Techno-economic Comparison of Small Scale Solar Thermal and Solar Photovoltaic Cooling Systems

Ph.D. Thesis

by

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(ID No. 2008 RME 902)

DEPARTMENT OF MECHANICAL ENGINEERING

MALAVIYA NATIONAL INSTITUTE OF TECHNOLOGY JAIPUR

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In memory of my beloved late father

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DEPARTMENT OF MECHANICAL ENGINEERING

CERTIFICATE

This is to certify that the thesis entitled "***Techno-economic Comparison of Small Scale Solar Thermal and Solar Photovoltaic Cooling System***" is being submitted by ***Bachchu lal (ID No.2008 RME902)*** to the Malaviya National Institute of Technology, Jaipur for the award of the degree of **Doctor of Philosophy** in Mechanical Engineering is a bonafide record of original research work carried out by him. He has worked under my guidance and supervision and has fulfilled the requirement for the submission of this thesis, which has reached the requisite standard.

The results contained in this thesis have not been submitted in part or full, to any other University or Institute for the award of any degree or diploma.

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ABSTRACT

This study covers the techno- economic comparison between solar energy based cooling systems using solar thermal and solar photovoltaic (PV) technology. Analysis has been carried through simulation of a typical office building considered to be located in four different cities, representing four climatic zones of India namely Hot and dry, Warm and humid, Moderate, and Composite. The fifth climatic zone of the country i.e. Cold and cloudy has not been considered due to very less and practically insufficient cooling demand as compared to other four. For both the cooling technologies multiple options have been considered; flat plate, evacuated and compound parabolic collector for solar thermal and mono crystalline, poly crystalline and thin film for PV. A single effect lithium bromide vapour absorption chiller has been considered for producing cooling effect in the solar thermal route, where as vapour compression cycle based cooling system is modeled in photovoltaic route. For a comparative analysis, the building geometry, user profile and construction have been considered identical for chosen locations in four climatic zones; Ahmedabad from hot and dry zone, Bangalore from moderate zone , Chennai from warm and humid zone and Delhi from composite zone. Energy simulation of building and coupled solar cooling system has been carried using TRNSYS v-17 software. Numerous iterations were carried out for different technology versions and with a wide variance of collector/PV area.

It has been analyzed that solar thermal cooling system offers a higher solar fraction and primary energy savings than its photovoltaic counterpart for the same collector/PV area for all climatic zones because in the thermal cooling system there is a storage device (hot storage tank) between the solar thermal collector and cooling machine resulting in continuous operation of vapour absorption machine without using the grid power for small fluctuation in solar radiations.

In the solar photovoltaic cooling system (grid supported) the annual solar fraction is calculated without considering the storage device. The vapour compression machine (Packaged air conditioner) requires a fix amount of power to drive the

compressor, if instantaneously it is available on PV it is supplied to the cooling system otherwise it is taken from the grid and not accounted for calculation of the annual solar fraction.

As compared to a conventional non solar air conditioner the primary energy savings reaches up to 74 % in the solar thermal cooling system for moderate climate because of the low cooling energy demand while in the solar photovoltaic primary energy savings reaches 60% in the moderate climate (Bangalore).

From the economic point of view the solar thermal cooling system using an absorption chiller has a high initial cost compared to vapour compression system resulting in higher payback periods (65-242 years) which is much higher than the system life itself, practically being the case of no payback period. The solar photovoltaic cooling system also has higher payback periods, however it is significantly lower than solar thermal systems in all the climatic zones and the least being 14 years for the hot and dry climate. When PV based systems are optimally used with net metering provisions during the non cooling periods then the payback period reduces to 4-6 years for all the four climate zones.

In order to increase the solar fraction of the PV cooling systems various techniques were analyzed using tracking, thermal mass, modifying sizing approach of air conditioner and use of VRF technology. It was observed that using VRF technology solar fraction reaches in the range of 0.84 to 0.95 from earlier range 0.37 to 0.60 as in the case of non VRF compressor. The payback comes down to 11 years for the warm and humid climate. By using the modified approach for sizing air conditioner due to higher indoor air velocity, the capacity of air conditioner reduced from 10 TR to 7 TR, which in turn increased the solar fraction to the ranges of 0.77 to 0.89 from earlier range 0.37 to 0.60. The payback comes down upto 10 year for the warm and humid climate as compared to 15 year in earlier case. Use of double axis tracker enhanced the solar fraction only by 5 to 9 %, and therefore its payback period increases over non tracking system. Use of thermal mass in building envelope was not found to have significant impact on solar fraction.

On the basis of techno-economic analysis, considering the prevailing costs and performance levels solar thermal cooling systems for small office building are not financially feasible. However this type of systems may be feasible in the remote areas where the grid electricity is not available and local generation of electricity is too costly. Grid supported solar PV based cooling system (using non VRF compressor) have higher financial payback than the acceptable limit of market. However use of VRF technology and modifying sizing approach of air conditioner makes the PV cooling system technically feasible. The financial feasibility with use of VRF technology and modifying sizing approach of air conditioner found to be closed to acceptable limit. Introducing the net metering system for small scale systems through modifying in renewable energy policy, brings the payback period of solar PV based cooling system significantly down and to the level of acceptance in free market. Hence this study recommends use of solar photovoltaic based cooling system through VRF compressor based air conditioner, used modified sizing approach and introduction of net metering systems with the utility.

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NOMENCLATURE

Notation	Description	Unit
A	Collector area	m^2
a_1 and a_2	Collector loss coefficients.	W/m^2-K
C_p	Specific heat of the water	kJ/kg-K
G_T	Solar radiation intensity	W/m^2
h	Convective heat transfer coefficient of air	$Wm^{-2}\ {}^{o}C^{-1}$
kWh_{el}	Electrical energy	kWh
kWh_{th}	Energy in cooling	kWh
l	Volume	liter
Q_1	Annual radiation on solar collectors	kWh
Q_2	Annual heat produced by solar collectors	kWh
Q_3	Annual required heat for ACM	kWh
Q_4	Annual heat removed by cooling tower	kWh
Q_5	Annual cooling produced by ACM	kWh
Q_6	Annual cooling produced by electrical chiller	kWh
Q_7	Annual overall cold production	kWh
Q_8	Annual cooling demand	kWh
Q_9	Annual heating demand	kWh
Q_{10}	Annual heat demand for domestic hot water	kWh
Q_{11}	Annual heating provided by backup of the thermal solar system	kWh
Q_{12}	Annual heating provided by the solar collectors	kWh
Q_{13}	Annual heat for domestic water provided by the backup of the thermal solar system	kWh
Q_{14}	Annual heat for domestic hot water provided by the solar collectors	kWh
Q_c	Condenser capacity	kW
Q_e	Evaporative capacity	kW
Q_g	Generative capacity	kW
Q_s	Thermal storage capacity	m^3
Rs	Indian currency	Rupees
U	Heat transfer coefficient	$Wm^{-2}\ {}^{o}C^{-1}$
V	Volume of the cold storage tank	m^3
ΔT	Temperature difference	°C
η_0	Conversion factor	Unit less

Notation	Description	Unit
ρ	Density of water	kg/m^3
$\eta_{sol-pow}$	Efficiency of solar panel	Unit less
$\eta_{pow-cool}$	Efficieny of refrigeration machine	Unit less
$\eta_{sol-cool}$	Overall efficiency of solar electric cooling system	Unit less
β	Slope of PV array	degree
γ	Empirical PV curve-fitting parameter	
η_c	Module conversion efficiency	Unit less
μ_{Isc}	Temperature coefficient of short-circuit current	A/K
μ_{Voc}	Temperature coefficient of open-circuit voltage	V/K
$\tau\alpha$	Module transmittance-absorptance product	
I	Current	A
I_L	Module Photo current	A
$I_{L,ref}$	Module photocurrent at reference conditions	A
$I_{o,ref}$	Diode reverse saturation current at reference conditions	A
I_{sc}	Short-circuit current	A
$I_{sc,ref}$	Short-circuit current at reference conditions	A
I_{mp}	Current at maximum power point along IV curve	A
$I_{mp, ref}$	Current at maximum power point along IV curve, reference conditions	A
IAM	Dimensionless incidence angle modifier	Unit less
G_T	Total radiation incident on PV array	W/m^2
$G_{T,Beam}$	Beam component of incident radiation	W/m^2
G_{Tdiff}	Diffuse component of incident radiation	W/m^2
$G_{T,gnd}$	Ground-reflected component of incident radiation	W/m^2
$G_{T,NOCT}$	Incident radiation at NOCT conditions	W/m^2
$G_{T,ref}$	Incident radiation at reference conditions	W/m^2
R_s	Module series resistance	Ω
R_{sh}	Module shunt resistance	Ω
NP	Number of modules in parallel in array	Unit less

Notation	Description	Unit
NS	Number of modules in series in array	Unit less
V	Voltage	V
V_{mp}	Voltage at maximum power point along IV curve	V
$V_{mp,ref}$	Voltage at maximum power point along IV curve, reference conditions	V
V_{OC}	Open-circuit voltage	V
$V_{oc,ref}$	Open-circuit voltage at reference conditions	V
P_A	Power from the solar cell	kJ/hr
P_D	Power demanded by load	kJ/hr
P_L	(+) Power sent to load from array and battery (-) Power sent to battery from utility	kJ/hr
P_{LMAX}	Output capacity of inverter (or if negative, Input current limit)	kJ/hr
P_R	Power "dumped" or not collected	kJ/hr
P_U	Power supplied by ($P_U > 0$) or fed back to ($P_U < 0$) utility	kJ/hr
P_B	Power to or from battery (+ charge, - discharge	kJ/hr
P_{BMAX}	Maximum Input (charge)	kJ/hr
P_{BMIN}	Minimum output (discharge) of battery	kJ/hr
P_C	Allowed charge rate when battery at high voltage limit VC	kJ/hr
P_{vd}	Allowed charge rate when battery is at low voltage limit V_D	kJ/hr
F	Fractional state of charge of battery (1.0 = full charge)	Unit less
F_C	High limit on F, when battery charging	Unit less
F_B	Limit on F, above which battery can begin to discharge after being charged	Unit less
F_D	Low limit on F, when battery discharging	Unit less
V	Battery voltage (and solar cell array voltage, in mode 3)	V
V_C	High limit on V, when battery charging	V
V_D	Low limit on V, when battery discharging	V
Efficiency 1,2	Power efficiencies of regulator and inverter (DC to AC and AC to DC)	Unit less
$T_{evap,in}$	Temperature of air entering the evaporator side of the coil	˚ C
$h_{evap,in}$	Enthalpy of air entering the evaporator side of the coil	kJ/kg

Notation	Description	Unit
$P_{evap,in}$	Pressure of air entering the evaporator side of the coil	atm
$\omega_{evap,in}$	Humidity ratio of air entering the evaporator side of the coil	kg H_2O/kg air
$T_{evap,out}$	Temperature of air exiting the evaporator side of the coil	˚ C
$h_{evap,out}$	Enthalpy of air exiting the evaporator side of the coil	kJ/kg
$P_{evap,out}$	Pressure of air exiting the evaporator side of the coil	atm
$\omega_{evap,out}$	Humidity ratio of air exiting the evaporator side of the coil	kg H_2O/kg air
Q_{Total}	Rate of total energy transferred by the coil	kJ/hr
$Q_{Rejested}$	Rate of energy rejected by the coil to ambient	kJ/hr
$Q_{Sensib;le}$	Rate of sensible energy transferred by the coil	kJ/hr
SHR	Sensible heat ratio	Unit less
m_{evap}	Flow rate of air on the evaporator side of the coil	kg/hr
Pwr_{Total}	Total power draw by the air conditioner (residential cooling coil)	kJ/hr
X	Mass fraction of LiBr	%
T_{sol}	Solution temperature	˚C
T_{ref}	Refrigerant temperature	˚C
h_{sol}	LiBr solution enthalpy	kJ/kg
T_{avg}	Average temperature of fluid	˚C
T_{amb}	Ambient temperature	˚C

LIST OF ABBREVIATIONS

AC	Alternating Current
ACH	Air Change per Hour
ACM	Absorption Cooling Machine
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BEE	Bureau of Energy Efficiency
CEA	Central Electricity Authority
CERC	Central Electricity Regulatory Commission
CFCs	Chloro- Fluoro Carbons
COP	Coefficient of Performance
COPs	Solar COP
CPC	Compound Parabolic Collector
CST	Cold Storage Tank
CSTB	Canadian Software Testing Board
CV	Coefficient of Variance
DBT	Dry Bulb Temperature
DC	Direct Current
DECS	Desiccant Evaporative Cooling Systems
ECBC	Energy Conservation Building Code
ETC	Evacuated Tube Collector
FPC	Flat Plate Collector
HCFCs	Hydrochlorofluorocarbures
HFCs	Hydrofluocarbues
HST	Hot Storage Tank
HVAC	Heating, Ventilation and Air Conditioning
INR	Indian Rupees
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal rate of return
kWh	Kilo Watt Hours
LiBr	Lithium Bromide

LiCl	Lithium Chloride
MBE	Mean Bias Error
MJ	Mega Joule
MNRE	Ministry for New and Renewable Energy Source
NPV	Net Present Value
OSE	Overall System Efficiency
PCM	Energy Consumed by Compression Chiller (kWh)
PCT	Energy Consumed by Cooling Tower (kWh)
PE	Primary Energy
PTAC	Packaged Terminal Air Conditioner
PV	Photo Voltaic
RH	Relative Humidity
SF	Solar Fraction
SHE	Solar Heat Exchanger
SPCS	Solar Photovoltaic Cooling System
STCS	Solar Thermal Cooling System
TEWI	Total Equivalent Warming Impact
TR	Tonne of Refrigeration
TRNSYS	TRaNsient Systems Simulation Program
VAM	Vapour Absorption Machine
VCS	Vapour Compression System
VRF	Variable Refrigerant Flow
WWR	Window to Wall Ratio
BLAST	Building Loads Analysis and System Thermodynamics