
Contents

Certificate	iii
Declaration	v
Copyright	vii
Acknowledgement	ix
Table of Contents	xi
List of Figures	xv
List of Tables	xxi
Nomenclature	xxiii
Abstract	xxvii
1 Introduction	1
1.1 PV/PCM systems: Background	2
1.2 Prior studies on PV/PCM systems	3
1.2.1 Conventional PV/PCM systems	3
1.2.2 PV/PCM system with finned PCM enclosures	4
1.2.3 PV/PCM system with comoposite PCM	4
1.2.4 Hybrid PVT/PCM systems	5
1.3 Research gap	5
1.4 Research methodology	7
1.4.1 Novel PCM encapsulation designs for PV/PCM systems	9
1.5 Objective of the thesis	13
1.6 Organization of the thesis	14
2 Effect of Novel PCM Encapsulation Designs on Electrical and Thermal Performance of a Hybrid Photovoltaic Solar Panel	15

2.1	Introduction	15
2.2	Material & method	20
2.2.1	Problem description & definition	20
2.2.2	Solution method	23
2.2.3	Grid independence test	26
2.2.4	Validation with experimental eesults	26
2.3	Results and discussions	28
2.3.1	Solid-liquid interface patterns	28
2.3.2	Temperature distributions	33
2.3.3	Effect of enclosure design on flow behavior during PCM melting	34
2.3.4	Heat transfer characteristics	36
2.3.4.1	Melting rate	36
2.3.4.2	Nusselt number	39
2.3.4.3	Heat storage Performance	40
2.3.5	Performance characteristics	42
2.3.5.1	PV cell temperature	42
2.3.5.2	Effect of enclosure design on PV electrical efficiency	44
2.4	Conclusions	46
3	Behaviour of Novel Design of Non-rectangular PCM Enclosure for PV/PCM Systems under Variable Boundary and Ambient Conditions	49
3.1	Introduction	50
3.2	Methodology	52
3.2.1	Problem description & definition	52
3.2.2	Boundary conditions	53
3.2.3	Solution method	54
3.3	Results and discussions	55
3.3.1	Thermal analogy of melting front propagation	55
3.3.2	Heat transfer characteristics	58
3.3.2.1	Liquid fraction	58
3.3.2.2	Nusselt number	60
3.3.2.3	Thermal energy storage performance	61
3.3.3	Performance characteristics	63
3.3.3.1	Effect of PV cell tempereare on electric conversion efficiency	63
3.3.3.2	Electric power output	64
3.3.3.3	Total heat loss from the system	67
3.3.3.4	Energy and exergy efficiency	67
3.3.4	Feasibility of the system:	71

3.4	Conclusions	75
4	Effect of New Overhead Phase Change Material Enclosure Designs on Thermo-electric Performance of a Photovoltaic Panel	77
4.1	Introduction	78
4.2	Methodology	80
4.2.1	Problem description & definition	80
4.2.2	Boundary conditions	81
4.2.3	Solution method	83
4.3	Results and discussions	83
4.3.1	Solid-liquid interface patterns	83
4.3.2	Temperature distributions	87
4.3.3	Heat transfer characteristics	88
4.3.3.1	Melting rate	88
4.3.3.2	Nusselt number	91
4.3.3.3	Thermal energy storage performance	92
4.3.4	Performance characteristics	94
4.3.4.1	PV cell temperature	94
4.3.4.2	Electrical conversion efficiency of PV cell	97
4.3.4.3	Total utilized radiation	98
4.4	Conclusions	102
5	Effect of New Extended Type Non-rectangular PCM Enclosure on Thermo-electric Performance of PV/PCM Systems	105
5.1	Introduction	105
5.2	Solution methodology	108
5.2.1	Problem formulation	108
5.2.2	Boundary conditions	108
5.2.3	Numerical solution	110
5.3	Results and discussions	111
5.3.1	Solid-liquid interface patterns	111
5.3.2	Temperature distributions	114
5.3.3	Heat transfer characteristics	116
5.3.3.1	Melting process	116
5.3.3.2	Nusselt number	120
5.3.3.3	Thermal energy storage performance	123
5.3.4	Performance characteristics	126
5.3.4.1	Effect of PV cell temperature on power conversion efficiency	126
5.3.4.2	Overall system performance	127

5.4	Conclusions	134
6	Thermal Energy Storage Design of a New Bifacial PV/PCM System for Enhanced Thermo-electric Performance	137
6.1	Introduction	138
6.2	Solution methodology	142
6.2.1	Problem formulation	142
6.2.2	Boundary conditions	142
6.2.3	Numerical solution	145
6.2.4	Experimental calibration of numerical model	145
6.3	Results and discussions	146
6.3.1	Solid-liquid interface patterns	146
6.3.2	Temperature distributions	149
6.3.3	Heat transfer characteristics	151
6.3.3.1	Melting process	151
6.3.3.2	Nusselt number	154
6.3.4	Performance characteristics	155
6.3.4.1	Effect of PV cell temperature on power conversion efficiency	155
6.3.4.2	Total electric power output	159
6.3.4.3	Overall system performance	161
6.3.4.4	Feasibility of the system	164
6.4	Conclusions	169
7	Conclusions and Recommendations	171
7.1	Conclusions	172
7.2	Major contribution from the thesis	178
7.3	Assumptions and limitations of present investigation	179
7.4	Recommendations for future research	180
	Bibliography	183
	Author's Personal Profile and Publication List	193

List of Figures

1.1	(a) Conventional PV/T system , (b) conventional PV/PCM system	3
1.2	Melting process inside a rectangular PCM enclosure showing all four different regimes of melting: (i) conduction regime, (ii) mixed regime, (iii) quasi-steady convection regime, and (iv) solid-shrinking regime.	7
1.3	(a) Conventional PV/PCM system, (b) PV/PCM system with non-rectangular enclosure of generic opposite wall profile	9
1.4	(a) PV/PCM system with overhead type rectangular PCM enclosure, (b) PV/PCM system with extended non-rectangular PCM enclosure with generic opposite wall profile.	10
1.5	Bifacial PV/PCM system with modified non-rectangular PCM enclosure.	11
2.1	Schematic diagram showing cross-section of PV/PCM system with (a) type-A conventional rectangular PCM enclosure, (b) type-B, C, & D non-rectangular PCM enclosure with a general profile, $y = (ax - b)^{(1/n)}$, $n=1$ for type-B, $n=2$ for type-C and $n=3$ for type-D.	17
2.2	Variation of centerline temperature at 3600 s for different number of grids. Inset shows the melting front of PCM. Location of centerline is marked in the figure by dash-dot line.	24
2.3	Variation of liquid fraction of PCM predicted from numerical model and experimental study (Kamkari et. al 2014). Two figures in the inset shows the instantaneous liquid fraction: left [experimental] and right [numerical].	25
2.4	Solid-liquid interface patterns predicted from (i) experimental study by Kamkari et al., (2014) and (ii) numerical model.	27
2.5	Sequential solid fraction contours of the melting process of PCM in rectangular enclosure (type – A) and in non-rectangular enclosure (type – B, C, and D) for Case 1.	29

2.6	Sequential solid fraction contours of the melting process of PCM in rectangular enclosure (type – A) and in non-rectangular enclosure (type – B, C, and D) for Case 2.	30
2.7	Sequential solid fraction contours of the melting process of PCM in rectangular enclosure (type – A) and in non-rectangular enclosure (type – B, C, and D) for Case 2.	31
2.8	Temperature distribution in all type of configuration of PV/PCM systems at 120 minutes.	35
2.9	Variation of Temperature along the height of PV panel at 120 minutes for case 3.	36
2.10	Velocity streamlines superimposed on solid volume fraction map for Case 3 at 120 minutes. Black color on the right wall shows solid PCM.	37
2.11	Expanded view of liquid fraction vs time shown in inset for all type of configurations for case 3.	38
2.12	Variation of Nusselt number for all type of configuration for case 3.	39
2.13	(a) Expanded view of variation of ESD with time shown in inset, (b) ESD values for all configurations at 120 minutes.	43
2.14	Variation of PV cell temperature with time for all type of configuration of PV/PCM system for case 3.	44
2.15	Variation of electrical efficiency with time for all type of configuration of PV/PCM system for case 3.	45
3.1	Schematic diagram showing cross-section of PV/PCM system with (a) type-A conventional rectangular PCM enclosure, (b) type-B, C, & D non-rectangular PCM enclosure with a general profile, $y = (ax - b)^{(1/n)}$, $n=1$ for linear, $n=2$ for parabolic and $n=3$ for cubic right wall profile.	53
3.2	Diurnal variation of (a) incident radiation, (b) ambient temperature with time.	54
3.3	Transient history of (a) solid-liquid interface patterns, and (b) temperature distribution patterns.	57
3.4	Transient variation of liquid fraction for both type of configurations. Full melting history has been shown in inset.	59
3.5	Comparison of transient history of Nusselt number for both type of configuration. Solid-liquid interface patterns for both configurations at end of quasi-steady convection regime are shown in inset.	61
3.6	Transient variation of ESD for all configurations.	62
3.7	Transient variation of average PV cell temperature for all configurations of PV and PV/PCM systems.	64
3.8	Transient Variation of electrical efficiency for all configurations of PV and PV/PCM systems.	65
3.9	Transient variation of electric power output for all configurations of PV and PV/PCM systems.	66

3.10	Transient variation of total heat loss for all type of configurations.	68
3.11	Comparison of energy efficiencies for all different configurations of PV and PV/PCM systems.	70
3.12	Comparison of exergy efficiencies for all different configurations of PV and PV/PCM systems.	72
4.1	Two-dimensional view of PV panel with integrated PCM enclosure (a) rectangular enclosure (type-A), (b) rectangular enclosure with extension H_e (type-B), (c) rectangular enclosure with overhead tank extension H_e (type-C), (d) rectangular enclosure with modified overhead tank extension H_e and depression H_d (type-D). Note that subsequent designs from type-B to type-D was arrive after analyzing the performance of the previous design.	82
4.2	Transient history of solid fraction contours of the melting of PCM superimposed with velocity streamlines for all type of configurations.	85
4.3	(a) Temperature contours for all type of configurations of PV/PCM system at 120 minutes, and (b) PV cell temperature variation with height of PV panel along PV-PCM interface at 120 minutes.	89
4.4	Expanded view of transient variation of liquid fraction shown in inset for all type of configurations. Full melting history has been shown in inset.	90
4.5	Comparison of transient history of Nusselt number among all type of configuration. Solid-liquid interface patterns for all configurations at 120 minutes are shown in inset.	92
4.6	(a) Distribution of ESD in all configurations of PV/PCM systems at 120 minutes and (b) transient variation of ESD ratio for all configurations.	95
4.7	Transient variation of average PV cell temperature for all configurations of PV/PCM system.	96
4.8	Transient Variation of electrical efficiency all configurations of PV/PCM system. . .	98
4.9	Variation of utilized radiation with time. (Expanded view for specific time period is shown in inset).	100
4.10	Variation of ratio of utilized radiation to unutilized radiation with time. (Expanded view for specific time period is shown in inset.)	101
5.1	Two dimensional schematic diagram of PV/PCM systems (a) with rectangular PCM enclosure (Type – A), and (b) non-rectangular extended PCM enclosure with a general right wall profile, $y = (ax - b)^{(1/n)}$, $n = 1$ for type-B, $n = 2$ for type-C and $n = 3$ for type-D.	109
5.2	Transient history of solid-liquid interface patterns for different configurations of PV/PCM system.	115

5.3	Transient history comparison of melting front contours with temperature distribution contours for type – B configuration of PV/PCM system at lower thickness ratio ($L_1/L = 0.3$) and extension ratio ($H_e/H_{pv} = 0.3$).	117
5.4	Temperature distribution at 120 minutes for different configurations of PV/PCM systems at lower thickness ratio	118
5.5	Transient variation of liquid fraction for type – B configuration of PV/PCM system at lower thickness ratio ($L_1/L = 0.3$). Expanded view of selected part of curve is shown in inset.	119
5.6	Fraction of liquid melted after 120 minutes of process for all configurations of PV/PCM system with non-rectangular PCM enclosure.	121
5.7	Variation of Nusselt number with time for type – B configuration of PV/PCM system at lower thickness ratio ($L_1/L = 0.3$). Transient history of melting front contours for same configuration at extension ratio ($H_e/H_{pv} = 0.3$) is shown in inset.	122
5.8	Comparison of Nusselt number at 120 minutes of process among all configuration of PV/PCM system with non-rectangular PCM enclosure.	123
5.9	Transient variation of energy storage density (<i>ESD</i>) for type – B configuration of PV/PCM system at lower thickness ratio ($L_1/L = 0.3$). Expanded view of selected part of curve is shown in inset.	124
5.10	Comparison of <i>ESD</i> at 120 minutes of process among all configuration of PV/PCM system with non-rectangular PCM enclosure.	125
5.11	Transient variation of (a) PV cell temperature (b) PV cell electric conversion efficiency for type – B configuration of PV/PCM system at lower thickness ratio ($L_1/L = 0.3$). Full transient history are shown in inset for each curve.	128
5.12	Comparison of (a) PV cell temperature, and (b) PV cell electric conversion efficiency at 120 minutes of process among all configuration of PV/PCM system with non-rectangular PCM enclosure.	129
5.13	Transient variation of total utilized radiation for type – B configuration of PV/PCM system at lower thickness ratio ($L_1/L = 0.3$). Expanded view of selected part of curve is shown in inset.	130
5.14	Comparison of total utilized radiation at 120 minutes of process among all configuration of PV/PCM system with non-rectangular PCM enclosure.	132
5.15	Transient variation of I_{gain} ratio for type – B configuration of PV/PCM system at lower thickness ratio ($L_1/L = 0.3$). Expanded view of selected part of curve is shown in inset.	133
5.16	Comparison of I_{gain} ratio at 120 minutes of process among all configuration of PV/PCM system with non-rectangular PCM enclosure.	134
6.1	Schematic diagram of conventional PV/PCM system.	140

6.2	Schematic diagram of BIF-PV/PCM system with sandwiched rectangular PCM unit.	141
6.3	Schematic diagram of modified BIF-PV/PCM system. Note how the rectangular PCM enclosure is modified to a bifurcated non-rectangular design. This design has been arrived after studying the melting front in the rectangular design.	144
6.4	Comparison of liquid fraction – time curve between numerical and experimental model for (a) conventional mono-facial heating of PCM , and (b) bifacial heating of PCM . Solid-liquid interface patterns are given in inset for specified time.	147
6.5	Solid-liquid interface patterns for PV/PCM systems and BIF-PV/PCM systems. . .	149
6.6	Temperature distribution at 120 minutes for PV/PCM systems and BIF-PV/PCM systems.	150
6.7	Variation of (a) liquid fraction with time, and (b) absolute amount of melted PCM with time.	152
6.8	Variation of (a) Nusselt number for top PV-PCM interface with time for PV/PCM systems and BIF-PV/PCM systems (b) Nusselt number for bottom PV-PCM interface with time for BIF-PV/PCM systems. Solid-liquid interface patterns at peaks and kinks are shown in inset.	156
6.9	Transient variation of PV cell electric conversion efficiency of (a) top PV panel, and (b) bottom PV panel for all configurations of PV and PV/PCM systems.	158
6.10	Variation of overall electric power output with time for different configurations of PV and PV/PCM systems.	160
6.11	Variation of overall system efficiency with time for different configuration of PV and PV/PCM systems.	163
6.12	Comparison of exergy efficiency for different configurations of PV and PV/PCM systems.	164
6.13	Schematic of calculation of land area requirement of integration of a single bifacial PV/PCM unit.	165
6.14	Comparison of (a) total energy utilization density, (b) power output density among bifacial PV/PCM unit, simple PV/PCM unit and conventional PV system unit. . . .	166

List of Tables

2.1	Relevant literature on PCM integrated with PV module. Note that only rectangular type encapsulation design has been reported.	17
2.2	Thermo-physical properties of materials	22
2.3	Design specifications and boundary conditions for all geometric configurations.	22
2.4	Results of PV and PV/PCM systems. The results in bold are crucial for comparing some of the top performing configurations to conventional ones.	41
3.1	Economic and exergoeconomic investigation for all configurations of PV and PV/PCM systems.	74
3.2	Enviroeconomic investigation for all configurations of PV and PV/PCM systems.	75
5.1	Design specifications for all PV /PCM configurations with non-rectangular PCM enclosure.	110
5.2	Timing of melting front reaching right and top wall for all non-rectangular configurations. Note 120* indicates that melting front does not reach the respective wall in 120 minutes of process.	113
6.1	Equations for energy efficiency and exergy efficiency analysis	161
6.2	Equations for energy efficiency and exergy efficiency analysis.	162
6.3	Equations for economic, exergoeconomic and enviroeconomic analysis	167
6.4	Economic, exergoeconomic, and enviroeconomic analysis for studied configuration of PV and PV/PCM systems.	168

Nomenclature

A_{pv}	Area of PV panel (m^2)
B_{mush}	Mushy constant (kg/m^3s)
C_{el}	Cost of electricity generation ($\$/kWh$)
C_{ex}	Cost of exergy generation ($\$/kWh$)
c_p	Specific heat at constant pressure (J/kgK)
C_{total}	Capital cost ($\$$)
E_{el}	Electric energy generation (kWh)
E_n	Annual electric energy generation ($kWh/year$)
$E_{overall}$	Overall energy generation (kWh)
E_{th}	Thermal energy generation (kWh)
E_{total}	Total incident energy (kWh)
Ex_{el}	Electric exergy output (kWh)
Ex_{in}	Total exergy input (kWh)
Ex_n	Annual exergy generation ($kWh/year$)
Ex_{out}	Total exergy output (kWh)
Ex_{loss}	Total exergy loss (kWh)
Ex_{th}	Thermal exergy output (kWh)
f_l	Liquid fraction (-)
G	Effective incident radiation (W/m^2)
H_{pv}	Height of PV panel (m)
h_t	Total heat transfer coefficient (W/m^2K)
H_d	Height of depression (m)
H_e	Height of extension (m)
h_n	Natural heat transfer coefficient (W/m^2K)
$r h_w$	Forced heat transfer coefficient (W/m^2K)
i	Interest rate (%)
i_d	Depreciation rate (%)
I_{max}	Maximum incident solar radiation (W/m^2)
$I_{gainratio}$	Ratio of utilized radiation to unutilized radiation (-)
I_{solar}	Incident solar radiation (W/m^2)
$I_{solar}^{reflected}$	Reflected solar radiation (W/m^2)
$I_{unutilized}$	Unutilized solar radiation (W/m^2)
$I_{utilized}$	Utilized solar radiation (W/m^2)
k	Thermal conductivity (W/mK)
L	Thickness of rectangular PCM enclosure (m)
L_1	Lower thickness of non-rectangular PCM enclosure (m)

L_2	Upper thickness of non-rectangular PCM enclosure (m)
L_{sf}	Latent heat of fusion (J/kg)
m_p	Mass of PCM (kg)
$\frac{m_{upper}}{m_{lower}}$	Bifurcation mass ratio (-)
Nu	Nusselt number (-)
p	Pressure (Pa)
P_{out}	Electric power output per unit area of PV panel (W/m ²)
P_{out}'''	Power output per unit volume (W/m ³)
$P_{out,top}$	Electric power output per unit area of top PV panel (W/m ²)
$P_{out,bottom}$	Electric power output per unit area of bottom PV panel (W/m ²)
q_{conv}''	Convective heat loss rate (W/m ²)
Q_{gen}'''	Heat generation rate per unit volume (W/m ³)
q_{in}''	Conductive heat flux into the system (W/m ²)
q_{loss}''	Cumulative effect of convective and radiative heat loss rate (W/m ²)
q_{rad}''	Radiative heat loss rate (W/m ²)
Q_{stored}	Stored heat inside PCM enclosure (J)
S	Salvage value (\$)
$S_{Boussenisq}$	Boussenisq source term (N/m ³)
S_{Darcy}	Darcy source term (N/m ³)
t	Time (s)
T_a	Ambient temperature (°C)
T_{amp}	Amplitude temperature (K)
T_{avg}	Average ambient temperature (K)
T_f	Final temperature (°C)
t_g	thickness of glass layer (m)
T_i	Initial temperature (°C)
T_m	Melting temperature of PCM (°C)
T_{PCM}	Local PCM temperature (°C)
t_{pv}	thickness of PV layer (m)
T_{ref}	Reference temperature of PV panel (°C)
T_s	Surface temperature (°C)
T_{sky}	Sky temperature (°C)
T_{sun}	Sun temperature (°C)
\vec{u}	velocity (m/s)
v_w	Wind speed (m/s)
V_L	Volume of left side of bifacial PCM enclosure (m ³)
V_{PCM}	Volume of PCM enclosure (m ³)
V_R	Volume of right side of bifacial PCM enclosure (m ³)

x, y	Cartesian coordinates (m)
z_{CO_2}	Global carbon value (\$)
Z_{CO_2}	Earned carbon credit (\$)

Greek symbols

α_{pv}	Absorptivity of PV surface (-)
β	Thermal expansion coefficient of PCM (K^{-1})
$\beta_{ref.}$	Reference thermal expansion coefficient of PV panel (K^{-1})
γ	Reflectivity (-)
ϵ	Emmissivity
ϵ	Small constant (-)
η_{pv}	Electric energy efficiency or electric conversion efficiency of PV panel (-)
$\eta_{Ex,el.}$	Electric exergy efficiency (-)
$\eta_{Ex,overall}$	Overall exergy efficiency (-)
$\eta_{Ex,th.}$	Thermal exergy efficiency (-)
$\eta_{overall}$	Overall energy efficiency (-)
$\eta_{pv,top}$	Electric conversion efficiency of top PV panel (-)
$\eta_{pv,bottom}$	Electric conversion efficiency of bottom PV panel (-)
$\eta_{ref.}$	Electrical efficiency at reference condition of PV panel (-)
η_{th}	Thermal energy efficiency (-)
μ	Dynamic viscosity (kg/ms)
ρ	Density (kg/m^3)
σ	Stefan-Boltzman constant (W/m^2K^4)
τ_{glass}	Transmissivity of glass (-)
φ_{CO_2}	CO_2 emissions (ton)

Subscripts

$a.$	Ambient condition
$conv$	Convective
cum	Cumulative
d	Depression
e	Extension
el	Electrical
f	Final condition
g	Glass layer
i	Initial condition
in	Input
L	Leftside of enclosure

<i>m</i>	Melting
<i>n</i>	Natural
<i>out</i>	Output
<i>s</i>	Surface
<i>sf</i>	Fusion
<i>t</i>	Total/cumulative
<i>th</i>	Thermal
<i>pv</i>	PV panel
R	Rightside of enclosure
<i>ref</i>	Reference condition
<i>rad</i>	Radiative condition
<i>w</i>	Wind

Abbreviations

<i>AE</i>	Absorbed energy
<i>AECP</i>	Annual electricity provurement cost
<i>AMC</i>	Annual Maintenance cost
<i>AS</i>	Annual savings
<i>ASV</i>	Annual salvage value
<i>BIF-PV</i>	Bifacial photovoltaic
<i>BIPV</i>	Building integrated photovoltaic
<i>BIF-PV/PCM</i>	Bifacial PV/PCM systems
<i>CRF</i>	Capital recovery factor
<i>ESD</i>	Energy storage density
<i>FAC</i>	First annual cost
<i>LESD</i>	Latent energy storage density
<i>PCM</i>	Phase change material
<i>PV</i>	Photovoltaic
<i>PV/PCM</i>	Photovoltaic integrated with phase change material
<i>PVT/PCM</i>	Photovoltaic thermal system integrated with phase change material
<i>SESD</i>	Sensible energy storage density
<i>SSF</i>	Sinking fund factor
<i>TAC</i>	Total annual cost

Abstract

The global energy demand of the world expands with population growth which causes excessive load on conventional energy resources such as fossil fuels. Conventional energy sources are limited and cause various environmental problems such as air pollution, global warming, and sudden climate changes. Therefore, an increase in unconventional energy resources such as solar energy, wind energy, geothermal energy, and other resources must be emphasized to meet future rising energy demands and reduce the growing environmental problems. Photovoltaic (PV) technology is an excellent clean and green energy option. PV panels convert solar energy directly into electrical energy. However, most incoming radiation is wasted in the form of heat that increases the operating temperature of the PV panel and degrades its electric conversion performance. The electric conversion efficiency of the PV panel is inversely proportional to its operating temperature. Hence, the electric performance of the PV panel can be enhanced by reducing its operating temperature using appropriate cooling technique. The application of the cooling technique enhances also enhances the utilization of incoming radiation by absorbing waste heat. The phase change material (PCM) integrated PV panels (PV/PCM systems) could be a viable option to enhance PV panel's electric performance and store heat for nocturnal hours. However, the conventional rectangular PCM enclosure exhibit degradation in performance in later stages of melting process. The unsymmetrical pattern of melting in conventional enclosures leads to non-uniform temperature distribution, which degrades the electric and heat storage performance of conventional PV/PCM systems. Therefore, design modifications and innovations of PCM encapsulations are desired to improve thermoelectric performance. In this thesis, a series of new design concepts of PCM encapsulations for PV/PCM systems and bifacial PV/PCM systems working on the principle of augmented convection dominated melting regime are proposed and investigated by developing experimentally validated computational fluid dynamics (CFD) models. Various geometric and governing parameters are optimized to improve electric conversion performance and heat storage performance. Firstly, a non-rectangular PCM enclosure (same volume as the conventional enclosure) is integrated into the PV panel to take advantage of unsymmetrical melting caused by the natural convection of liquid PCM. The PV panel exhibits significant enhancement in thermoelectric performance; however, the compactness of the PV/PCM system is partially compromised. Secondly, an overhead type rectangular PCM enclosure is examined for the PV/PCM system to take the waste heat away from the PV panel and reduce the PV panel temperature. This design modification is based on the concept that the melting front can propagate in both (horizontal and vertical directions) if the enclosure is extended to an optimum height. Further, another novel enclosure design is conceived in the

form of an extended non-rectangular enclosure to investigate the effect on performance. The idea was to provide optimum distance to the melting front to travel in horizontal and vertical directions. This modified configuration exhibits better thermo-electric performance and provide compact geometry. Lastly, a more efficient bifacial PV/PCM system is proposed to enhance thermoelectric performance. This modification involves radiation reflection by an L-shape mirror system and PCM enclosure modification according to melting morphology. The bifacial PV/PCM system enhanced power output by 1.91 times that of the conventional PV system and 1.77 times that of the conventional PV/PCM system. The energy, exergy, economic, and environmental analysis were carried out for the bifacial PV/PCM system. The proposed system not only exhibits better thermo-electric performance but also help in reducing energy procurement cost and carbon emissions. All the aforesaid new designs show significant improvement in thermos-electric performance compared to conventional systems.

Chapter 2 explored the avenues to improve the electrical efficiency of photovoltaic (PV) panel by absorbing waste heat in encapsulated phase change materials (PCM) during the melting process. Previous investigators reported the melting process of PCM in a rectangular encapsulation and observed four transient regimes of heat transfer in sequence as: conduction, mixed conduction-convection, quasi-steady convection and solid-shrinking regimes. For higher heat extraction from the PV panel, longer duration of quasi-steady convection regime is desirable. However, this steady regime is suppressed in the rectangular PCM enclosure due to the nature of natural convection and consequently, the melting rate of the PCM is arrested. In this chapter, we report on electrical and thermal performance of non-rectangular PCM integrated PV panels using an experimentally validated numerical model that enhances the quasi-steady regime by more than 100% compared to the conventional rectangular design. The strategic mass distribution of PCM for better thermal management was achieved with encapsulation designs having profile of right wall varying as $y = (ax - b)^{1/n}$, with $n = 1$ (linear), 2 (parabolic) and 3 (cubic) with different lower thickness ratio. Compared to conventional design, the proposed design increased the PCM melting rate by 17% due to which PV cell temperature dropped by 11.5% and consequently, electrical conversion efficiency approaches to 12%.

Chapter 3 examines the feasibility of non-rectangular type encapsulation for PV/PCM system under variable boundary and ambient conditions (similar to real conditions). The conventional design exhibits slow melting rates and degraded thermo-electric performance due to shorter regime of convective melting (ends before maximum insolation). The unsymmetrical loading of PCM in non-rectangular enclosure encourages characterization of melting according to natural convection. The proposed non-rectangular PCM enclosure for PV/PCM systems exhibits elongated quasi-steady convection regime far beyond the maximum insolation time causing increased melting rates. Compared to conventional design, the proposed design exhibits 20% more melting and PV panel works at 92% of its rated performance. The heat loss from the proposed system is approximately half compared to conventional system that explains higher

insolation utilization ability of the system. Energy efficiency, exergy efficiency, economic, exergoeconomic, and enviroeconomic analysis are carried out for both conventional and proposed systems. The proposed system exhibits higher exergy efficiency (13.81%) and energy efficiency (73.95%) whereas conventional system exhibits somewhat lower exergy efficiency (13.66%) and a lower energy efficiency (69.77%). The economic analysis suggests that the proposed system exhibits approximately 3% lesser cost of production of electricity compared to conventional PV/PCM system. In terms of earned carbon credits, the proposed system also helps in reducing the CO_2 emissions to the environment. Hence, the proposed design of PV/PCM system would be beneficial in domestic and industrial applications.

In the chapter 4, a new design concept of overhead phase change material (PCM) enclosure design attached with a photovoltaic panel has been investigated. Various design configurations studied and based on the melting front characteristics, an optimum final design is proposed. The new design enhances the solar radiation gain (ratio of utilized to unutilized radiation) by about 17 times the conventional PV system. Higher solar radiation utilization manifests in about 10% increase in energy storage density. With strategic distribution of PCM, duration of quasi-steady regime where convection dominates, has been increased that manifested into higher melting rates of PCM compared to the conventional rectangular design. The study revealed that electrical conversion efficiency of PV panel can approach to about 12% if suitable strategies are adopted as demonstrated in this chapter. The liquid PCM has a tendency to rise against gravity force but restricted by the top wall of enclosure alongside of PV panel in conventional PV/PCM system. However, the usage of extended enclosure allows the convection current to erode the melting interface in both horizontal and vertical direction. This phenomenon accelerates the melting process as the excessive heat is being taken away from the PV panel in the extended part of enclosure. This modification in design also solves the issue of compactness of the system and also provide encouraged thermo-electric performance. This study would be useful in developing efficient PV technologies to meet the ever-growing energy needs. The findings of this investigation are reported from an experimentally validated numerical model that accurately captures the melting behavior of PCM and other thermal characteristics of the system.

Chapter 5 examines an innovative concept of extended non-rectangular phase change material (PCM) enclosure integrated with a photovoltaic (PV) panel that manifests 7.26 times incoming solar radiation than the simple PV system. In extended rectangular type enclosures, the horizontal width of the PCM encapsulation is customized with same volume of PCM is maintained in the enclosure. This will hinder the movement of melted PCM in horizontal direction and affects thermo-electric performance due to slower melting rates. Hence the enclosure design is changed to an extended non-rectangular enclosure to improve further performance. The strategic distribution of PCM is achieved by controlling certain geometric parameters such as lower thickness ratio, extension ratio and profile of right wall. With optimization of these pa-

rameters, the span of convection dominated regime is prolonged to more than 120 minutes which conceded 20.5% more melting compared to the conventional rectangular design of same PCM volume. Electric conversion efficiency can approach to 96.37% of its rated value with the application of strategies demonstrated in the paper. Moreover, incoming radiation absorbing capacity can approach to 67.35% for recommended configuration. An experimentally validated numerical model is used to report the findings of this investigation which can predict exact melting morphology and thermal behavior of the system. This study provides useful information that will be helpful in developing more efficient PV techniques that can meet the ever rising global energy demands.

Chapter 6 examines a new concept of bifacial PV/PCM (BIF-PV/PCM) system with sandwiched thermal energy storage enclosure that possesses 1.21 times power output density and 7.39 times total energy utilization density per unit land area compared to the conventional PV system. Based on the melting morphology and thermo-electric performance of the initially rectangular PCM enclosure, an optimized bifurcated non-rectangular design of the enclosure is proposed to enhance the incident radiation utilization ability by 87% more than a simple one PV/PCM system. Enhanced utilization of solar radiation manifests into 105% more melting compared to conventional PV/PCM system. With the strategic mirror reflection and bypassing the solar radiation towards the rear PV panel and strategic design of PCM enclosure to aid convection-driven melting, electric power output has been increased significantly (about 77%) compared to similar conventional PV/PCM system. The study revealed that overall system efficiency could approach about 74% if suitable strategies are adopted, as demonstrated in this chapter. Results are discussed in terms of energy utilization efficiency, exergy efficiency, power conversion efficiency, tracking melting front morphology, and its effect on heat transfer characteristics, etc. This investigation has been carried out with the help of an experimentally validated numerical model that accurately mimics the melting morphology of PCM and other heat transfer characteristics of the system. The findings of this study would help design and develop a more efficient BIF-PV/PCM system to meet exponentially increasing energy needs.

A series of novel designs of PCM encapsulation for PV/PCM systems have been investigated in the thesis using computational fluid dynamics with an objective to meet global energy demands. The efforts put in the present research certainly adds contribution to the global theme of '*Clean and green energy for all*'.