.2 NOT taking into account the PV production
Average EER$_{\text{grid}}$ = 30.7 taking into account only the electricity taken from the grid
Average thermal COP = 0.72

Seven days of continuous stand-alone operation
27% of electricity taken from the grid
73% of electricity produced by PV

Results of ENEA freescoo prototype
SUMMARY OF MAIN RESULTS OF TESTS

- Low temperature of the regeneration of the desiccant (40-60°C)
- Desiccant bed is used as sorption storage permitting to supply cooling energy several hours after the sunset
- Control of the dehumidification process acting on the temperature of the bed is possible
- Pre-heating of regeneration air flow rate due to the metal casing of the machine
- Good performances both in terms of EER and thermal COP values registered
- Nominal cooling power never reached during the monitoring period
- Low electricity power (150W and 250W, resp. for the small and the bigger machine)
- Off-grid operation possible thanks to the internal PV production
- Control strategy of the desorption process of each desiccant bed can be optimized
Life Cycle Assessment (LCA) is a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (Norma ISO 14040). LCA is a useful tool to estimate resource use (raw materials and energy), energy and environmental burdens related to the life cycle of products and services.
The main goal of the LCA study is to assess the energy and environmental impacts of the manufacturing of Freescoo.

**FUNCTIONAL UNIT**

The functional unit (FU), which is defined as the reference unit through which the performance of a product system is quantified in a LCA, is one unit of Freescoo.

**BOUNDARIES**

The system boundaries include the supply of raw materials and energy sources, and the manufacturing of the examined product.

The other life-cycle steps as transports, operation and end-of-life, are not included in this analysis.
The inventory analysis is carried out in order to quantify inputs and outputs of the examined system by means of a mass and energy balance.

This step allows for the estimation of resource consumption, air, water and soil emissions, and waste production, during the life cycle of the FU.

The eco-profiles of materials and energy sources are mainly referred to the Ecoinvent database.
# LIFE CYCLE ASSESSMENT: LIFE-CYCLE INVENTORY

<table>
<thead>
<tr>
<th>COMPONENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADSORBENT BEDS (2)</td>
</tr>
<tr>
<td>SOLAR BATTERIES (2)</td>
</tr>
<tr>
<td>AIR DUCTS</td>
</tr>
<tr>
<td>ELECTRICRICY WIRES</td>
</tr>
<tr>
<td>PUMPS (2)</td>
</tr>
<tr>
<td>SOLAR PVT</td>
</tr>
<tr>
<td>TROTTLE VALVE (2)</td>
</tr>
<tr>
<td>AIR FILTERS</td>
</tr>
<tr>
<td>THERMAL INSULATION</td>
</tr>
<tr>
<td>EVAPORATIVE COOLING SUBSYSTEM</td>
</tr>
<tr>
<td>CASE</td>
</tr>
<tr>
<td>ELECTRIC SWITCHBOARD</td>
</tr>
<tr>
<td>CONTROL BOARD</td>
</tr>
<tr>
<td>SERVOMOTOR</td>
</tr>
<tr>
<td>INTERNAL FRAME</td>
</tr>
<tr>
<td>MAIN STRUCTURAL FRAME</td>
</tr>
<tr>
<td>COOLING TOWER</td>
</tr>
<tr>
<td>PLUMBINGS</td>
</tr>
<tr>
<td>4-WAY TROTTOLING VALVE</td>
</tr>
<tr>
<td>FANS (2)</td>
</tr>
</tbody>
</table>
LIFE CYCLE ASSESSMENT: LIFE-CYCLE INVENTORY

**MATERIALS (% OF MASS)**

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>MASS (kg)</th>
<th>MATERIAL</th>
<th>MASS (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIBERGLASS</td>
<td>5,0</td>
<td>GLASS WOOL</td>
<td>0,02</td>
</tr>
<tr>
<td>PVC</td>
<td>3,057</td>
<td>GLUE</td>
<td>0,138</td>
</tr>
<tr>
<td>BRASS</td>
<td>1,064</td>
<td>PV MODULE</td>
<td>12</td>
</tr>
<tr>
<td>PP</td>
<td>0,637</td>
<td>POLYCARBON</td>
<td>0,222</td>
</tr>
<tr>
<td>STAINLESS STEEL</td>
<td>29,354</td>
<td>SILICONE</td>
<td>1,393</td>
</tr>
<tr>
<td>GALVANIZED STEEL</td>
<td>179,118</td>
<td>ELASTROMERI</td>
<td>0,097</td>
</tr>
<tr>
<td>AL</td>
<td>44,994</td>
<td>HEPR/G21</td>
<td>0,097</td>
</tr>
<tr>
<td>COPPER</td>
<td>6,966</td>
<td>POLYESTER</td>
<td>0,18</td>
</tr>
<tr>
<td>CARBON STEEL</td>
<td>3,312</td>
<td>EPDM</td>
<td>2,902</td>
</tr>
<tr>
<td>SILICA GEL</td>
<td>24,4</td>
<td>TiNOX</td>
<td>0,0049</td>
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<tr>
<td>RUBBER</td>
<td>1,78</td>
<td>ALUMINIUM</td>
<td>0,27</td>
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<tr>
<td>ROCK WOOL</td>
<td>4,897</td>
<td>SILICON</td>
<td>0,019</td>
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<tr>
<td>GLASS</td>
<td>23,562</td>
<td>TIN</td>
<td>0,021</td>
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<tr>
<td>POLYESTER</td>
<td>0,139</td>
<td>PBT</td>
<td>0,3381</td>
</tr>
<tr>
<td>NYLON/PA 66</td>
<td>1,315</td>
<td>SILICA</td>
<td>0,0028</td>
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<tr>
<td>PAINTING</td>
<td>2,791</td>
<td></td>
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## Global energy requirement (GER)

<table>
<thead>
<tr>
<th>Primary energy consumption</th>
<th>Total (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non renewable, fossil</td>
<td>20,191.51</td>
</tr>
<tr>
<td>Non-renewable, nuclear</td>
<td>3,878.99</td>
</tr>
<tr>
<td>Non-renewable, biomass</td>
<td>0.12</td>
</tr>
<tr>
<td>Renewable, biomass</td>
<td>258.17</td>
</tr>
<tr>
<td>Renewable, wind, solar, geothermal</td>
<td>42.72</td>
</tr>
<tr>
<td>Renewable, water</td>
<td>2,858.02</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>27,229.53</strong></td>
</tr>
</tbody>
</table>

88.4% of the total

11.6% of the total
Global Energy Requirement

- PV/Solar Thermal panel: 23%
- Solar Batteries: 17%
- Evaporative cooling module: 12%
- Absorbent beds: 10%
- External frame: 7%
- Internal frame: 7%
- Air Filters: 7%
- Other Components: 17%
ROUGH ASSESSMENT OF PRIMARY ENERGY PAYBACK

Return of the total GER of the System

Assuming Average Low Voltage UE Mix
**LIFE CYCLE ASSESSMENT:**
**IMPACT ASSESSMENT AND INTERPRETATION**

<table>
<thead>
<tr>
<th>Environmental impacts</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global Warming Potential - GWP (kg CO$_{2eq}$);</td>
<td>1.59E+03</td>
</tr>
<tr>
<td>Ozone Depletion Potential - ODP (kg CFC-11$_{eq}$)</td>
<td>1.61E-04</td>
</tr>
<tr>
<td>Human toxicity (cancer effect) - HTc ($\text{CTU}_h$)</td>
<td>6.91E-04</td>
</tr>
<tr>
<td>Human toxicity (non-cancer effect) - HTn-c ($\text{CTU}_h$)</td>
<td>2.28E-03</td>
</tr>
<tr>
<td>Particulate Matter - PM (kg PM 2,5$_{eq}$);</td>
<td>1.19E+00</td>
</tr>
<tr>
<td>Ionizing Radiation (effect on human health) - IRh (kg U235$_{eq}$);</td>
<td>3.68E+02</td>
</tr>
<tr>
<td>Ionizing Radiation (effect on ecosystem) - IRe ($\text{CTU}_e$);</td>
<td>1.11E-03</td>
</tr>
<tr>
<td>Photochemical Ozone Formation - POF (kg NMVOC$_{eq}$)</td>
<td>5.20E+00</td>
</tr>
<tr>
<td>Acidification - Ac (mol H$_{eq}$)</td>
<td>1.15E+01</td>
</tr>
<tr>
<td>Terrestrial Eutrophication - TE (mol N$_{eq}$)</td>
<td>1.69E+01</td>
</tr>
<tr>
<td>Freshwater Eutrophication - FE (kg P$_{eq}$)</td>
<td>1.56E+00</td>
</tr>
<tr>
<td>Marine Eutrophication - ME (kg N$_{eq}$)</td>
<td>1.64E+00</td>
</tr>
<tr>
<td>Freshwater Ecotoxicity - FET ($\text{CTU}_e$)</td>
<td>5.52E+04</td>
</tr>
<tr>
<td>Land Use - LU (kg deficit C)</td>
<td>1.79E+03</td>
</tr>
<tr>
<td>Water Resource Depletion - WRD (m$^3$ water$_{eq}$)</td>
<td>4.60E+03</td>
</tr>
<tr>
<td>Mineral, Fossil, Renewable Resources Depletion - RD (kg Sb$_{eq}$)</td>
<td>3.14E-01</td>
</tr>
</tbody>
</table>

The main contribution to the other environmental impacts is due to solar batteries except for:

- ODP, IRh, IRe, WRD and RD, that are mainly caused by PV/solar thermal panel.
CONCLUSIONS

- The study aimed at evaluating the energy and environment impacts of the manufacturing step of Freescoo. The analysis was carried out through the application of the LCA methodology, in accordance with the standards of the ISO 14040 series.
- The analysis highlighted that the main energy and environmental impacts related to the manufacturing of the selected FU are caused by PV/solar thermal panel, solar batteries, evaporative cooling module and adsorbent bed.
- The results of the research can represent a “knowledge basis” to assess the real advantages arising from the use of new all-in-one compact solar Desiccant Evaporative Cooling air conditioner systems as Freescoo.
- Further analyses of the Freescoo technology will include the impacts assessment of the other life-cycle steps as transports, operation and end-of-life.
Thank you for your attention

Prof. Marco Beccali       e-mail: marco.beccali@unipa.it

Dipartimento di Energia, Ingegneria dell’Informazione e Modelli Matematici
University of Palermo,
Viale delle Scienze Ed.9, 90128 Palermo, Italy