Development of an Advanced Solar-hybrid Adsorption Cooling System for Decentralised Storage of Agricultural Products in India

S. Mande, P. Ghosh, V.V.N. Kishore
Tata Energy Research Institute
Darbari Seth Block, Habitat Place
Lodhi Road
New Delhi - 110 003
India

K. Oertel, U. Sprengel
Deutsche Forschungsanstalt für Luft- und Raumfahrt e.V.
Institut für Technische Thermodynamik
Pfaffenwaldring 38-40
70569 Stuttgart, Germany

Abstract

Agricultural products play a significant role and could yield substantial amount of foreign exchange for a tropical country like India. However, in India 30% of the agricultural products are spoiled in storage and transit. In this present investigation, funded by EC (DG-XII), TERI (Tata Energy Research Institute) and DLR (German Aerospace Establishment) have jointly designed and tested a solar-hybrid methanol/silicagel based adsorption cooling system for its possible application for decentralised cold storage of agricultural products in India where electricity is either not available or not reliable.

A 10 kW (2.9 TR) system (for 100 t of agro-products, 240 m^3 in volume) has been designed and preliminary testing has been completed successfully. Methanol/silica gel working pair has been used in the adsorption refrigeration unit. It is operating with a very low (75-80 °C) generation outlet temperature and rejecting heat at near ambient. This 10 kW$_{th}$ capacity cooling unit has offered cooling with a coefficient of performance (COP) for cooling of 0.3 to maintain a cold storage at 1 to 3°C and cooling density of 100 W/kg silicagel at an evaporator temperature of 0°C. The system is designed as a stand alone solar and waste heat driven cold storage with a dual-fuel engine, which generates 5 kW$_e$ electricity side by side. It has been estimated that the pay back period of such a system will be about 5 years with a 30-50% increment in electricity purchase rate of Indian State Electricity Board.

Key words Adsorption cooling, cold storage, dual fuel engine, methanol/silicagel, solar-hybrid

1. Introduction

In a tropical country like India the demand for cold storage in agricultural sector can hardly be over emphasised. Agricultural products play a significant role and could yield a substantial amount of foreign exchange of the country. However, between production and actual sales, about 30% of the products are spoiled in storage and transit. In India agricultural production centres are usually situated in areas where electricity supply for running refrigeration plant is either not available or not reliable. Under these circumstances, a non electric decentralised cold storage is one of the feasible options for agricultural cold storage in rural India. Solar assisted refrigeration with low grade heat input is one of the promising solutions to this problem. Solar arrays require large area and hence high capital cost. Hence, it has been decided that a solar-hybrid (solar and biomass dual fuel engine waste heat) system will be an ideal option for this application as this will require electricity for pumping and controls. This will simultaneously address to the decentralised storage of agricultural products as well as power generation in rural India. Solar is a zero emission technology and acts as a buffer as far as carbon dioxide emissions potential is concerned.

Heat operated cooling systems are of two types, absorption cooling system, adsorption cooling system. At present the market of sorption refrigeration systems is dominated by water-lithium-bromid (H_2O-LiBr) systems, which are normally used for air-conditioning applications. The $COP_{cooling}$ (coefficient of performance) is about 0.7 for the single effect system and 1.2 for the double effect cooling machines.

Ammonia-water (NH_3-H_2O) absorption refrigeration systems are normally preferred for low temperature applications, but the heat input required is at a temperature higher than 120°C for steam and 340°C in case of exhaust gas. So invention of new cooling technology is needed which can operate with low temperature heat source. In this connection adsorption cooling technology will provide a viable option for the decentralised cold storage of agricultural products in India.

In this present investigation, a 10 kW system (for 100 t of agro products, 240 m^3 in volume) has been designed and preliminary testing has been completed successfully. Methanol/silicagel working pair has been used in the adsorption refrigeration unit. It is operating with a very low generation outlet temperature of 80 to 85°C and rejecting heat at near ambient. This cooling unit can offer 3.6 kW_{th} cooling (average) and 10 kW_{th} (peak), with a cooling *COP* of 0.3 at -2°C. The system is designed as a stand alone solar and waste heat driven cold storage with a dual-fuel engine, which generates 5 kW_e electricity side by side. It has been estimated that the pay back period of such a system will be about 5 years with a 30-50% increment in electricity purchase rate of Indian State Electricity Board [1, 2].

2. Adsorption refrigeration system

Likely in a vapour compression system the adsorption refrigeration system also consists of a compressor, a condenser, a throttle valve, and an evaporator. However, in this system the compressor is replaced by a thermal compressor which is operated by heat instead of a mechanical energy. The vaporised refrigerant is adsorbed in the pores of the adsorbent in the reaction chamber. Thus the operation of the adsorption cooling system depends on

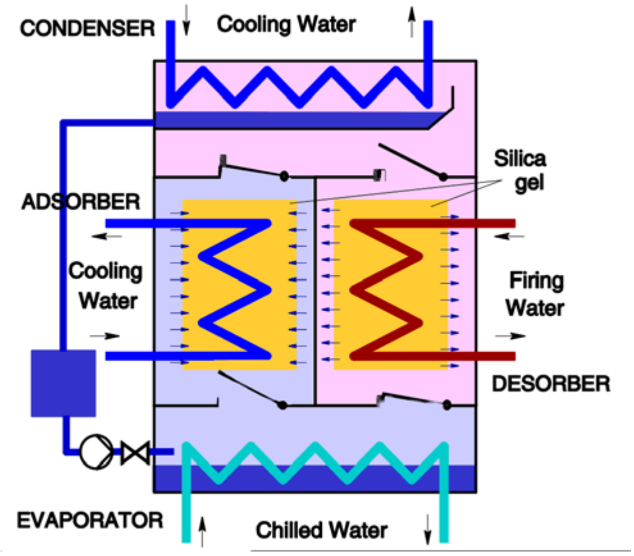


Figure 1 Two chamber adsorption cooling system [3]

adsorption/desorption characteristics of the particular adsorbent/refrigerant pair. Due to the loading of the adsorbent, the thermal compressor is operated intermittently. During the first phase of the operation the refrigerant is evaporated at a low pressure and low temperature in the evaporator and is adsorbed by refrigerant under isobaric conditions.

In the next phase, the charged refrigerant is regenerated by heating up the adsorber (temperature swing). A two chamber adsorption cooling system, described in Figure 1, enables continuos operation.

2.1 Choice of refrigerant

Ammonia/activated carbon, methanol/silicagel, water/silicagel are the common adsorbate/adsorbent pair in adsorption cooling systems. Activated carbon/ammonia pair requires high temperature (>120°C) input heat for regeneration. So this pair will not be suitable for this particular application. Water/silicagel, methanol/silicagel are the ideal pair which may get activated even at a temperature of 60-70°C. But water is not a suitable refrigerant for sub-zero temperature application, hence for this cold storage application methanol/silicagel adsorbent/ refrigerant has been selected [4].

2.2 Thermodynamics

Concentration *C* of methanol in silicagel is a function which is defined as the ratio of adsorbent and adsorbate.

$$C = \frac{m_{adsorbate}}{m_{adsorbent}}$$

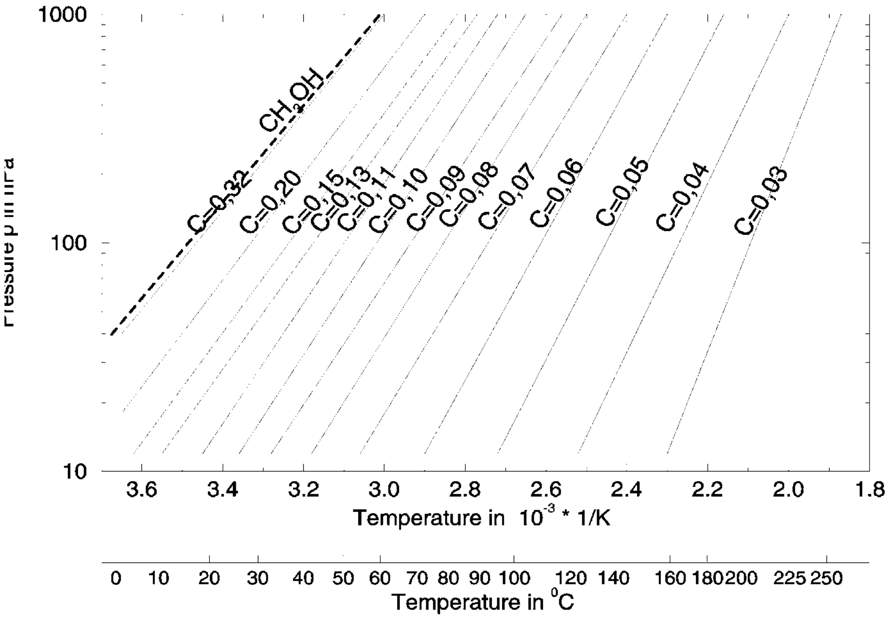


Figure 2 p-T-C diagram of methanol/silica gel as adsorbent/refrigerant pair [6]

The concentration of methanol in silicagel is based on the equilibrium pressure and temperature of the methanol/silicagel mixture.

$$C = f(p,T)$$

The *p-T-C* diagram obtained for methanol/silicagel pair is given in Figure 2.

Transient adsorption isosters start from the initial concentration C_0. The maximum uptake C_{max}, which is reached at an adsorption process, depends on the condenser cooling water temperature, T_c and the evaporator pressure p_0.

The time behaviour of adsorption can be described by the differential equation [5],

$$\frac{dC(T)}{dt} = k_s a_p \left(C_{\max} - C_0\right)$$

with the temperature dependent mass transfer coefficient $k_s a_p(T)$.

$$k_s a_p = \frac{C_1}{r_{part}^2} \exp\left(\frac{-C_2}{T}\right)$$

C_1 and C_2 are material constants and r_{part} is the size of the adsorbent particle.

At an ideal system the cooling power Q_0 of the evaporator is equivalent to the energy set free during the adsorption. Thus Q_0 is the sum of the adsorption heat and the sensible heat of the adsorber

$$Q_0 = \frac{dC}{dt} m_{dry\ ads} \Delta h_{ads} + Q_{sensible}$$

The $COP_{cooling}$ can is defined as the quotient of heat transferred in the evaporator to the heat required for regeneration Q_H

$$COP_{cooling} = \frac{Q_0}{Q_H}$$

A laboratory test facility has also been built up at DLR to examine the real operational conditions for an adsorption cooling system with the working pair methanol/silicagel. Figure 3 shows the schematic diagram of the test setup. The central part of the system is a vacuum chamber. In the chamber a finned tube heat exchanger packed with silicagel is placed on an electronic scale to record the weight of the adsorbent as well as adsorbate. Pressure, temperature in the reaction chamber and mass flow rate as well as inlet and outlet temperature in the different heating and cooling loops can also be measured to calculate the heat duty of different component under real operating conditions. Specifications of the adsorption test facility have been described in Tab. 1.

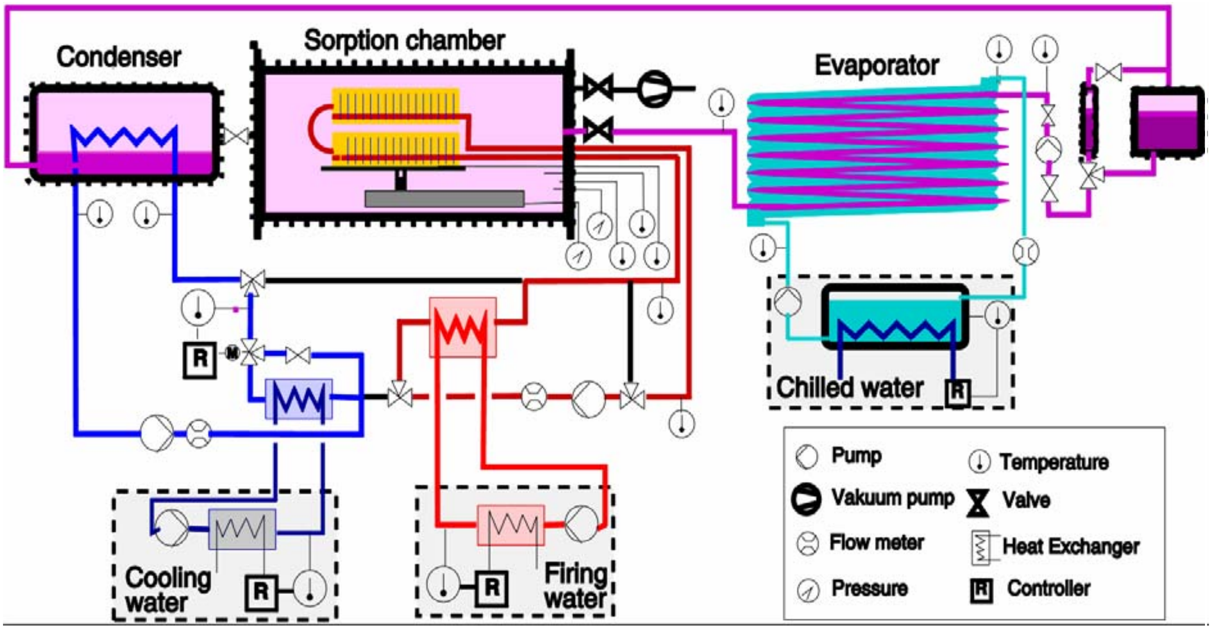


Figure 3 Test set up to evaluate the performance of methanol/silicagel based adsorption refrigeration system

Table 1. Specifications of the adsorption refrigeration test set up and real evaluation of the performance parameters of adsorption refrigeration system with methanol/silicagel pair

Sorption chamber	Volume Mass of silicagel	24 l 0.6 kg
Condenser cooling water	Temperature range Heat duty at 30 °C	0-40 °C 2 kW_{th}
Generator firing water	Temperature range Heat duty	20-95 °C 6 kW_{th}
Evaporator	Temperature range Heat duty at 0 °C	-5-30 °C 2 kW_{th}
Cooling density at T_o=0°C, T_H=85°C, T_C=28°C		10 $W/kg_{silicagel}$

Exhaustive testing have also been carried out with silicagel/methanol to evaluate the cooling power as well cooling rate and cycle time. Figure 4 indicates that, the cooling power for methanol/silicagel adsorbent/refrigerant pair is providing almost 100 W of peak cooling at T_0 =-2 °C, T_H = 85 °C and T_c = 30 °C. In this particular case 40 min is the total cycle time, which reduces the cooling rate. This indicates that this system requires better heat transfer augmentation in adsorber/generator section and reduction of thermal mass in the evaporator and condenser section to reduce the sensible losses.

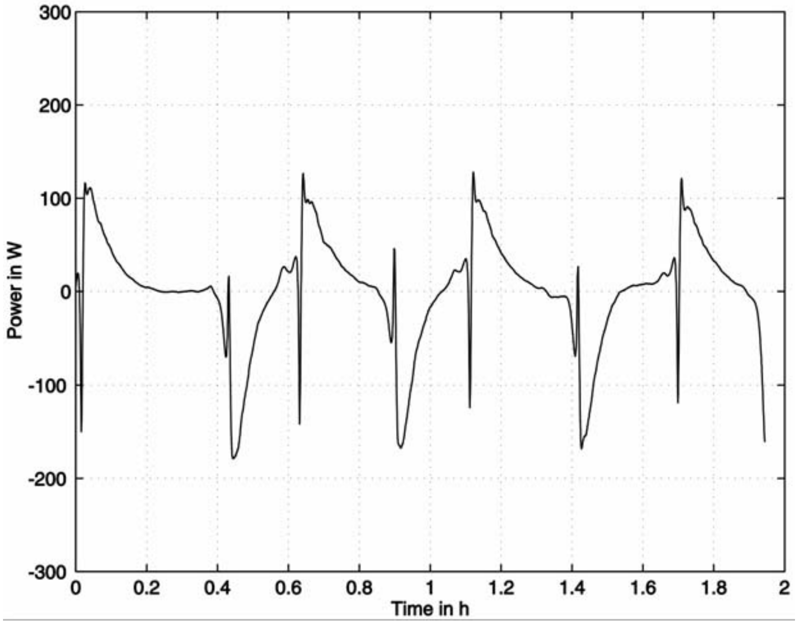


Figure 4 Measured cooling power for methanol/silica gel adsorption refrigeration system at T_o=-2°C, T_H=85°C and T_c=30°C

Table 2. Performance of the modified methanol/silicagel based adsorption chiller [1]

Generator	Firing water temperature Outlet temperature Volume flow rate	85 °C 75 °C 1.2 m^3/hr
Chilled water/brine	Inlet temperature Outlet temperature Volume flow rate	2 °C -2 °C 1.5 m^3/hr
Condenser cooling water	Inlet water temperature Outlet temperature Volume flow rate	30 °C 34 °C 4 m^3/hr
COP	Cooling/input energy rate	0.3

A German company is marketing Japanese water/silicagel based adsorption chiller in Europe for air-conditioning application. The technical specification of this chiller with 10 kW_{th} nominal capacity as been presented in Table 2.

It is evident that, the COP of water/silicagel based refrigeration system is higher than of a methanol/silicagel based refrigeration system due to the higher latent heat of evaporation of water and latent heat of desorption under same operating conditions (Table 3). Moreover, specific heat of methanol is much lower than that of the water which increases the heat requirement for preheating.

Table 3. Heat of evaporation and desorption of water and methanol with silicagel [6]

Refrigerant	Latent heat of evaporation *p*=100 hPa, in kJ/kg	Latent heat of desorption *C*=8%, in kJ/kg
Water	2400	3020
Methanol	1200	1680

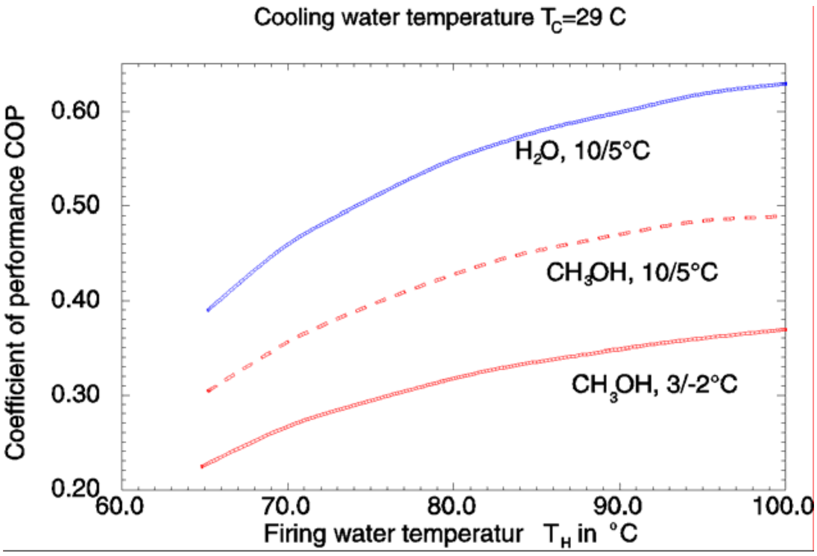


Figure 5 Variation of COP with the variation of driving water temperature for water/silica gel and methanol/silica gel at T_c=30°C

Variation of COP with driving temperature, both for water/silicagel and methanol/silicagel pair, is given in Figure 5. The lower ratio of phase change energy to energy needed for heating up reduces the COP for methanol/silicagel additionally be about 25% compared to the system with water/silicagel pair. By lowering the cold water temperature the COP decreases further due to the efficiency of the Carnot cycle.

$$COP_{methanol} = 0.75\ COP_{water}$$

3. System simulation and results

In this study system design and size have been done by using a balanced trade among parametric study, technical feasibility, economic analysis as well as global warming potential.

In this connection it can be mentioned that this kind of cooling technology requires some electricity for controls and pumping etc. So it seems to be more convenient, to combine the solar thermal system with a backup of waste heat from agricultural waste based power generation through biomass gasifier based dual fuel engine has been selected.

So as a base case a silicagel/methanol vapour adsorption refrigeration system (VAdRS) will be driven by solar thermal process heat as well as waste heat from the biomass gasifier based dual fuel engine has been chosen. System description and simulation scheme of the test plant has been described in Figures 6 and 7 respectively.

To implement the heat demand controlled generator set, a special control mechanism has been used to balance the buffer storage temperature, the temperature of the generator set and flue gas temperature.

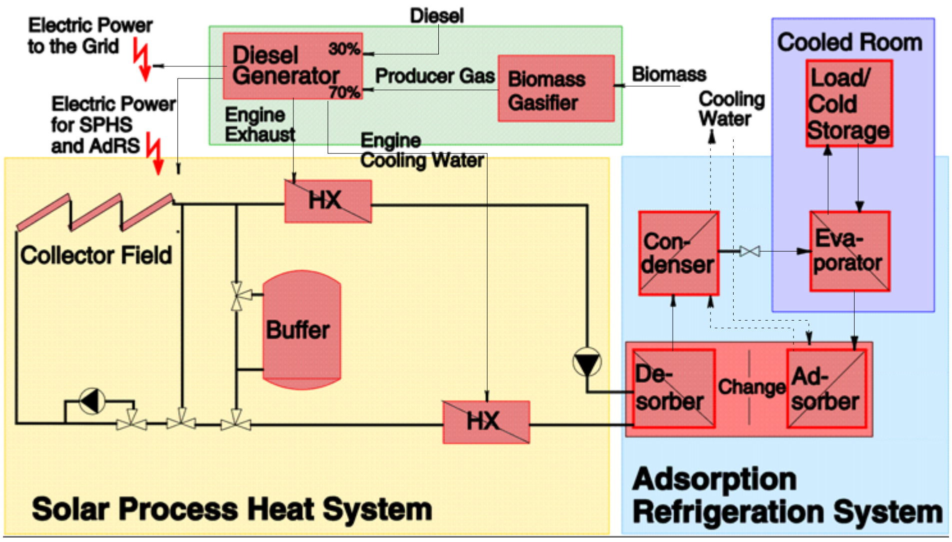
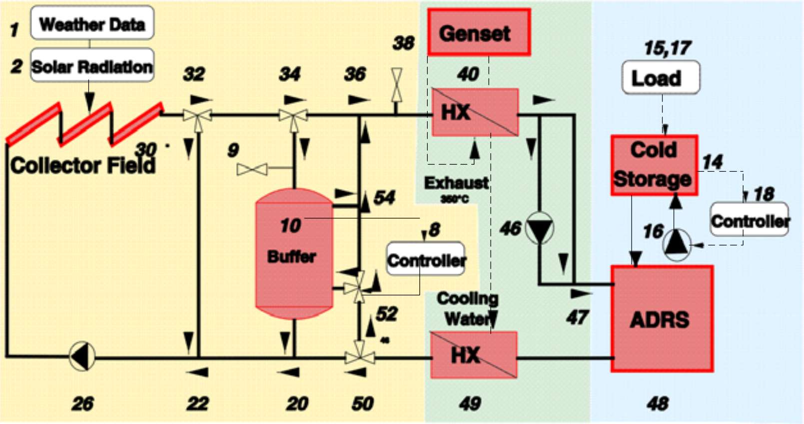


Figure 6 System description of the test plant



Unit	Component	Unit	Component
1, 2, 15, 17	Data input	20, 22, 36, 47, 54	T-Piece
8, 18	Controller	30	Collector
9, 38	Pressure relief valve	32, 34, 45, 50, 52	Flow diverter
10, 14	Storage tank	40, 49	Heat exchanger
16, 26, 46	Pump	48	Adsorption chiller

Figure 7 Simulation scheme for the test plant

The simulation has been developed, basing on the programme package TRNSYS, with this system description as a basic case [7]. All the system components are modelled by separate FORTRAN subroutines, which describe the physical behaviour of these components. Size and performance of each component has been predicted through this simulation programme by using economic analysis as a boundary conditions.

In this configuration modified diesel genset operating on dual fuel mode has been selected in such a way that the waste heat recovered from its exhaust will meet the balance heat requirement (apart from that obtained by solar collectors). The temperature of the engine cooling water is limited by 85 °C. So the engine cooling water will heat up the outlet water of the desorber. Generator exhaust will pass through a heat exchanger where it will heat up the water which will be stored in the buffer storage. Two pressure relief valves have been incorporated in the buffer storage to avoid superheating and steam formation up to 100 °C.

4. Economic analysis and CO_2 emission potential

A detailed economic feasibility has been carried out for this solar-hybrid adsorption cooling system. It has been estimated so far, that an increase in solar fraction will increase the payback period due to the additional investment on solar collectors. In order to improve the economic viability of the solar-hybrid cooling system, the contribution of dual fuel engine waste heat in the process heat demand has been increased. Thus, a reasonable balance between the solar and biomass/diesel fraction has been done to optimise the cost as well as carbon dioxide emission potential. Solar fraction is limited by initial investment costs, the necessary higher amount of waste heat from dual fuel genset provides additional power which will be fed to the grid. The selling of this surplus electric power means additional revenue without much increment

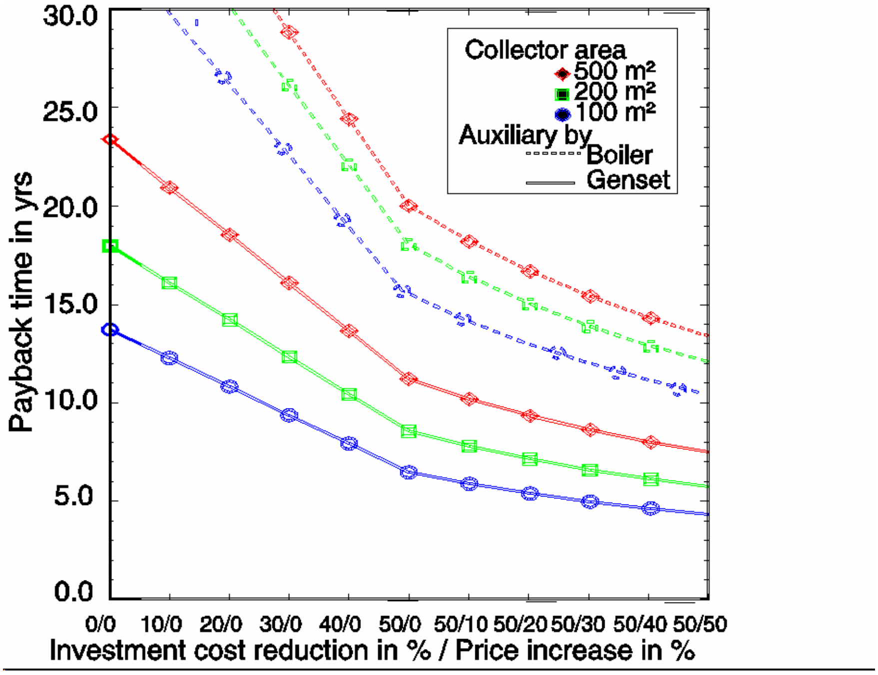


Figure 8 Payback period for variation of cost reduction and price increase of electricity

in capital and operating cost of the cooling system. Increment in state electricity price by 30-50% (from present level of Rs. 2.25 per kWh) and proper commercialisation of this silicagel/methanol based cooling system in India will provide a payback period of 3-5 years [1]. A comprehensive economic analysis has been presented herewith in Figure 8. Design parameters of the pilot test plant, which will be constructed at TERI's Gual Pahari campus in the next phase of the project has been described in Table 4.

Table 4. Design parameters of the pilot plant to be constructed at TERI campus

Cold storage	Volume Temperature	240 m^3 1-3 °C
Adsorption cooling m/c	Effective capacity COP	10 kW_{th} 0.3
Cooling tower Gasifier Genset	Heat duty Thermal capacity Electric power Amount of waste heat	18 kW_{th} 20 kW_{th} 5 kW_e 5-8 kW_{th}
Solar collector (CPC)	Outlet temperature Average heat rate Peak heat rate	85 °C 4.8 kW_{th} 19 kW_{th}
Buffer tank	Volume	5 m^3
Solar fraction		50%

Solar-hybrid cooling systems will also address to the global warming problem due to the use of non CFC based refrigerant and reduction in carbon dioxide emission due to the increase in primary energy efficiency. While, solar systems are zero emission technologies, biomass system can also be turned into zero emission one through compensated afforestation. In this particular hybrid cooling system solar thermal collectors have been used with the thermal mix of waste heat of gasifier based power generation. In Figure 9 carbon dioxide production in this solar-hybrid cooling system has been plotted with kgCO$_2$/kWh of cooling at different solar fractions. Excess amount of generated power will be used by the near by community for their household purposes which means that the amount of power has been generated without generating extra amount of carbon dioxide. This analysis has been done, for a properly selected engine which can cater a heat requirement of a dedicated waste heat driven cooling system as well as solar-hybrid cooling system. At 20 % solar fraction, when diesel engine will be running at 74-75 % loading of the engine, diesel replacement dips down sharply and it dips the kgCO$_2$ production/kWh of cooling too. It has also been observed that with the increase of solar fraction production of kgCO$_2$/kWh of cooling will be reduced due to the maximum use of solar thermal energy in the thermal form.

It has been clearly indicated that, the specific CO$_2$ production is about 0.5 kgCO$_2$/kWh$_{cooling}$ in such a conventional system. In the solar-hybrid cooling system using 50 % solar fraction, which will be used in the test plant, CO$_2$ production is 0.6 kgCO$_2$/kWh $_{cooling}$. So the configuration of the test plant is almost in the break even of the conventional and the solar-hybrid system as far as CO$_2$ production is concerned. It has also to be mentioned that, compensated afforestation or usage of agricultural waste as a biomass fuel will reduce the CO$_2$ production significantly in the solar-hybrid cooling system.

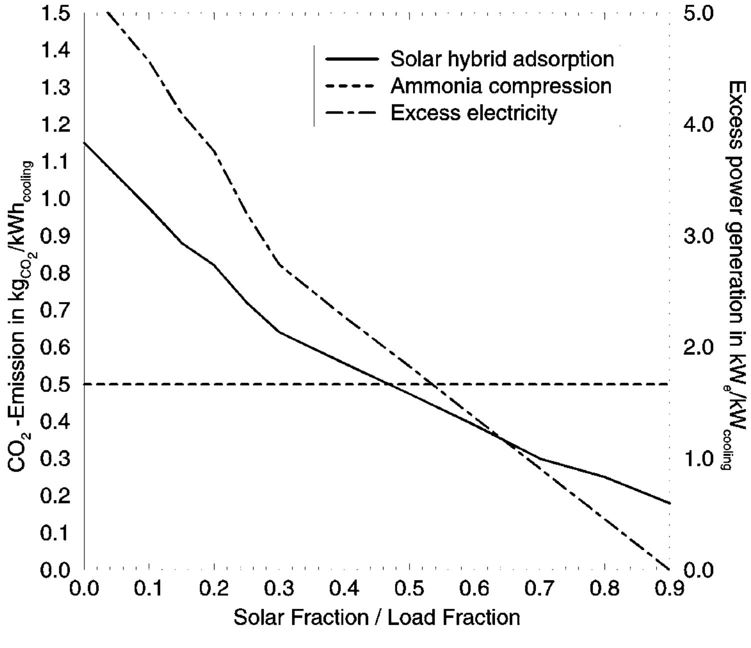


Figure 9 CO2-Analysis for conventional and solar hybrid cooling system

5. Conclusions

Solar-hybrid adsorption cooling system is a techno-economically sustainable option for the decentralisation of Indian cold storage of agricultural products. The demonstration plant in India will lead this solar-hybrid cold storage technology towards commercialisation of this product. Moreover, silicagel/methanol based 10 kW_{th} (~2,9 TR) capacity adsorption chiller can cater the need of air-conditioning as well as low temperature applications with a low driving water temperature, which is not available off the shelf, by the joint research of DLR (German Aerospace Research Establishment) and TERI (Tata Energy Research Institute) with the active co-operation of German and Indian corporates in the refrigeration sector.

Nomenclature

C	Concentration
COP	Coefficient of performance
p	Pressure (Pa)
T	Temperature (°C)
$k_s a_p$	Mass transfer coefficient
t	time (s)
Δh	Heat of adsorption (J)
m	Mass (kg)
r_{part}	Radius of the particle (m)
Q	Heat duty (W)

Subscripts**:**

ads	Adsorption
c	Condenser
0	Evaporator
H	Heat input
max	Maximum

References

1. Oertel K. et al.: DLR-TERI Joint project report: Advanced solar-hybrid adsorption cooling system for decentralized storages of agricultural products in India; submitted to The Commission of the European Communities, DG-XII, 1996.
2. Köhne R., Oertel K. and Zunft, S.: Investigation of control and simulation of solar process heat plants using a flexible test facility; Solar Energy, Vol. 56, No. 2, pp. 169-182, 1996.
3. GBU GmbH: Adsorption - Chiller TYPE NAK, 50-430 kW; Technical information, Bensheim, Germany.
4. Critoph R.E.: Performance limitation of adsorption cycles for solar cooling; Solar Energy; Vol. 41, No. 1; pp. 21-31; 1988.
5. Sakoda, A. and Suzuki, M.: Fundamental study on solar powered adsorption cooling system; Journal of Chemical Engineering of Japan, Vol. 17, No. 1; 1984.
6. Khelifa N.: Das Adsorptionspaar Silicagel-Wasserdampf, Anwendung als solares Klimatisierungssystem; Diss.; München; 1985.
7. Klein, S.A., et. al.: TRNSYS - A transient system simulation program - Engineering Experimentation Station Report 38-13, Solar Energy Laboratory; Madison-Wisconsin; 1990.