

TECHNOECONOMICAL ANALYSIS OF
A RESIDENTIAL PHOTOVOLTAIC
VAPOUR COMPRESSION AIR CONDITIONING SYSTEM

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To whom care for
the environment
the next generation
peace and equality

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ABSTRACT

Photovoltaic (PV) is becoming a significant solar applications. Air conditioning is one of the basic needs for residential indoor comfort in tropical areas. A vapour compression air conditioning (VCAC) unit powered by PV is evaluated in this thesis by simulations. For energy-saving purpose, the VCAC unit is working with R134a, and variable compressor speed and condenser air mass flow rate are assumed. A typical residential house located in Senai is modeled and simplified cooling load temperature differential (CLTD) is used to find the peak load and determine the cooling capacities. Based on the peak load demands, psychrometric study is performed and VCAC model is developed to calculate the power supply needed. Then a crude stand-alone PV (SAPV) system size is predicted. To estimate the SAPV VCAC system performance, long-term average and detailed approaches are employed. The former adapted the simplified design method proposed by Hove (2000). It is found that without backup utility, 42.336 m² of PV array area and 441.14 Ah of battery capacity are required to achieve annual solar fraction of 0.9, using PV mean efficiency of 0.13. In the latter approach, transfer function method (TFM) and VCAC simulations are performed to compute the hourly cooling loads. A detailed modeling of SAPV system based on generality usage is developed and system performance for seven days during the highest cooling demands is studied. The simulations results are discussed and parametric analysis are shown. The SAPV VCAC system is found to be not cost-effective due to efficiency constraint of PV technology and high PV capital costs. Electricity cost of minimum RM1/kW will make PV applications favourable. The simulation methodology requires empirical data to verify. Recommendations are made for improved computations. However, this study believes PV still has potential beneficial effects for large-scale residential energy applications.

ABSTRAK

Fotovoltaik (PV) merupakan aplikasi suria yang semakin penting. Penyaman udara adalah suatu keperluan asas untuk keselesaan dalam rumah di kawasan tropika. Seunit penyaman udara mampatan wap (VCAC) yang dibekal kuasa oleh PV telah dinilai dengan simulasi. Demi tujuan menjimat tenaga, unit VCAC beroperasi dengan R134a, halaju pemampat dan kadar aliran jisim udara memeluwap dianggap sebagai pembolehubah. Sebuah rumah kediaman di Senai dimodel dan CLTD mudah diguna untuk mencari beban puncak dan menentukan muatan pendinginan. Berdasarkan keperluan beban puncak tersebut, psikrometrik dikaji dan model VCAC dibina untuk menghitung bekalan kuasa yang diperlukan. Seterusnya, saiz sistem SAPV kasar diramalkan. Untuk menjangka prestasi sistem SAPV VCAC itu, pendekatan secara purata jangka panjang dan perincian telah digunakan. Pendekatan secara purata jangka panjang disesuaikan daripada kaedah rekabentuk mudah yang diutarakan oleh Hove (2000). Tanpa utiliti backup, annual solar fraction sebanyak 0.9 dapat dicapai dengan menggunakan PV mean efficiency sebanyak 0.13, PV array seluas 42.336 m² dan kemuatan bateri sebanyak 441.14 Ah. Bagi pendekatan secara perincian, TFM dan simulasi VCAC dilakukan untuk mendapatkan beban pendinginan setiap jam. Satu permodelan sistem SAPV secara perincian berasaskan kegunaan umum dibina dan prestasi sistem dikaji selama tujuh hari semasa permintaan pendinginan adalah tertinggi. Keputusan simulasi telah dibincangkan dan analisis parameter telah ditunjukkan. Sistem SAPV VCAC didapati tidak berkesan dari segi kos kerana had kecekapan teknologi PV dan kos PV yang tinggi. Kos elektrik sekurang-kurangnya RM1/kW akan menjadikan aplikasi PV ini lebih digemari. Metodologi simulasi memerlukan pengesahan data empirikal. Cadangan telah dibuat untuk memperbaiki komputasi. Malah, kajian ini yakin bahawa PV mempunyai potensi membawa kesan bermanfaat terhadap aplikasi tenaga kediaman berskala besar.

TABLE OF CONTENTS

CHAPTER	TITLE	PAGE
	Title page	i
	Declaration of originality and exclusiveness	ii
	Dedication	iii
	Acknowledgement	iv
	Abstract (English)	v
	Abstrak (Bahasa Melayu)	vi
	Table of Contents	vii
	List of Tables	xi
	List of Figures	xiii
	List of Symbols	xvi
	List of Appendices	xxiii
1	INTRODUCTION	
	1.1 Air Conditioning and Solar Energy	1
	1.2 Main Types of Solar Energy Application in Air Conditioning	2
	1.3 Other Attempts of Cooling Methods	3
	1.4 Environmental Considerations	4
	1.5 Problem Statement	5
	1.6 Objectives	6
	1.7 Scopes	6
2	LITERATURE SURVEY	
	2.1 VC System as an Alternative	7

2.2	Power Source of VC System	8
2.3	PV for Future Benefits	10
2.4	Simulations Solutions	13
2.4.1	SAPV System	13
2.4.1.1	Detailed Simulations Approach	13
2.4.1.2	Simplified Design Methods	16
2.4.2	R134a VCAC Systems	18
3	METHODOLOGY	
3.1	Introduction	21
3.1.1	Simple SAPV System	22
3.1.2	Simple VCAC System	23
3.2	SAPV VCAC System Design Procedure	24
3.2.1	Typical Residential House Building Characteristics and Peak Load	25
3.2.2	Sizing of VCAC System	27
3.2.2.1	Cooling Coil Study	28
3.2.2.2	VCAC Analysis	29
3.2.3	SAPV Sizing Method	32
3.3	Performance Study Methods	32
3.3.1	Simplified Design Method	34
3.3.2	Detailed Simulation Approach	34
3.3.3	Transfer Function Method (TFM)	36
3.3.4	VCAC Energy Analysis	38
4	MATHEMATICAL FORMULATIONS	
4.1	Introduction	40
4.2	SAPV VCAC System Design Procedure	41
4.2.1	Peak Load Calculations	41
4.2.2	Sizing of VCAC System	42
4.2.2.1	Cooling Coil Study	42
4.2.2.2	VCAC Analysis	47
4.2.3	SAPV Sizing Method	52

4.3 Performance Study Methods	53
4.3.1 Simplified Design Method	53
4.3.2 Detailed Simulations	56
4.3.2.1 PV Generator Sub-model	56
4.3.2.2 Controller Sub-model	58
4.3.2.3 Battery Storage Sub-model	59
4.3.2.4 Inverter and Load Sub-models	62
4.3.2.5 Descriptions of the Simulation Model	62
4.3.3 Hourly Load Computations	65
4.3.3.1 Hourly Load Calculations Methodology	68
4.3.3.2 Heat Gain Calculations	69
4.3.3.3 Cooling Load Conversion Using Room Transfer Function (RTF)	73
4.3.3.4 Psychrometric Analysis	74
4.3.3.5 Heat Extraction Rate and Space Air transfer Function (SATF)	74
4.3.3.6 Hourly VCAC Energy Analysis	77
5 RESULTS AND DISCUSSIONS	
5.1 Chapter Outline	78
5.2 Design Stage Results	79
5.2.1 Peak Cooling Load Calculations	79
5.2.2 VCAC Calculations	80
5.2.3 SAPV Sizing Method	82
5.3 System Performance Estimations Inputs Data	83
5.4.1 Case Study- Design Stage	85
5.4.2. Performance Comparisons	86
5.5 Cooling Loads and Solar Radiation	92
5.6 Long-term Average Simulation Results	94
5.7 Detailed Simulation Results	99
5.7.1 Inputs Parameters	99
5.7.2 Simulations Results Analysis	100
5.7.2.1 Loads and Meteorological Data During	103

11/5/2002-17/5/2002	
5.7.2.2 Detailed Performance of S_{11} During 11/5/2002-17/5/2002	104
5.7.2.3 Detailed Performance of S_{59} During 11/5/2002-17/5/2002	109
5.7.3 Effects of Parameters on Simulation Results	113
5.7.3.1 Time Step	113
5.7.3.2 Nominal Voltage	116
5.7.3.3 Controller Limiting Voltage	118
5.8 Comparisons of Simplified Design and Detailed Simulations Results	121
5.9 Economical Optimisation	124
6 CONCLUSIONS	127
LIST OF REFERENCES	132
Appendices	137

LIST OF TABLES

TABLE NO.	TITLE	PAGE
2.1	Brief Summary of VCAC Modelling Selective Surveys	20
4.1	Air States in Air conditioning	42
4.2	Summary of the Operating Principles of Controller Process	58
5.1	Results of VCAC Variables of Every Conditioned Rooms at Peak Load Conditions	81
5.2	Design Piston Volumes Calculated from VCAC Analysis of Every Conditioned Room	82
5.3	Results of Typical PV Sizing Method of the Typical Residential House	83
5.4	Simulations of Average Daily Energy Flows in a Residential SAPV VCAC System of $\frac{A^A}{A_o^A} = 5$ and $\frac{B}{\overline{L}_y} = 0.8$ Provided with Monthly Average Data of May 2002	98
5.5	SAPV Size Combinations S with Ratio $\frac{A^A}{A_o^A}$ and $\frac{B}{\overline{L}_y}$	100
5.6	Performance of SAPV Systems with Sizes of S_{11} and S_{59} during 11/5/2002-17/5/2002	104
5.7	Important Parameters from 0100 h to 1200 h on 11/5/2002	105
5.8	Comparisons of Simulations Results for Various Δt	113
5.9	Mean Difference (%) of F_s for Every S due to Different F_s during 11/5-17/5/2002 and 22/9-28/9/2002	116

5.10	Controller Process V_{lim} as Comparisons	118
5.11	Comparisons of Simulations Results for S_{11} with Alternative Controller V_{lim}	118
5.12	Economic Optimisations of SAPV VCAC Systems (costs values in RM)	125

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
3.1	SAPV System Configuration	23
3.2	Basic VC Refrigeration Cycle	23
3.3	Floor Plan of Typical Residential House	26
3.4	Schematic Diagram of Heat Transfer from Conditioned Room to Evaporator	29
3.5	Pressure-enthalpy Refrigeration Cycle	30
3.6	Temperature-entropy Refrigeration Diagram (Isentropic Compression Assumed at Design Stage)	30
3.7	Block Diagram for the SAPV System in this Study	35
3.8	Temperature-entropy Refrigeration Diagram (Polytropic Compression Assumed at Performance Study Stage)	39
4.1	Block Diagram to Calculate Coil Load	46
4.2	Block Diagram of R134a VCAC System Design Procedure	51
4.3	Block Diagram of PV Generator Sub-model	57
4.4	Flow Chart of Detailed Simulations of SAPV System	64
4.5	Block Diagram of Hourly Load Computations	66
4.6	Block Diagram of Heat Extraction Rate Calculations	76
4.7	Block Diagram of VCAC Performance Evaluation	77
5.1	Distribution of Peak Cooling Loads (kW) among the Conditioned Rooms in the Typical Residential House	79

5.2	P-H Diagrams Showing the VCAC Cycles for the Conditioned Rooms at Peak Load Conditions (Temperature T_e is higher in the living room)	80
5.3	Outdoor Temperature (°C) and Comparisons of Operating Temperatures	87
5.4	Comparisons of Condensing and Discharge Temperatures	87
5.5	Comparisons of Refrigerant Mass Flow Rate and Enthalpy at Discharge State	88
5.6	Comparisons of Compressor Work Supply and Coefficient of Performance	88
5.7	Comparisons of Air Temperature Leaving Condenser and Heat Rejected by Condenser to Ambient	89
5.8	Comparisons of Compressor Rotation Speed for Piston Volume of 16.2 cm ³ and Volumetric Efficiency	90
5.9	Comparisons of Air Mass Flow Rate over Condenser and Condenser Power Supply Ratio	91
5.10	Various Cooling Loads of Living Room	94
5.11	Monthly Average Daily Compressor Load, and Irradiation on Horizontal and Tilted Surface	95
5.12	Annual Solar Fraction Against the Normalised Array Area, with ratio $\frac{B}{\overline{L}_y}$	96
5.13	Solar Fraction Achieved by Various S from 11/5/2002 to 17/5/2002	101
5.14	Solar Fraction Achieved by Various S from 22/9/2002 to 28/9/2002	102
5.15	Comparisons of Daily Average Loads and Tilted Irradiance Between 11/5-17/5 and 22/9-28/9	102
5.16	Loads and Meteorological Data of Detailed Simulations during 11/5/2002-17/5/2002	104
5.17	Detailed Simulations of S_{11} at $V_{nom} = 24$ V for 11-17 May 2002	107
5.18	Detailed Simulations of S_{59} at $V_{nom} = 24$ V for 11-17 May 2002	110

5.19	Battery Cell Voltage at Various SOC at I_{10}^B for Various $\frac{B}{L}$	112
5.20	Comparisons of Parameters for S_{11} on 11/5/2002 with $\Delta t = 5 \text{ min}$ and 1 h	115
5.21	Detailed Simulations Results of S_{59} using Alternative V_{lim} during 11/5/2002-17/5/2002	119
5.22	Solar Fraction Obtained from Detailed and Simplified Design Simulations	123
5.23	Net Present Values of the SAPV VCAC System at Various Optimal System Sizes at Different Electricity Costs	126

LIST OF SYMBOLS

A	= area, m ²
A_L	= effective leakage area, m ²
A_o^A	= reference array area defined in equation (4.44), m ²
AC	= alternating current
AD	= array disconnection
ADP	= array disconnection probability
AF	= array failure
AFP	= array failure probability
B	= battery capacity, kWh
BF	= battery failure
BFP	= battery failure probability
BPF	= by-pass factor
b_n	= conduction transfer function coefficients
C_B	= battery capacity, kWh
C_W	= wind coefficient
C_S	= stack coefficient
C_{B10}	= battery capacity with discharge regime of 10 hours, kWh
$Conv$	= convective portion of instantaneous heat gain
CLTD	= cooling load temperature differential
COP	= coefficient of performance
CTD	= condenser temperature difference, °C
CTF	= conduction transfer functions
c_p	= specific heat at constant pressure, kJ/kg K
specific heat of air c_{p_a}	= 1.006 kJ/kg K
c_n	= conduction transfer function coefficients

d_n	= conduction transfer function coefficients
E	= energy per day, kWh/day
ER	= heat extraction rate, kW
E_t	= equation of time, min
EE	= excess energy
EEP	= excess energy probability
ERSH	= effective room sensible heat, kW
ERLH	= effective room latent heat, kW
ESH	= equivalent sun hours, h
F_c	= fraction of the input energy lost back to the surroundings
F_s	= solar fraction
F_d	= dump fraction
F_{sa}	= special allowance factor
F_{sh}	= degrading factor due to the influence of superheated region
F_{ul}	= lighting use factor
G	= Irradiance, kW/m ²
g_n	= SATF coefficients
H	= Irradiation, MJ/h/m ²
H	= enthalpy, kJ
h	= specific enthalpy, kJ/kg
h_s	= hour angle, °
specific enthalpy of evaporation of water at 0 °C $h_{fg0} = 2500.81$ kJ/kg	
h_w	= specific enthalpy of condensation of water, kJ/kg
I	= electric current, A
I_{cc}	= circuit consumed current, A
I_o	= dark saturation current, A
I_{ph}	= photocurrent, A
I_{10}^B	= battery discharge current of C_B at discharge regime, A
$I_{c\max}^B$	= maximum allowable charging current, A
$I_{d\max}^B$	= maximum allowable discharging current, A
IAB	= increment annual benefits, RM
IAOC	= increment annual operating costs, RM

ICC	= increment capital costs, RM
J	= parameter defined in equation (3.6)
K_{θ}	= unit length conductance between the space air and surroundings, W/(m ² .K)
L	=load per day, kWh/day
L_F	= length of space exterior wall, m
LD	= load disconnection
LDP	= load disconnection probability
LHG	= latent heat gain, W
\dot{m}	= mass flow rate, kg/s
N	= number of day
N	= number of PV components in the connections
N	= number of people
N_p	= compressor rotational speed, rpm
NPV	= net present value, RM
n	= polytropic index of compression
n	= summation index
P	= pressure, kPa
P_w	= partial pressure of water vapour, kPa
PV	= photovoltaic
PWAF	= present worth annuity factor
PWAF _E	= present worth annuity factor of main electricity costs
p_n	= SATF coefficients
Q	= heat transfer, kJ
Q	= amount of exchanged charge during interval between previous time and current time of interest, kAh
\dot{Q}	= heat transfer rate, kW
q	= component heat gain, kW
\dot{q}	= heat flux, W/m ²
gas constant of air $R = 287$ J/kg K	
R_B	= battery internal resistance, Ω
RH	= relative humidity, %
RTF	= room transfer functions
r	= compressor clearance ratio

S	= PV size combinations
SHG	= sensible heat gain, W
SAPV	= stand-alone photovoltaic
SATF	= space air transfer functions
$SHGF_t$	= solar heat gain factor at time t , W/m^2
SC	= shading coefficient
SOC	= state-of-charge
SOC	= standard operating conditions
SOCp	= state-of-charge at previous measured time
STC	= standard test conditions
s	= specific entropy, $kJ/kg\ K$
T	= temperature/dry bulb temperature, $^{\circ}C$ or temperature, K
T_{ADP}	= room apparatus dew-point temperature, $^{\circ}C$
T_{sol}	= sol-air temperature, $^{\circ}C$
T^*	= wet bulb temperature, $^{\circ}C$
TFM	= transfer function method
t_{PB}	= pay-back period, year
t_{std}	= standard time, h
t_{sol}	= solar time, h
U	= overall heat transfer coefficient, $kW/m^2\ K$
U_L	= thermal loss coefficient per unit area between array and ambient, $W/m^2.^{\circ}C$
V	= voltage, V
V	= volume, m^3
V_p	= piston displacement volume, m^3
V_{nom}	= nominal system voltage, V
\dot{V}	= volume rate of flow, m^3/s
\dot{V}_p	= piston displacement rate, m^3/s
VC	= vapour compression
VCAC	= vapour compression air conditioning
v	= specific volume, m^3/kg
v_n	= room transfer function coefficients
v_w	= wind speed, m/s
W	= work, kW

$Watt_{app}$ = watts input from appliances (Section 4.3.3.1), W

w = humidity ratio, kg/kg d. a.

w_n = room transfer function coefficients

w^* = humidity ratio based on wet-bulb temperature, °C

Greek symbols

β = module temperature coefficient of maximum power efficiency, V/°C

Δt = time step, s

δ = declination, °

δ = time interval, h

ε = heat exchanger effectiveness

η = efficiency

η_v = volumetric efficiency

λ = latitude, °

$\mu_{V_{ov}}$ = temperature coefficient of V_{oc} , V/°C

ρ = density, kg/m³

ρ_g = ground reflectivity

τ = time constant, h

$\tau\alpha$ = array transmissivity-absorbance product

$\frac{\alpha}{h_o}$ = surface colour factor

$\delta \frac{R\varepsilon}{h_o}$ = long-wave radiation factor, °C

Superscripts

A = array

B = battery

C = solar cell

I = inverter

L = load

M = module

Subscripts

<i>a</i>	= air
<i>amb</i>	= ambient
<i>c</i>	= condenser air/condenser/condensing
<i>con</i>	= conventional air conditioning system
<i>D</i>	= design
<i>d</i>	=day
<i>e</i>	= evaporating air/evaporator/evaporating
<i>f</i>	= refrigerant
<i>i</i>	= inlet
<i>in</i>	= indoor
<i>ini</i>	= initial
<i>inf</i>	= infiltration
<i>isen</i>	= isentropic
<i>h</i>	= hour
<i>l</i>	= latent
<i>lim</i>	= limit
<i>m</i>	= mixture of room return air and outdoor air
<i>mp</i>	= maximum power point
<i>max</i>	= maximum
<i>mech</i>	= mechanical, include motor
<i>min</i>	= minimum
<i>out</i>	= outdoor
<i>o</i>	= outlet
<i>oc</i>	= open circuit
<i>P</i>	= parallel in connection
<i>p</i>	= compressor/compression
<i>pc</i>	= power conditioning equipment
<i>pv</i>	= photovoltaic
<i>r</i>	= room
<i>r</i>	= reference
<i>s</i>	= sensible
<i>S</i>	=series in connection
<i>sol</i>	= sol-air temperature

<i>sh</i>	= superheat
<i>sc</i>	= subcool
<i>sup</i>	= supply
<i>sys</i>	=system
<i>t</i>	= time
<i>T</i>	= tilt
<i>var</i>	= variable speed air conditioning system
<i>ven</i>	= ventilation
<i>w</i>	= condensation
<i>y</i>	= year
1'	= saturated gas state point, at evaporating temperature
1	= compressor inlet state point
2	= compressor discharge state point
2'	= saturated gas state point, at condensing temperature
3	= condenser outlet state point
3'	= saturated liquid state point, in the condenser
4	= evaporator inlet state point

LIST OF APPENDICES

APPENDIX.	TITLE	PAGE
A.1	Residential Building Component Data	137
A.2	Residential Building Component Areas	139
P.1	SAPV System Parameters	140
P.2	Main Equations of Simplified Design Method (Refer Hove, 2000)	141
P.3	PV Generator Model Equations (Refer Lorenzo, 1994)	142
P.4	Battery Model Equations (Refer Lorenzo, 1994)	148
P.5	Tilted Radiation Calculations Procedure	149
I.1	Inputs Data Values and References for Peak Load Calculations	150
I.2	Inputs Data Values and References for VCAC Analysis	151
I.3	Inputs Data of TFM	152
I.4	Ambient Temperature and Heat Extraction Rate to Maintain Residential Room at 24 °C with 1 °C Throttling Range	153
I.5	Outputs Values of Design Calculations of Section 5.4.1	154
I.6	(i) PV Array N_s^M and N_p^M Connections Correspond to $\frac{A^A}{A_o^A}$ in the Detailed Simulations	155

	(ii) The N_S^B and C_{B10} Configurations Corresponded to $\frac{B}{\overline{L}_y}$ in the Detailed Simulation	
	(iii) The Limiting Voltage Values of the Controller Process	
I.7	Economic Conditions for Economical Optimisations	156
R.1	Results of Peak Load Calculations	157
R.2	Results of Cooling Coil Calculations	160
R.3	Hourly Cooling Loads and VCAC Calculations of Every Room on 11/5/2002	166
R.4	PV System Detailed Simulations Parameters Results	174
R.5	Detailed Simulations Comparisons of Different Time Steps	175

CHAPTER 1

INTRODUCTION

1.1 Air Conditioning and Solar Energy

Generally, high solar irradiation requires cooling for food preservation or human comfort. Therefore, the application of solar energy instead of popular electricity or gas for cooling purposes appears logical for countries with a high solar energy supply (Erhard *et al.*, 1997). In Malaysia, air conditioning is a popular facility. The necessity of air conditioning for thermal comfort in hot areas and the abundance of sunshine have always intrigued the mind of researchers on how to combine the two for people's benefit.

For Grossman (2002), the greatest demand for cooling occurs when the solar radiation is most intense, thus making its use for cooling all the more attractive. Alizadeh (2000) agreed with similar point, stating that cooling load and availability of solar radiation are approximately in phase.

Today, the attractive idea of solar air conditioning has been put into numerous ways of practices.

1.2 Main Types of Solar Energy Application in Air Conditioning,

Two types of large commercial solar-driven cooling systems have been developed: (1) generating electricity from solar radiation to operate a mechanical chiller, and (2) converting sunlight to heat which in turn drives an absorption chiller (Gordon *et al.*, 2000).

A mechanical chiller involves a vapour compression refrigerator, with a solar-powered prime mover. This may be done through converting solar energy into electricity via means of photovoltaic devices, and then using the electricity in an electric motor to drive the vapour compressor, or by Rankine heat engine.

Absorption systems are similar to vapour compression air conditioning systems but differ in the pressurization stages. An absorbent on the low-pressure side absorbs an evaporating refrigerant. The most usual combinations of fluids include lithium bromide-water ($\text{LiBr-H}_2\text{O}$) and ammonia-water ($\text{NH}_3\text{-H}_2\text{O}$) systems where water vapour and ammonia are the refrigerants respectively. The pressurization is achieved by dissolving the refrigerant in the absorbent in the absorber section. Subsequently, the solution is pumped to a high pressure with an ordinary liquid pump. The addition of heat in the generator is used to separate the low-boiling refrigerant from the solution. In this way the refrigerant vapour is compressed without the need of large amounts of mechanical energy that a vapour compression air conditioning system demands (Florides *et al.*, 2002).

The most widely used solar air conditioning system operates on absorption cycle for the time being. One reason is, absorption air conditioning is the only air conditioning system compatible with the upper collection temperature limits imposed by currently available flat-plate collectors (Kreider *et al.*, 1982).

1.3 Other Attempts of Cooling Methods

The weaknesses of solar absorption cooling have lead to numerous efforts of exploring other cooling cycle possibilities (Refer Chapter 2).

All the refrigeration processes can be classified into open and close cycle. Experience has shown that closed-cycle systems most suitable for solar cooling, is based on absorption cycles (Grossman, 2002). Absorption and adsorption process are referred as sorption process as a whole. In these sorption processes, they can still be divided into whether the cycle is continuous or intermittent.

Adsorption cooling is another class of sorption air conditioners besides absorption cooling that utilizes an adsorbent for adsorbing moisture from the air then allow air to evaporative cooling. Besides, when simple absorption and adsorption refrigerators operate discontinuously rather than in a cycle, this is called intermittent operation. An intermittent solar powered system operates on diurnal cycle with one-generation cycle per day (Bansal *et al.*, 1997). During this operation, the thermodynamic processes are far from reversible, and are dependent upon the properties of the refrigerant-absorbent combination used and the proportion of refrigerant present at the commencement of generation. Most work to date on these cycles has been directed at food preservation rather than comfort cooling. These cycles may be of interest in air conditioning because they offer potential solutions to the energy storage problem (Duffie *et al.*, 1980).

In the solid sorption systems, silica gel is taken for utilized commercial chiller. In contrast, complex compounds of ammonia are used more often whereas zeolites and hydrides play a minor role in the R&D field (Lamp *et al.*, 1998).

Another air conditioning system has been given focus is the open-cycle desiccant cooling system. It uses a desiccant dehumidifier to convert latent cooling load into sensible load and then meet this load using evaporative coolers (Sheridan *et al.*, 1985). Its advantage is using low-grade heat such as solar energy can do the regeneration of desiccant. Open cycle regenerates the weak absorbent solution by losing refrigerant to the atmosphere. Cooling takes place by evaporating refrigerant from an external source in the evaporator (Collier, 1979). The system usually can operate in one of two modes: ventilation and recirculation (Kreider *et al.*, 1982).

1.4 Environmental Considerations

Solar energy is certainly more environmental friendly compared to current main conventional energy sources. Most conventional cooling systems are either directly or indirectly driven by gas and fuel or dam-generated electricity. It is our main environmental concerns today that lead us to replace them with renewable energies. In a tropical country such as Malaysia, the rich solar energy throughout the year is ready for us to fully utilize.

From the energy supply perspective, air conditioners can be classified into thermally and electrically driven coolers. Most researches have focused on the former method since the providing work from solar heat seems convenient. The main problem arise here is storage. In the mean time, electrically driven coolers are relatively lack of attentions.

One of the becoming popular ways to produce electricity from sun is photovoltaic (PV) technology.

For air conditioning applications, an ideal PV system is producing energy, which exceeds the load demand when sunlight is intense. The excess energy shall be stored to maintain the storage component such as battery in a fully charged state. When solar radiation is less or during the nights, the battery can be discharged to provide energy to the load.

Europe, Japan, United States and Australia have installed large-scale residential PV roof subsidised programs (Green, 2004). Our society should have preparations regarding popularise renewable energy applications at residential level. As shall be illustrated in Chapter 2, PV energy has a great potential in terms of performance and costs in the future. Therefore, researchers have to work on exploring the future benefit of PV applications such as air conditioning.

Besides the power supply of air conditioning requires attentions, the refrigerants used in the conventional vapour compression air conditioning (VCAC) units have been identified to cause environmental destructions. R134a is one of the ecological refrigerants for its replacement.

1.5 Problem Statement

Study the potential of applying photovoltaic power, to generate the highly efficient commercial VCAC system for residential application in Malaysia. This is one of the efforts to overcome the low-efficiency and high-costs problems encountered by current solar cooling methods, particularly those operate in absorption cycle. The ultimate goal is to enhance energy saving as well as environmental friendly engineering design.

1.6 Research Objectives

The research objectives are:

- To develop a program to simulate a photovoltaic vapour compression air conditioning system working with R134a
- To study the system performance and suggest the optimum system sizing

1.7 Scopes

The scopes of the study are:

- The air conditioning system is designed for typical residential purpose
- Only vapour compression cooling cycle is investigated
- Consider environmental factor, R134a is used as the cooling refrigerant
- As an attempt for energy saving purpose, variable compressor speed and condenser air flow rate is permitted in this study
- Analysis is done based on Malaysian climatic conditions
- Stand-alone photovoltaic (SAPV) powers the major load portion of the air conditioning unit, i.e. the compressor energy demand only
- Silicon is the solar cell material type to allow applications of some modelling assumptions.
- Modelling of PV system is based on typical SAPV system configurations, and generality of component model is allowed
- Long-term economic study is performed on the PV system

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