

**OPTIMISATION OF GLASS CLADDING BIPV
CONFIGURATION BASED ON ENERGY AND
DAYLIGHTING PERFORMANCE FOR
UNIVERSITY'S CLASSROOM**

SUSAN

UNIVERSITI SAINS MALAYSIA

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**OPTIMISATION OF GLASS CLADDING BIPV
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UNIVERSITY'S CLASSROOM**

by

SUSAN

**Thesis submitted in fulfilment of the requirements
for the degree of
Doctor of Philosophy**

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TABLE OF CONTENTS

ACKNOWLEDGEMENT	ii
TABLE OF CONTENTS.....	iii
LIST OF TABLES	vii
LIST OF FIGURES.....	ix
LIST OF SYMBOLS.....	xiv
LIST OF ABBREVIATIONS.....	xvi
LIST OF TERMINOLOGIES	xxi
LIST OF APPENDICES	xxiv
ABSTRAK.....	xxv
ABSTRACT.....	xxvii
CHAPTER 1 INTRODUCTION	1
1.1 Research Background	1
1.2 Problem Statements	3
1.3 Research Aim	8
1.4 Research Objectives.....	8
1.5 Research Questions	8
1.6 Significance of Study	9
1.7 Research Methodology.....	9
1.8 Limitation of Study	10
1.9 Summary	11
CHAPTER 2 LITERATURE REVIEW.....	13
2.1 Solar Energy	13
2.1.1 The Solar Energy Potential in Indonesia	15
2.1.2 The Challenges and Future Development of Solar Energy Use...	16
2.2 Lighting	18
2.2.1 Daylighting	18

2.2.1 (a) Daylighting Design Options.....	21
2.2.1 (a)(i) Top lighting	21
2.2.1 (a)(ii) Side lighting	22
2.2.1 (b) Daylighting Control Strategies.....	23
2.2.1 (b)(i) Site Development	23
2.2.1 (b)(ii) External Elements.....	25
2.2.1 (b)(iii) Internal Elements	26
2.2.1 (b)(iv) Roof and In-walls	27
2.2.1 (c) Daylighting Metrics	29
2.2.2 Artificial Lighting	33
2.3 Photovoltaic (PV) and Building Integrated Photovoltaic (BIPV).....	35
2.3.1 Photovoltaic (PV)	35
2.3.1 (a) PV-cell Temperature	36
2.3.1 (b) PV Types.....	38
2.3.1 (c) Number of PV-Cells in a Module	40
2.3.1 (d) PV-cell Color	41
2.3.1 (e) PV Efficiency	42
2.3.1 (f) Transparent PV's Visible Transmittance	43
2.3.2 Building Integrated Photovoltaic (BIPV).....	45
2.3.2 (a) Building's Form	45
2.3.2 (b) Potential Area.....	46
2.3.2 (c) Tilt and Orientation Angle.....	48
2.3.2 (d) Shading Condition.....	50
2.4 Daylighting and Energy Performance on Glass Cladding BIPV	51
2.5 Green Building	63
2.5.1 Energy Efficiency and Conservation (EEC)	65
2.5.2 Indoor Health and Comfort (IHC)	67
2.6 Multistorey School Building.....	68

2.7	Summary	74
CHAPTER 3	RESEARCH METHODOLOGY	80
3.1	Introduction	80
3.2	Research Design	80
3.3	Data Collection Technique.....	83
3.4	Site Selection.....	85
3.4.1	Criteria of Site Selection	86
3.4.1 (a)	The Geographical Location	86
3.4.1 (b)	Obstruction.....	86
3.4.1 (c)	Building Typology	86
3.4.1 (d)	Comparison for Site Selection.....	87
3.4.2	Detail of Selected Site.....	92
3.5	Research Instruments.....	93
3.5.1	The Classroom Models	104
3.5.2	Setting of Treatments and Post-test Models	106
3.6	Simulation Setting.....	108
3.6.1	HelioScope.....	109
3.6.1 (a)	HelioScope Validation	109
3.6.1 (b)	HelioScope Simulation Procedure	115
3.6.2	Velux	117
3.6.2 (a)	Velux Validation	117
3.6.2 (b)	Velux Simulation Procedure.....	121
3.7	Optimization.....	122
3.8	Method of Data Analysis.....	124
3.9	Summary	125
CHAPTER 4	RESULTS AND DISCUSSION.....	128
4.1	Energy Performance.....	128
4.1.1	Electrical Energy Substitution	128

4.1.2	Energy Performance across Models with Different Opening Type, Room Geometry, Orientation	133
4.1.3	Energy Performance based on PV Cell Coverage Ratio	137
4.1.4	Energy Performance based on PV Efficiency	141
4.2	Daylighting Performance	142
4.2.1	Illuminance Level	145
	4.2.1 (a) Illuminance Level for Single-sided Models.....	145
	4.2.1 (b) Illuminance Level for Multi-sided Models	155
4.2.2	Daylit Area Percentages	164
4.3	Optimum Glass Cladding BIPV Configurations	167
CHAPTER 5 CONCLUSION AND RECOMMENDATION		172
5.1	Overview of The Study	172
5.2	The Key Findings of The Study	172
5.2.1	Findings for Energy Performance of Glass Cladding BIPV.....	172
5.2.2	Findings for Daylighting Performance of Glass Cladding BIPV ..	173
5.2.3	Findings for Optimum Configurations of Glass Cladding BIPV...	174
5.3	Contribution of The Study	174
5.4	Recommendation.....	175
5.4.1	Recommendation for Future Research.....	175
5.4.2	Recommendation for Industry	177
5.5	Conclusion	177
REFERENCES		178
APPENDICES		
LIST OF PUBLICATIONS		

LIST OF TABLES

	Page
Table 2.1 Renewable Energy Potential (source: National General Energy Plan, 2019)	15
Table 2.2 Glazing Properties of Various Glazing Types (source: Asahimas, n.d).....	28
Table 2.3 Summary of Daylighting Metrics (source: Green Building Council Indonesia, GREENSHIP Existing Buildings Version 1.1, 2014; M. Wang et al., 2025)	33
Table 2.4 Lighting Power Density (LPD) for Educational Facility (source: Badan Standardisasi Nasional, 2000)	34
Table 2.5 Specification of PV Glass (source: Onyx PV Specification, n.d).....	40
Table 2.6 Potential Area for BIPV Installation (source: Kuhn et al., 2021)	47
Table 2.7 Previous Research	53
Table 2.8 Rating Criteria and Points for Greenship Existing Building V 1.2 (source: Green Building Council Indonesia, 2021)	65
Table 2.9 Rating Criteria and Points for Energy Efficiency and Conservation (source: Green Building Council Indonesia, 2021)	66
Table 2.10 The EUI Standard (source: Departemen Pendidikan Nasional, 2006).....	66
Table 2.11 Rating Criteria and Points for Indoor Health and Comfort (source: Green Building Council Indonesia, 2021)	67
Table 2.12 Level of Illuminance (source: Badan Standardisasi Nasional, 2000).....	68
Table 2.13 Occupancy and Receptacle Power Density (source: ASHRAE, 2016).....	71
Table 2.14 Classification of School Building based on EUI (source: Departmen Pendidikan Nasional, 2006).....	73
Table 3.1 The Experimental Method.....	82

Table 3.2	Data Collection Technique.....	84
Table 3.3	Options of University Buildings for Site Contextual Reference.....	89
Table 3.4	Climatic Data (source: BMKG Surabaya)	90
Table 3.5	Floor to Floor Layout Plans and The Details	94
Table 3.6	Models' Configuration based on Room Geometry	105
Table 3.7	Classroom Models	105
Table 3.8	Material and Finishing Setting (source: Velux)	108
Table 3.9	Calculation of Transparent PV Area	108
Table 3.10	Comparison of Default Internal Models from Solar Design Software (source: Guittet & Freeman, 2018)	109
Table 3.11	Comparison of HelioScope (as web-based software) to Other Desktop-based Software	111
Table 3.12	PV Specifications Used in the Prototype	112
Table 3.13	Calculation of Power Output	114
Table 3.14	Measured Illuminance Value (lux) on 21 st May	120
Table 3.15	Simulated Illuminance Value (lux) on 21st May	120
Table 4.1	Data from HelioScope.....	129
Table 4.2	Energy Substitution Percentages	131
Table 4.3	Selected Models for Daylighting Performance Assessment	144
Table 4.4	Multi-sided Models meet the Illuminance Threshold.....	163
Table 4.5	Illuminance for 50%-40%-30% Daylit Area	164
Table 4.6	Variables and Impact on Glass Cladding BIPV Optimization	170

LIST OF FIGURES

	Page
Figure 2.1	Solar Energy Potential in Indonesia (Silalahi & Gunawan, 2022).....16
Figure 2.2	Various Source of Natural Lighting for Building (Lechner, 2014).....19
Figure 2.3	Comparison of Illuminance Level at Clear Sky Condition (Lechner, 2014).....19
Figure 2.4	Comparison of Illuminance Level at Overcast Sky Condition (Lechner, 2014)20
Figure 2.5	Correlation of FAR, Site Coverage, and Adequately Daylit Room Depth (Šprah & Košir, 2020).....24
Figure 2.6	The Impact of Temperature to Relative Current and Voltage (Roberts & Guariento, 2009).....36
Figure 2.7	Structure of PV with Radiative Cooling Coating (W. Wang et al., 2024).....37
Figure 2.8	Crystalline Silicon Photovoltaic Glass (https://onyxsolar.com/the-essentials/crystalline-silicon-photovoltaic-glass , downloaded on March, 4 th , 2025).....39
Figure 2.9	The Impact of Cell Numnbers to Relative Current and Voltage (Roberts & Guariento, 2009).....40
Figure 2.10	Model used for Analysis of Performance and Future Development Paths of PV Glass (Kyrou et al., 2023).....43
Figure 2.11	Comparison of PV Glass Performance: under several options, within the sama Climat Condition (Kyrou et al., 2023).....44
Figure 2.12	Comparison of PV Glass Performance: under certain VT, in several Climate Conditions (Kyrou et al., 2023)44
Figure 2.13	Comparison of PV Surface-to-Volume Ratio: five types of building's form under the same volume (Markus & Morris, 1980)46
Figure 2.14	A. Plan, B. Section, and C. 3D of the Building Prototype (Mangkuto et al., 2023).....49
Figure 2.15	Full-size Photovoltaic Array (Song et al., 2025).....51

Figure 2.16	Setting of Shadow Experiment (Song et al., 2025).....	51
Figure 2.17	School Building Various Layout. (Montenegro et al., 2012).....	71
Figure 2.18	Models Set-up in Different Room Width-to-Depth Ratios, within Near-Constant Floor Area (Czachura et al., 2024).....	72
Figure 2.19	Multi-storey School Buildings in Indonesia: A. Universitas Indonesia, B. Institut Teknologi Bandung, C. Universitas Kristen Maranatha, D. Unuversitas Parahyangan, E. Universitas Ciputra Makassar (https://www.ui.ac.id ; https://www.itb.ac.id ; https://art.maranatha.edu/facilities/ ; https://unpar.ac.id ; https://www.ciputramakassar.ac.id/ . Accessed January 3, 2024).....	74
Figure 2.20	Consideration Factors in Designing Glass Cladding BIPV	76
Figure 2.21	Theoretical Framework	78
Figure 2.22	Conceptual Framework.....	79
Figure 3.1	Condition of Selected Site – Site Plan Image (https://www.google.com/maps)	91
Figure 3.2	Condition of Selected Site – Perspective Image (https://www.ciputra.ac.id)	91
Figure 3.3	Existing Building of Universitas Ciputra Surabaya: A. West Elevation, B. Central Corridor Layout, C. Existing Classroom Condition.....	92
Figure 3.4	Experiment, Treatment, and Post-test Modelling.....	107
Figure 3.5	PV Mechanical Diagrams Used in the Prototype	111
Figure 3.6	Installation Area of the PV Prototype.....	113
Figure 3.7	A. The Recording System and B. The Recorded Annual Data.....	113
Figure 3.8	A. Output for 135° Orientation and B. Output for 225 ° Orientation	114
Figure 3.9	Create New Project.....	115
Figure 3.10	Create New Design.....	116
Figure 3.11	Simulation Result in HelioScope.....	117
Figure 3.12	Lux Meter	118
Figure 3.13	Measurement Grids	118

Figure 3.14	Simulation Grids	119
Figure 3.15	A. Measured and B. Simulated Distribution Pattern for 21 st May....	120
Figure 3.16	Setting 15% Transmittance on Transparent PV	121
Figure 3.17	Setting 76% Transmittance on low-E Glass	121
Figure 3.18	Location and Weather Data Input in Velux	122
Figure 3.19	Setting Camera and Render	122
Figure 3.20	Workflow of Research.....	125
Figure 3.21	Comparison of Architectural Design Approach.....	127
Figure 4.1	Comparison of Energy Substitution Percentages under Different Opening Type, Room Geometry, and Orientation: : A. Single-sided Opening-2:3 Room Geometry, B. Single-sided Opening-3:2 Room Geometry, C. Single-sided Opening-1:1 Room Geometry, D. Multi-sided Opening-2:3 Room Geometry, E. Multi-sided Opening-3:2 Room Geometry, F. Multi-sided Opening-1:1 Room Geometry	134
Figure 4.2	Comparison of Electrical Energy Substitution Ranges for Single-sided Openings-PV1. Under Different Room Geometry	135
Figure 4.3	Comparison of Electrical Energy Substitution Ranges for Single-sided Openings-PV2, under Different Room Geometry.....	135
Figure 4.4	Comparison of Electrical Energy Substitution Ranges for Multi-sided Openings-PV1, under Different Orientations.....	136
Figure 4.5	Comparison of Electrical Energy Substitution Ranges for Multi-sided Openings-PV2, under Different Orientations.....	137
Figure 4.6	Comparison of Electrical Energy Substitution under Different Cell Coverage Ratio, for Multi-sided Openings, with 16% PV efficiency	138
Figure 4.7	Comparison of Electrical Energy Substitution under Different Cell Coverage Ratio, for Single-sided Opening, with 16% PV efficiency	138
Figure 4.8	Comparison of Electrical Energy Substitution under Different PV Efficiency, for Single-sided Opening.....	141

Figure 4.9	Comparison of Electrical Energy Substitution under Different PV Efficiency, for Multi-sided Opening	143
Figure 4.10	Illuminance Results for Single-sided Opening – 2:3 Room Geometry: A. North Opening, B. South Opening, C. East Opening, D. West Opening	146
Figure 4.11	Illuminance Results for Single-sided Opening – 3:2 Room Geometry: A. North Opening, B. South Opening, C. East Opening, D. West Opening	147
Figure 4.12	Illuminance Results for Single-sided Opening – 1:1 Room Geometry: A. North Opening, B. South Opening, C. East Opening, D. West Opening	148
Figure 4.13	Range of Illuminance Comparison for Single-sided Models under Different Orientations and Room Geometry	149
Figure 4.14	Illuminance Comparison under Different Cell Coverage Ratios for Single-sided - 1:1 Room Geometry – A Scenario - PV1	151
Figure 4.15	Illuminance Comparison under Different Cell Coverage Ratios for Single-sided – 2:3 Room Geometry – B Scenario - PV1	151
Figure 4.16	Illuminance Comparison under Different Cell Coverage Ratios for Single-sided – 3:2 Room Geometry – C Scenario - PV1	152
Figure 4.17	Illuminance Level under Different PV's Visible-transmittance for Single-sided – 3:2 Room Geometry – A, B, C Scenarios	153
Figure 4.18	Illuminance Level under Different Scenarios for Single-sided – 2:3 Room Geometry – PV 1	154
Figure 4.19	Illuminance Results for Multi-sided Opening – 2:3 Room Geometry: A.North and East Opening, B. South and East Opening, C. South and West Opening	156
Figure 4.20	Illuminance Results for Multi-sided Opening – 3:2 Room Geometry: A.North and East Opening, B. South and East Opening, C. South and West Opening	157
Figure 4.21	Illuminance Results for Multi-sided Opening – 1:1 Room Geometry: A.North and East Opening, B. South and East Opening, C. South and West Opening	158

Figure 4.22	Comparison for Ranges of Illuminance Level under Different Opening Types and Room Geometry	159
Figure 4.23	Illuminance Comparison under Different Cell Coverage Ratios for Multi-sided – 1:1 Room Geometry – A Scenario - PV1	160
Figure 4.24	Illuminance Comparison under Different Cell Coverage Ratios for Multi-sided – 2:3 Room Geometry – B Scenario - PV1	160
Figure 4.25	Illuminance Level under Different Scenarios for Multi-sided – 2:3 Room Geometry – PV 1.....	161
Figure 4.26	Illuminance Level under Different Cell Coverage Ratios for Multi-sided – 2:3 Room Geometry – C Scenario – A. PV1 & B. PV2	162
Figure 4.27	Illuminance Level under Different Cell Coverage Ratios for Multi-sided – 3:2 Room Geometry – C Scenario – A. PV1 & B. PV2	162
Figure 4.28	Illuminance Level under Different Cell Coverage Ratios for Multi-sided – 3:2 Room Geometry – C Scenario – A. PV1 & B. PV2	162
Figure 4.29	Comparison of Illuminance Level in 30% Daylit Area Percentages under Different Room Geometry.....	166
Figure 4.30	Comparison of Illuminance Level in 30% Daylit Area Percentages under Different Cell Coverage Ratios	167
Figure 4.31	Optimization Diagram	169
Figure 5.1	Optimum Configuration across All Room Geometries and Orientations	174

LIST OF SYMBOLS

η_m	PV Efficiency
μ -Si	Microcrystalline Silicon
a-Si	Amorphous Silicon
A	PV area
ASE _{1000,250}	Annual sun exposure at 1000 lux or more for at least 250 occupied hours per year
c-Si	Crystalline silicon
DA ₃₀₀	Climate-based measurement of 300 lux daylight adequacy in a room
E	Illuminance
E _{avg}	Average illuminance
E _i	Internal Illuminance
E _o	External Illuminance
G	Solar radiation intensity/irradiance
I _{mpp}	Current of maximum power point
MS	Multi-sided openings models
NE	North- and East- facing openings
nSE _{1000lx≥250h}	Area that receives 1000 lux or more for at least 250 occupied hours per year
PV1	Higher efficiency PV (16%) with lower visible transmittance (15%)
PV2	Lower efficiency PV (9.3%) with lower visible transmittance (38%)
R _{fl}	Reflectance value for room surface
R _{gh}	Roughness for room surface
sDA _{300/50%}	Spatial daylight autonomy where 50% of the area receives 300 lux or more
SE	South- and East- facing openings
Spec	Specularity of room surface

SS	Single-sided opening model
SW	South- and West- facing openings
$t_{E=200-500}$	Working time when the target illuminance can be achieved by daylight
$t_{E\geq 300}$	Time in which daylight illuminance values are at least 300lx.
$UDI_{200-500}$	Useful Daylight Illuminance, targeted in 200-500lx
$UDI_{100-3000}$	Useful Daylight Illuminance, targeted in 100-3000lx
$UDI_{250-750}$	Useful Daylight Illuminance, targeted in 250-750lx
U_o	Uniformity Ratio
U_{value}	Air-to-air thermal transmittance
V_{mpp}	Voltage of maximum power point
VT1	Lower visible transmittance of transparent substrate (71%)
VT2	Higher visible transmittance of transparent substrate (76%)

LIST OF ABBREVIATIONS

AC	Air Conditioning
ASD	Appropriate Site Development
ASE	Annual Sun Exposure
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BAPV	Building Attached Photovoltaic
BEM	Building and Environment Management
BIPV	Building Integrated Photovoltaic
BIPVT	Building Integrated hybrid Photovoltaic-Thermal
BITPV	Building Integrated Transparent Photovoltaic
BMKG	Badan Meteorologi, Klimatologi & Geofisika
BREEAM	Building Research Establishment Environmental Assessment Method
BRIN	Badan Riset dan Inovasi Nasional
BSN	Badan Standardisasi Nasional
CAD	Computer Aided Design
CdTe	Cadmium Telluride
CdTe-PV	Cadmium Telluride Photovoltaic
CEC	California Energy Commission
CIE	Commission Internationale de l'Eclairage
CIGS	Copper Indium Gallium Selenide
CIS	Copper Indium Selenide
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
COE	Cost of Energy
CPVW	Concentrator Photovoltaic Window

CRI	Colour Rendering Index
CS	Circadian Stimulus
DA	Daylight Autonomy
DAYSIM	Dynamic Daylight Simulation
DC	Direct Current
DC-AC	Direct Current – Alternating Current
DF	Daylight Factor
DGP	Daylight Glare Probability
DHI	Diffuse Horizontal Irradiance
DNI	Direct Normal Irradiance
DOE-2	Department of Energy-2
ECI	Energy Consumption Index
EEC	Energy Efficiency and Conservation
EEC-P1	Energy Efficiency and Conservation-Prerequisite 1
EEC-P2	Energy Efficiency and Conservation-Prerequisite 2
EML	Equivalent Melanopic Lux
EN	European Standard
EPD	Environmental Product Declaration
EPW	Energy Plus Weather
ESI	Environment and Sustainability Institute
EUI	Energy Utility Index
FAR	Floor Area Ratio
FAST	Features from Accelerated Segment Test
GBCI	Green Building Council Indonesia
GBI	Green Building Initiative
GHI	Global Horizontal Irradiance
GIS	Geographic Information Systems
GSAS	Global Sustainability Assessment System

GW	Giga-watt
GWp	Giga-watt Peak
HOMER	Hybrid Optimization Model for Electric Renewables
HVAC	Heating, Ventilating, and Air Conditioning
IDN	Indonesia
IEC	International Electrotechnical Commission
IECC	International Energy Conservation Code
IEEE	Institute of Electrical and Electronics Engineers
IEQ	Indoor Environment Quality
IES-VE	Integrated Environment Solution – Virtual Environment
IET	The Institution of Engineering and Technology
IHC	Indoor Health and Comfort
IHC-P	Indoor Health and Comfort - Prerequisite
JUST	Jordan University of Science and Technology
KW	Kilowatt
LED	Light Emitting Diode
LEED	Leadership in Energy and Environmental Design
Low-E	Low Emissivity
LPD	Lighting Power Density
LSCs	Luminescent Solar Concentrators
MDPI	Multidisciplinary Digital Publishing Institute
Mono-Si	Mono-crystalline Silicon
MPC	Model Predictive Control
MRC	Material Resources and Cycle
MWh	Megawatt hour
NASA	National Aeronautics and Space Administration
NOCT	Nominal Operating Cell Temperature
NREL	National Renewable Energy Laboratory

PBT	Payback Time
PLoS	Public Library of Science
POA	Plane of Array
PV	Photovoltaic
PVs	Photovoltaics
PVSC	Photovoltaic Specialist Conference
PVSDs	Photovoltaic Integrated Shading Devices
PVsyst	Photovoltaic
PVSyst	Photovoltaic System software
PVTEB	Photovoltaic Thermoelectric-Battery
ROI	Return of Investment
SAM	System Advisor Model
sDA	Spatial Daylight Autonomy
SGA	Spatial Glare Autonomy
SGCC	Safety Glass Council
SGHAT	Solar Glare Hazard Analysis Tool
SHGC	Solar Heat Gain Coefficient
SIPV	Skylight Integrated Photovoltaic
SNI	Standar Nasional Indonesia
STC	Standard Test Condition
STPV	Semi-transparent Photovoltaic
STPVG	Semi-transparent Photovoltaic Glazing
STPVW	Semi-transparent Photovoltaic Window
TE	Thermoelectric
TPA	Taman Pendidikan Al Quran
TPV	Transparent PV
TRNSYS	Transient System Simulation Tool
UCS	Universitas Ciputra Surabaya

UDI	Useful Daylight Illuminance
UK	United Kingdom
USA	United States of America
USGBC	United States Green Building Council
UV	Ultraviolet
UV-T	Ultraviolet transmission
VSC	Vertical Sky Component
VT	Visible Transmittance
WAC	Water Conservation
WFR	Window-to-Floor Ratio
WWR	Window-to-Wall Ratio
ZEBs	Zero Energy Buildings

LIST OF TERMINOLOGIES

Annual Sun Exposure (ASE)	Daylighting metric that indicate the presence of glare and additional heat due to excessive direct light.
Cell coverage ratio	The percentage of a surface area covered by photovoltaic cells within a PV modul or system.
Daylight Autonomy	A daylighting metric that is defined as a climate-based measurement of daylight adequacy in a room.
Daylit area percentages	The percentage of floor area that reach the standard illuminance level, compared to overall floor area.
Discrepancy factor	A numerical value that quantifies the difference or deviation between two quantities.
Daylight Factor	A ratio of internal illuminance measured at a point in an indoor daylit room, to external horizontal illuminance, at the same time, under the standard CIE overcast sky condition
Daylight Glare Probability	Daylighting metrics that relate to glare analysis, which evaluate glare conditions in certain times
Energy substitution	The ratio of electricity generated by the PV to the building's electricity demand.
Energy Utility Index (EUI)	A typical amount of energy usage by building which can be different from one to another based on its typology.

GreenSHIP	A green building rating tool issued by Green Building Council Indonesia.
Illuminance	A measurement of the illumination on a surface, measured in lux, which is caused by 1lm incident on 1m ² area (incident flux density of 1lm/m ²).
Irradiance	A measurement of energy flow density of solar radiation, defined as the mean total electromagnetic energy from the Sun, integrated over all wavelengths, incident per unit area per unit time.
Latitude	A geographic coordinate that specifies the north-south position of a point on the Earth's surface, measured in degrees from the equator.
Lighting Power Density (LPD)	A number that indicates lighting power consumption in every unit area.
Longitude	A geographic coordinate that specifies the east-west position of a point on the Earth's surface, measured in degrees from the prime meridian.
Receptacle power density	The amount of electrical power capacity assigned to receptacles (electrical outlets) in a given area.
Spatial Daylight Autonomy	A comparison of floor area with DA ₃₀₀ to overall floor area, presented in percentages.
Uniformity Ratio	Daylighting metric that is measured as the minimum illuminance compared to the average illuminance.
Useful Daylight Illuminance	A comparison of working time when the target illuminance at a certain point in space can be

achieved with daylight, to the whole working hours.

Visible transmittance

A measure how much visible light passes through a glazing system.

PV efficiency

The comparison of output power to input power of a PV.

Spatial Glare Autonomy

Daylighting metrics that relate to glare analysis, which evaluate glare conditions throughout the year.

LIST OF APPENDICES

Appendix 1	Measured and Simulated Results for Illuminance Level
Appendix 2	Comparison of Distribution Pattern
Appendix 3	HelioScope Simulation Results
Appendix 4	Illuminance Level (for Models Comply to Energy Metric Threshold)
Appendix 5	Illuminance Level (for Models Comply to Illuminance Threshold)
Appendix 6	Illuminance Level for 50%-40%-30% Daylit Area (for Models Comply to Illuminance Threshold)
Appendix 7	Other Publications

**PENGOPTIMUMAN KONFIGURASI PANEL KACA BIPV
BERDASARKAN PRESTASI TENAGA DAN PENCAHAYAAN SIANG
BAGI BILIK KULIAH DI UNIVERSITI**

ABSTRAK

Permintaan tenaga yang ketara dalam bilik darjah universiti tropika membawa kepada keperluan pembinaan penyelesaian yang menyepadukan penjanaan tenaga dan pencahayaan siang yang berkesan. Kajian ini menyiasat prestasi pelapisan kaca Building Integrated Photovoltaics (BIPV) untuk menentukan konfigurasi optimum yang meningkatkan prestasi tenaga dan pencahayaan siang hari. Objektifnya adalah untuk mengenal pasti konfigurasi BIPV pelapisan kaca yang paling berkesan yang mengoptimumkan penjanaan tenaga sambil memastikan pencahayaan siang yang mencukupi untuk bilik darjah universiti tropika. Untuk mencapai matlamat ini, eksperimen berasaskan simulasi telah dijalankan menggunakan HelioScope dan Velux untuk menilai beberapa model yang dibangunkan berdasarkan jenis pembukaan, geometri bilik dan orientasi. Pembolehubah termasuk nisbah dan kecekapan liputan sel PV, pemancaran ketara PV dan substrat lutsinar, dan pemantulan permukaan bilik. Prestasi pencahayaan siang dinilai berdasarkan kecerahan dan peratusan kawasan siang hari, manakala prestasi tenaga dianalisis melalui penggantian tenaga elektrik. Analisis mendapati 20 konfigurasi optimum yang memenuhi kedua-dua sasaran tenaga dan pencahayaan siang secara serentak. Model ini secara konsisten menampilkan bukaan berbilang sisi, nisbah liputan sel 30-50% dan pantulan permukaan bilik yang optimum. Di antara keputusannya, didapati prestasi tenaga kurang terjejas oleh geometri bilik dalam model berbilang sisi tetapi terjejas dengan ketara dalam satu sisi. Sementara itu, pemantulan permukaan bilik berperanan sebagai faktor penting berbanding ketransmisian yang boleh dilihat. Oleh itu, nisbah liputan sel yang rendah (cth., 20%) tidak mencukupi untuk memenuhi

sasaran penggantian tenaga 2%. Kajian ini menyumbang rangka kerja untuk mengoptimumkan reka bentuk BIPV pelapisan kaca dalam bangunan pendidikan di bawah keadaan tropika. Penyelidikan masa depan digalakkan untuk mengesahkan penemuan ini dengan percubaan berskala penuh, meneroka integrasi BIPV mendatar, dan melanjutkan analisis kepada jenis bangunan yang lain dan skop ekonomi.

OPTIMISATION OF GLASS CLADDING BIPV CONFIGURATION BASED ON ENERGY AND DAYLIGHTING PERFORMANCE FOR UNIVERSITY'S CLASSROOM

ABSTRACT

A significant demand of energy in tropical university classrooms lead to the need of building solution that integrated energy generation and effective daylighting. This study investigates the performance of glass cladding Building Integrated Photovoltaics (BIPV) to determine optimum configurations that enhance both energy and daylighting performance. The objective is to identify the most effective configurations of glass cladding BIPV that optimize energy generation while ensuring adequate daylighting for tropical university classrooms. To achieve this, simulation-based experiments were conducted using HelioScope and Velux to assess several models which were developed based on opening types, room geometry, and orientations. Variables include PV cell coverage ratio and efficiency, visible transmittance of PV and transparent substrate, and room surface reflectance. Daylighting performance was evaluated based on illuminance and daylit area percentages, while energy performance was analyzed through electrical energy substitution. The analysis found 20 optimal configurations that simultaneously meet both energy and daylighting targets. These models consistently feature multi-sided openings, 30-50% cell coverage ratios, and optimum room surface reflectance. Among the results, it is noticed that energy performance was less affected by room geometry in multi-sided models but significantly affected in single-sided. Meanwhile, room surface reflectance played as an important factor over visible transmittance. Hence, low cell coverage ratio (e.g., 20%) is insufficient to meet the 2% energy substitution target. This study contributes a framework for optimizing glass cladding BIPV design in education buildings under tropical conditions. Future research is

encouraged to validate these findings with full-scale experiment, explore horizontal BIPV integration, and extend analysis to other building types and economic scope.

CHAPTER 1

INTRODUCTION

1.1 Research Background

Energy consumption is a major challenge in building's life, since building consumes energy both in its development, operational, and even on its demolishing stage. Data shows that building consumes 30% of world energy and contributes to almost 15% global emissions (World Energy Outlook 2022, n.d.). Aside of energy, daylighting also plays a critical role in sustainable architectural design, including in large-scale buildings such as universities. As university accommodate numbers of students and staff daily, the building will need substantial amounts of energy for lighting, cooling, and other operational needs. At the same time, daylighting has been recognized for its potential to better improve educational process, to make the students performed and achieved better (Tsikra & Andreou, 2017). Achieving optimal balance between energy and daylighting remains a challenge.

Related to energy concern, strategies to achieve a better energy performance are needed, such as: switching to renewable energy resources (National General Energy Plan, 2019), reducing energy consumption by choosing energy-saving equipment and energy-saving management (Lai et al., 2020); and increasing energy efficiency by converting waste energy into recovered energy (Karnama, 2019). Switching to renewable energy has potential to be implemented in Indonesia due to the resource availability, particularly for the solar energy. The solar energy potential in Indonesia reaches 207.8 Gwp (National General Energy Plan, 2019), measured in relatively higher amount compared to other sources of renewable energy.

This solar energy can be converted into electrical energy through the use of photovoltaic (PV). PV, that is made from semiconductor material, is a technology that could convert received light into electricity. Supported by the facts of its implementation growth, PV technology can be considered as the most powerful

microgeneration technology to optimize the use of solar energy (Camilo et al., 2021; Rabaia et al., 2021; Y. Shi et al., 2021). One of its installation systems called BIPV (Building Integrated Photovoltaic) gives advantage in terms of substituting the building conventional materials. The application of BIPV requires a building to optimize the solar radiation received. One of the potential strategies that can be applied to optimize the solar radiation received is the use of building vertical façade in a high-rise building (Mangkuto et al., 2023). Mangkuto et al (2023) discussed that this potential presents based on the availability of huge vertical area compared to the horizontal one.

Related to energy saving strategy, building placed in the tropical climate such as Indonesia can take advantage by optimizing the use of daylighting to reduce the need of artificial lighting energy consumption. It is known that daylighting can reduce artificial lighting consumption from 26%-50% (Konstantoglou & Tsangrassoulis, 2016; Manzan & Clarich, 2017). Regarding to users' performance, daylight will affect users on their health, social interaction, psychology, feelings, and visual task (Kim & Kim, 2010; MBC Aries et al., 2013). It gives advantage to users because the spectrum of daylight is the most suitable spectrum regarding the human visual response. Therefore, it is essential to provide indoor environment that promote the optimum penetration of daylight.

Daylight comes from the sunlight, skylight, and reflected sunlight and skylight. The sunlight, skylight, reflected sunlight and skylight can penetrate to a building from top lighting as well as side lighting. In particular, side lighting is known as the most widely used natural lighting system in buildings (Hesti et al., 2015) and has several other functions such as providing surrounding view, ventilation, and sound dampening. Sequentially, the design of vertical façade as a place to put side lighting aperture will then be crucial (Alhagla et al., 2019).

From the discussion above, it is noticed that whilst the vertical facade can be used for façade integrated photovoltaic, it is also needed to supply natural lighting in a building. The finding of transparent PV technology promotes an opportunity to serve

both needs. This technology let certain amount of visible light transmit into indoor area. The visible transmittance (VT) value for transparent PV may be lower compared to other glazing systems, since higher VT will reduce the ability of PV to absorb solar irradiance and to produce electricity. Glass cladding BIPV, which also known as Building Integrated Transparent Photovoltaic (BITPV), or BIPV windows, refers to the system that incorporate this transparent PV to the window/glazing area of buildings to generate electricity on site and transmit visible light (Li et al., 2023). One of the challenges in using transparent PV as glass cladding BIPV is the optimization between daylighting and electricity generation. Presenting a systematic method to find the optimum configuration is also important so that the indoor daylighting and the energy performance can be well optimized.

1.2 Problem Statements

As discussed above, energy and daylighting performance are critical aspects for building design, including for university classrooms where certain amount of energy and daylighting are required for its operational needs and for better performance of its users. For daylighting needs, prior study has found that students at daylighting schools performed and achieved better than students in artificially illuminated schools (Tsikra & Andreou, 2017). In terms of energy needs, university buildings that consist of multiple room-types require continuous energy supply. Aside for general usage (such as artificial lighting, cooling load, and buildings' utility), university buildings are accounted for a certain amount of energy consumption due to the needs of digital technology in education, such as computers, projectors, and many other electronic equipment for the laboratory needs (Hoxha et al., 2021).

University buildings are characterized by high occupancy rates and extended operational hours (Alfalah et al., 2023; Wei & Calautit, 2023), leading to an intensive use which is shown by its relatively high energy utility index (EUI), occupancy density and receptacle power density (ASHRAE, 2016). The EUI standard for educational

buildings is divided into some criteria, from very inefficient to very efficient. The one categorized as inefficient educational building has EUI ranges between 19.17-23.75 kWh/m²/month or 230.04-285.00 kWh/m²/year (Departemen Pendidikan Nasional, 2006). It is similar to the EUI for office buildings which ranges around 250 kWh/m²/year (Green Building Council Indonesia, Greenship Existing Buildings Version 1.1, 2014). The relatively high EUI of educational buildings aligns with its high occupancy density and high receptacle power density that reach 7.0 m²/person (or 9.7 W/m²) and 5.4 W/m². Respectively, it is the second and the third highest among other building typologies (ASHRAE, 2016).

In general, optimization of energy and daylighting performance can be conducted through several strategies. Prior study found that modifying the building envelope parameters can improve daylight and energy performance within the building (Lakhdari et al., 2021). The selection of glazing for side lighting aperture is also essential when it comes to the consideration of energy saving and users' performance (Alhagla et al., 2019; Hee et al., 2015). Hence, when it comes to daylight distribution, selection of building layout, room geometry, and the internal room surfaces are also important. Prior study found that room surface reflectance has a dominant impact on the level of illuminance promoted in a room. Improving surface reflectance is a better approach than expanding the window area for daylighting penetration (Cai et al, 2018). Particularly in the tropics, expanding the window area is not preferable since it causes additional heat gain and higher energy cost for the cooling load. In fact, the window-to-wall ratio (WWR) suggested within 20%-40% only (Gupta & Deb, 2023; Pathirana et al., 2019; Tong et al., 2019).

Despite of those observed strategies, BIPV has emerged as a promising technology to enhance energy performance in buildings by integrating PV elements into the building envelopes (Gholami & Røstvik, 2020; Kurz et al., 2023; Susan et al., 2021). Among various BIPV application, glass cladding BIPV is gaining attention due to its potential to provide energy while influencing daylighting conditions. However,

challenge remains since there is a trade-off between the ability of transparent PV to generate energy with its ability to provide daylighting (K. Lee et al., 2020). Hence, achieving an optimal balance between energy generation and daylighting performance in glass cladding BIPV requires a well-defined configuration, considering factors such as transparent PV glazing properties, cell coverage ratio, and reflectance of surfaces within classroom environment.

Existing studies on BIPV have primarily focused on the significance used of vertical façade for glass cladding BIPV, aimed particularly to investigate the impact on human visual comfort (Hu et al., 2023), to determine the optimum orientation (Mangkuto et al., 2023), and to evaluate the performance of semi-transparent PV window as well as to analyze the effect of window design on overall energy efficiency (Sun et al., 2018). Hence, existing research have also tried to optimization BIPV performance through certain strategies such as by modifying opening shape to optimize daylighting performance (Y. Wu, Li, et al., 2024), modifying cell strip width and cell coverage ratio to optimize daylight performance and visual characters (Li et al., 2023), modifying tilt and orientation angle to optimize energy production (Basak et al., 2025; Ghosh et al., 2024), and arrange the spatial distribution for PV systems to optimize the power generation (Jing et al., 2023).

Specifically on façade integrated photovoltaic, existing studies have primarily focused in mid to high latitude area, for example in Italy, US, UK, and China (Do et al., 2017; Hu et al., 2023; Musameh et al., 2022; Polo López & Sangiorgi, 2014). A study in UK found the advantage of PV windows in terms of lower heat transfer coefficient and lower solar heat gain compared to the one on transparent single glazing (Alrashidi, Ghosh, et al., 2020). Experimental investigation was conducted on PV window in China and found that human comfort in a room with PV window can be achieved when the working surface illuminance range in between 500-2200lx (Hu et al., 2023). An investigation in China has found that building shadow influences the percentage decrease more to power generation and efficiency than to solar radiation

received (Xiong et al., 2022). A concentrator photovoltaic was proposed to enhance the energy performance of PV window (Xuan et al., 2021). Meanwhile, another study has tried to find optimal area ratio-based design strategies of skylight integrated photovoltaic based on indoor light performance (Fan et al., 2021).

Aside of different aims, treatments, and locations, different PV-types has also been used in prior research. For example, the impact of glass cladding BIPV on human comfort conditions were studied by comparing several semi-transparent modules: mono-crystalline silicon, c-Si, amorphous silicon, and copper indium selenide thin film technology CIS (Polo López & Sangiorgi, 2014). CdTE PV-types was used to observe thermal, daylight, and energy performance (Alrashidi, Ghosh, et al., 2020; Sun et al., 2019; Y. Wu, Li, et al., 2024). Meanwhile, another study used crystalline silicon (c-Si) transparent PV and found the advantages in terms of efficiency and fabrication line (Pulli et al., 2020).

Accordingly, various metrics system were used to analyze the performance of energy and daylighting within the building. In the daylighting scope, prior studies were found using metrics such as illuminance level (Ayoosu et al., 2021; Freewan & Al Dalala, 2020; Hu et al., 2023; Lakhdari et al., 2021; Mangkuto et al., 2023; Pilechiha et al., 2020; Sahputra et al., 2022), and daylit area percentages (Kusuma Wardhani & Susan, 2022; Greenship Net Zero, Net Zero Healthy Masterclass, 2020). Hence, within the scope of energy performance, the electrical energy generation by PV is used as the indicator (Freewan & Al Dalala, 2020; Giouri et al., 2020; Kirmat et al., 2022; Lakhdari et al., 2021; Mangkuto et al., 2023; Pulli et al., 2020; Tsikra & Andreou, 2017). The energy evaluation of a building is usually assessed based on its energy utility index/EUI (Nam et al., 2025). This EUI presents a typical amount of energy usage by building which can be different from one to another based on its typology (Biantoro & Permana, 2017).

Concern on energy and lighting performance is also shown by councils and government such as Green Building Council Indonesia (GBCI) as well as the

Indonesian government itself. GBCI has already issued a rating tools named Greenship, where energy efficiency and conservation (EEC) and indoor health and comfort (IHC) become two from many indicators assessed (Green Building Council Indonesia, Greenship New Building 1.2, 2012). Within the tools, on-site renewable energy, illuminance level, and daylight percentages area are used as the metrics to assess the building performance. Furthermore, the Indonesian Government has issued an Indonesia Energy Mix Program that measure percentages of substitution, from renewable electrical energy production to conventional electrical energy production (National General Energy Plan, 2019). Meanwhile for lighting, Indonesian Government has also issued a general guideline for energy conservation in lighting system (Badan Standardisasi Nasional, 2011), and a specific guideline for implementation of energy conservation and supervision in Ministry of National Educational Environment (Departemen Pendidikan Nasional, 2006).

Overall, existing studies on BIPV and glass cladding BIPV have primarily focused on either energy performance of daylighting impact separately, while few studies integrated both aspects. Furthermore, research on glass cladding BIPV in university buildings remains limited, particularly the ones that consider classroom indoor environments in tropical climate. Whilst glass cladding BIPV has potential to address the needs of energy and daylighting, the effectiveness of the approach is dependent on its design configuration. Therefore, a study is needed to determine the optimal configuration of glass cladding BIPV that maximizes buildings' energy and daylighting performance. In this study, the optimum configurations of glass cladding BIPV arranging on transparent PV glazing properties, cell coverage ratio, and reflectance of room surfaces are expected to be one of any strategies to address the issue of energy and daylighting simultaneously.

1.3 Research Aim

This research aims to determine the optimum glass cladding BIPV configurations based on energy and daylighting performance for university classrooms. The configurations are evaluated by considering transparent PV glazing properties, cell coverage ratio, and reflectance of room surfaces in order to achieve an optimal balance between energy generation and lighting performance.

1.4 Research Objectives

To achieve the research aim, the following objectives are established:

1. To evaluate the performance of different glass cladding BIPV (Building-Integrated Photovoltaics) configurations against specific energy metrics in tropical climate classroom settings.
2. To analyse the extent to which glass cladding BIPV configurations that meet generic energy metrics also support daylighting performance in tropical climates.
3. To identify the optimal glass cladding BIPV configurations (optimal combination of transparent PV glazing system, cell coverage ratio, and reflectance of room surfaces, within models with certain opening type, room geometry, and orientation) that maximize both energy generation and daylighting performance in tropical university building designs.

1.5 Research Questions

This study seeks to answer the following research questions:

1. How do different glass cladding BIPV configurations perform against specific energy metrics in tropical climate classroom settings?
2. To what extent do glass cladding BIPV configurations that meet generic energy metrics support daylighting performance in tropical climate?
3. What are the optimal glass cladding BIPV configurations that maximize energy generation and lighting performance in tropical university building designs?

1.6 Significance of Study

This study contributes to the field of sustainable architecture, particularly to green building design, by: providing scientific insights on optimal integration of glass cladding BIPV in university classrooms, enhancing the understanding how different glass cladding BIPV configurations influence both energy and daylighting performance in tropical buildings, offering a practical reference for architects, engineers, and policymakers in developing green university buildings, and contributing to the broader adoption of BIPV technology in university building and any other similar building typology.

Specifically, regarding the practical reference, architectural design needs a comprehensive consideration and approach. In general, there are four main considerations in designing architecture, including the site development, building envelope, building layout, and development of building interior (Heerwagen, 2003). Furthermore, Lechner (2014) described the three tiers of architectural design. They are the basic building design (tier 1), passive systems (tier 2), mechanical system (tier 3). In terms of glass cladding BIPV, there should be a specific method to find the optimum configurations. The considerations and approach used in this study is summarized as a systematic method that is generalizable and can be broader adopted by scientific community to design glass cladding BIPV in any similar building typology.

1.7 Research Methodology

This research employs a quantitative approach using experimental method with simulation and gradient diagram as its tools. This methodology consists of the following steps:

1. Site observation and literature review, respectively to examine the tropical climate classroom setting in university building and to examine existing research on glass

cladding BIPV and any related research regarding energy performance and daylighting strategies.

2. Experimental method, to develop classroom models and design variables as treatments and provide various configurations of glass cladding BIPV.
3. Simulation, to assess the energy and daylighting performance of various glass cladding BIPV configurations, respectively by using HelioScope and Velux software. Mathematical calculation follows the simulation to generate data that is ready to be compared with the energy metrics used.
4. Optimization process, to use gradient diagram to identify the best-performing glass cladding BIPV configurations based on energy and daylighting performance criteria.

1.8 Limitation of Study

Limitations of this study are listed as below:

1. The study focuses on tropical university classrooms, placed within the context of multistorey buildings. This context is chosen based on the theoretical knowledge that the intensity of solar irradiance is decreasing when the area latitude is increasing (McMullan, 2018). Based on the context, the findings may not be directly applicable to other building types.
2. Building envelope that will be studied here is the vertical building envelope (wall). Even though solar irradiance is received by the whole building envelopes (Markus & Morris, 1980) and PV can be integrated both to building's horizontal and vertical elements (Kuhn et al., 2021), this study will focus more on vertical façade due to its significance use as side lighting aperture in tropical climate.
3. This study uses an experimental method with simulation as its tool. The variables used in this study are the PV glazing property (visible transmittance), cell coverage ratio, and reflectance of room surfaces. To better understanding the causality impact of the variables to energy and lighting performance, external

variables such as shadow, and the height of PV placement are set based-on certain constraints. The main consideration to set the constraints is the need of uninterrupted access to solar irradiance by any buildings that try to optimize the use of solar energy (Fuller Moore, 1993).

4. The energy and daylighting performance of glass cladding BIPV were based on a pre-test model which then simulated and calculated through mathematical equation. The real daylight and energy performance can be monitored in future research with full-scale physical samples, with the cooperation of PV industry.
5. PV material that is used in this study is made from crystalline silicon transparent PV that varies in transparency, power peak, and efficiency. The first type has 15% transparency, 38Wp/m², 16% efficiency, and the second type has 38% transparency, 22Wp/m², 9.3% efficiency. The crystalline silicon type is chosen since it has the highest efficiency.
6. Based on above considerations, the findings of this study are subject to the buildings that relevance to the indicated building typologies (which is presented based on site development, building's layout, form, proportion, orientation, and PV material selection).

1.9 Summary

This chapter has outlined the research background, problem statement, objectives, methodology, and significance of the study. The research focuses on optimizing glass cladding BIPV configurations in university classrooms by evaluating energy and daylighting performance. The findings from this study are expected to contribute to the enrichment of knowledge in scope of environmental architecture, particularly in green building design, in which the building contributes to reduce the use of unrenewable energy and becoming the energy source itself (on-site renewable energy), as well as providing good daylighting performance for the users. The findings

are also expected to provide practical solutions in designing glass cladding BIPV, where the method can be quite different to prior architectural design approach.

CHAPTER 2

LITERATURE REVIEW

The literature review for this study is divided into several subsections. It is started with the literature of solar energy (2.1) and lighting (2.2). Then, it is followed with the literature review of PV and BIPV (2.3), studies on daylight and energy performance on glass cladding BIPV (2.4), green building (2.5), and multi-storey university building (2.6). Summary of the literature review is then presented in sub section 2.7.

2.1 Solar Energy

The sun is the main source of energy on earth. The solar energy travels 93 million miles to Earth at the speed of 186,000 miles per second (Handayani & Ariyanti, 2012). This energy can be used directly or indirectly in the forms of water heater system, solar dryers, space heating, daylighting, cooling systems, water desalination, and PV technology that convert solar energy into electrical energy. According to (Szokolay, 2014), this solar energy is fluctuating. The fluctuation is caused by several reasons. First, it is because the orbit of earth's revolution is ellipse. Second, it is because the earth's axis forms a 23.5° angle to its orbit. Third, it is because the activity of the sun's surface fluctuates as well, so the energy that is produced by the sun also varies. The average of solar irradiance that fluctuates is around 1353 to 1373 watt/m² (Almorox et al., 2021; Tansel et al., 2013). This value is known as solar constant. The value of solar constant varies around $\pm 2\%$ because of the sun's fluctuation itself and around $\pm 3.5\%$ because of the distance between the earth and the sun.

The quantity of solar radiation received in any certain area depends on the latitude and longitude of the area, as well as the azimuth and altitude of the sun. Area with different latitude and longitude will receive different intensity of solar radiation. Hence, it is known that the intensity of solar radiation received is getting less as the latitude of the area is getting higher (McMullan, 2018). Azimuth and altitude will

determine the sun position. The sun movement which is shown by its azimuth and altitude will cause different solar radiation received in certain time. The solar radiation received on the building's envelope, both on the roof and on the wall, will constantly change because of the sun's movement. Solar radiation is emitted in the form of electromagnetic wave that consist of 50% of infrared, 45% of visible light, and 5% of UV (Lechner, 2014).

Szokolay (2014) explained that the solar radiation can be measured in the form of irradiation and irradiance. Irradiation is an integration of energy quantity in a certain period (hour, day, month, or year) on a certain area on the earth. The unit measurement is J/m^2 or Wh/m^2 . Irradiance or mostly known as intensity is a measurement of energy flow density of solar radiation. The unit measurement is W/m^2 . Furthermore, Almorox et al (2021) described that measurement of irradiance is important for several scientific fields. Referring to this study, total solar irradiance is defined as the mean of total electromagnetic energy from the Sun, integrated over all wavelengths, incident per unit area per unit time. It is often used as an important variable for solar energy and evaluation of solar effects on the climate system.

The calculation for solar irradiance is different to solar radiation emitted. The total solar irradiance is a summary of direct, diffuse, and reflected solar radiation. Hence, the solar irradiance on a vertical plane is different to the one on horizontal plane. Irradiance measurement can be done by using meteorological data (particularly data of sunshine duration) and empirical model (Almorox et al., 2021), or by using software that incorporate climatic data based on longitude and latitude of an area (Basoglu & Demir, 2022; Zin & Dr. Wunna Swe, 2024).

Aside from the calculation for the irradiance, potential of solar energy can be calculated by measuring the areas of land mass and water bodies that can be utilized, particularly in terms of solar panel farms (Silalahi et al., 2021). Indonesia, which is located in the equator area, is considered as one of many tropical countries that has abundant solar energy potential.

2.1.1 The Solar Energy Potential in Indonesia

As described before, the intensity of solar radiation decreases as the latitude of an area increases (McMullan, 2018). Indonesia particularly Surabaya which is in 7°9' - 7°21' LS, receive relatively high solar radiation intensity. Additionally, the selected location which is placed around the equator gets long sunshine duration throughout the day, although there are periods when the solar radiation is slightly disturbed by the presence of clouds. National General Energy Plan (2019) described that the potential of solar energy is around 208GW from the total 443GW potential renewable energy in Indonesia. The comparison of solar energy potential to other renewable energy potential in Indonesia is tabulated in Table 2.1. In contrast with this potential, it is found that the share of renewable energy in Indonesia is relatively low compared to source of energy, calculated in 9.2% by 2019. This number is far from Indonesia's target of the renewable energy mix, which 23% by 2025 and 31% by 2030.

Table 2.1 Renewable Energy Potential

Types	Potential
Hydropower	94.3 GW
Geothermal	28.5 GW
Bioenergy	80PLT Bio: 32.6 GW
	BBN: 200 Ribu Bph
Solar energy	207.8 GWp
Wind	60.6 GW
Ocean energy	17.9 GW

(National General Energy Plan, 2019)

Silalahi & Gunawan (2022) explained that Indonesia which is located in the equator area has advantages of solar irradiance in terms of high irradiance amount as well as even distribution. In terms of amount, the average of global horizontal irradiance (GHI) in Indonesia is 4.8 kWh/m² per day, higher than average GHI in Germany, Japan, China, and Singapore which are measured respectively in 2.9, 3.6, 4.2, and 4.5 kWh/m² per day. Monthly variation of solar irradiance in Indonesia ranges in 9-10% (Handayani & Ariyanti, 2012). The relatively high amount of solar irradiance

in Indonesia is followed by another advantage of its distribution. Figure 2.1 presents the distribution of solar energy potential in Indonesia. As seen if the Figure, the solar energy potential is evenly distributed in Indonesia. Some of the areas, such as Surabaya, have slightly higher GHI compared to other area.

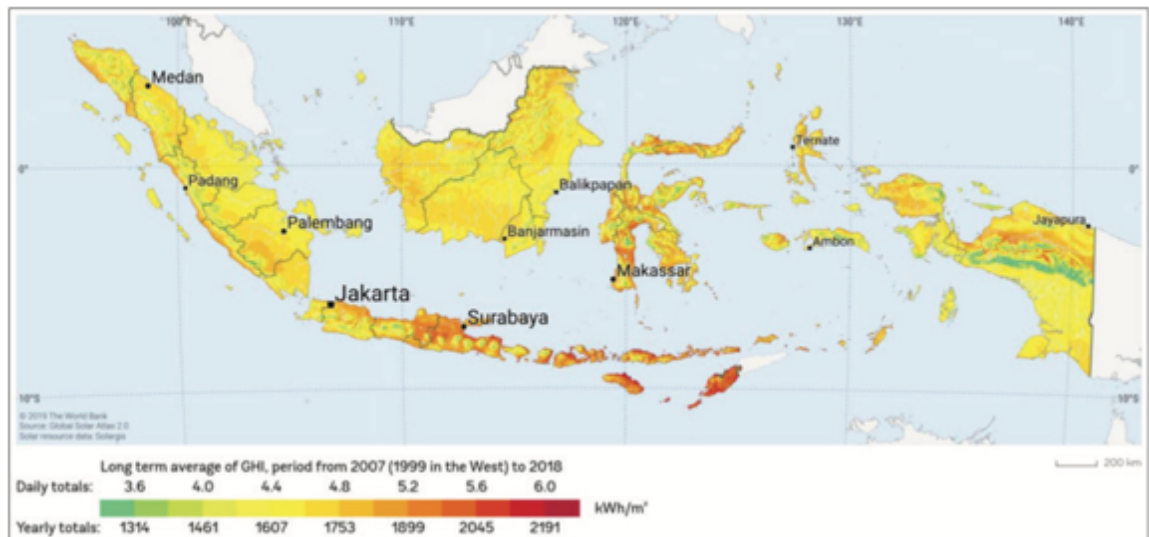


Figure 2.1 Solar Energy Potential in Indonesia (Silalahi & Gunawan, 2022)

2.1.2 The Challenges and Future Development of Solar Energy Use

Even though there is opportunity to use abundant solar energy, several challenges for its utilization exists. These challenges cover some issues such as high capital cost, intermittency of solar energy, land-use footprint of solar energy, hazardous solar panel waste (Silalahi et al., 2021, 2022; Silalahi & Gunawan, 2022).

Solar energy is widely utilized using PV, which is considered as the most potential micro-generation technology. China, United States, and India are found as countries that employ solar energy mostly by using PV (Joshi et al., 2025). The high capital cost of solar energy use is often associated with this technology, which considered as the high capital expenditure. However, the trend shows that the price of PV modules has reduced over the past decade (K. Lee et al., 2020; Silalahi & Gunawan, 2022). The high capital cost of utilizing solar energy is often compromised by less payback period and higher return of investment (ROI). Hence, there's also a finding regarding Renewable Energy Return of Investment (RExROI) which indicates

the degree of renewability of such technologies (Torrubia et al., 2024). The metric quantifies the renewable energy obtained from each unit of renewable energy invested in energy systems and might use as a compromise of high capital cost issue regarding the use of solar energy.

Another problem of using solar energy is the intermittency problem, which refers to its supply and demand. The constrain of using solar energy is its utilization that based on baseload power. Solutions on energy storage is needed to overcome this issue. Silalahi & Gunawan (2022) described two solutions which classified into short-term solution and long-term solution. In short-term solution, energy storage for solar energy in terms of PV technology can support supply-demand balancing by using batteries, supercapacitors, and compressed air. Hence, the study described pumped hydro as the alternative for long-term solution. However, despite of the needs for energy storage, Indonesia that has low variation of solar insolation does not require seasonal solar energy storage. The storage needed is for short-term only, mainly for day-night system balancing (McCormick & Suehrcke, 2018; Silalahi et al., 2021).

Due to the massive use of solar energy, it is predicted that solar energy utilization will require significant land areas. Several potential applications are observed, including the use of Building Integrated Photovoltaic (BIPV) System (Calise et al., 2020a; Kumar et al., 2020; Rounis et al., 2021), abandoned mine sites, agricultural lands, and water bodies (Van de Ven et al., 2021). Particularly for BIPV, there are advantages in terms of its ability to generate on-site renewable energy, as well as its installation that replaces the use of buildings' conventional material. In more detail, the options for PV integration were divided into the ones integrated into the external building envelope and those integrated into the building envelope (Kuhn et al., 2021). Furthermore, it can be installed as wall-cladding (by using opaque PV) or glass-cladding (by using transparent PV or PV glass).

PV that is used to utilize solar energy has a lifespan within 25-30 years. Concerns on recycling process at the end-of-life of PV modules has significantly explored in recent studies. Hence, certain approaches are needed to treat recycling silicon-based solar panels. The process usually consists of mechanical recycling that involves mechanical disassembly, thermal recycling that employs high temperatures to break down the panels and recover materials, and chemical recycling method to dissolve and recover specific materials using certain kind of solvent (Ramírez-Cantero et al., 2025). Further consideration is needed particularly in developing regulations and standard regarding the recycling process and life cycle assessment of the panels (Latunussa et al., 2016; Liang et al., 2023; Marszal et al., 2012).

Potential and challenge of solar energy utilization through PV are important things that need to be considered in future development. Hence, aside from the significant use of solar energy in generating electricity through PV, solar energy also plays a crucial role in daylighting performance of buildings. Solar radiation of which 45% is visible light, reaching the Earth as direct, global, and diffuse radiation. A study that was conducted to measure direct normal irradiance, diffuse horizontal irradiance, global horizontal irradiance, and downward longwave irradiance found that direct beam and diffuse radiation known as the most influencing radiation for indoor visual conditions (Overen et al., 2021). A review on daylighting and any factors related to its performance will be further discussed in the next subsection.

2.2 Lighting

2.2.1. Daylighting

Daylight, or natural light, is light that is sourced from the sun. Furthermore, daylight is the sunlight (direct from the sun), skylight (sunlight that is scattered by the sky, both in clear, cloudy, or partly cloudy condition), as well as sunlight and skylight that are reflected by the surroundings (Lechner & Andrasik, 2021). Various source of natural light can be seen in Figure 2.2.

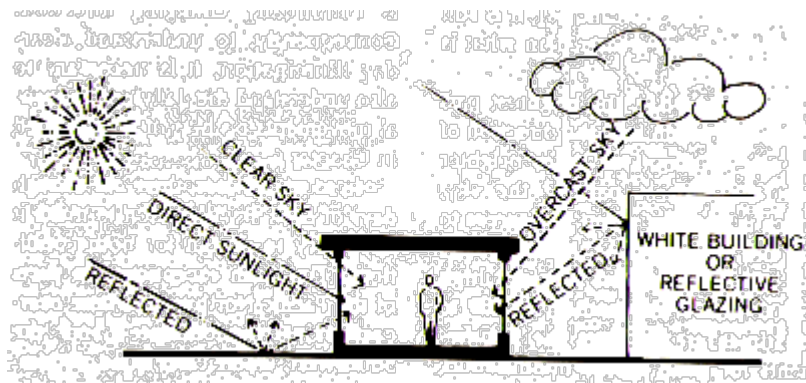


Figure 2.2 Various Source of Natural Light for Building (Lechner, 2014)

The sunlight is direct and has high level of brightness and intensity. Sunlight is usually avoided since it causes glare and causes over intensity of brightness and heat. Meanwhile, skylight is diffuse and has lower level of brightness and intensity. Skylight that comes in clear sky condition has 100-200 times higher illuminance level, compared to the one needed in indoor room. The outdoor illuminance level ranges about 60,000-100,000 lux. Figure 2.3 shows the comparison between indoor illuminance level (floor area) and outdoor illuminance level (window area) at clear sky condition.

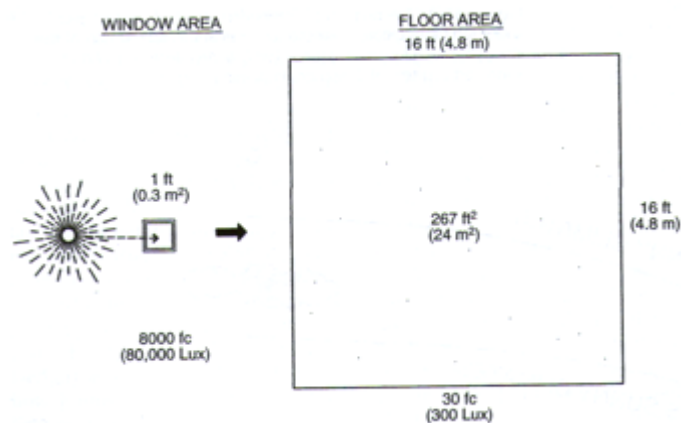


Figure 2.3 Comparison of Illuminance Level at Clear Sky Condition (Lechner, 2014)

Level of illuminance at overcast sky varies based on the cloud density and the sun's altitude. The level of illuminance at overcast sky is relatively lower than the one at the clear sky. It ranges around 5,000 – 20,000 lux. However, the amount is still 10

times higher compared to the one needed in indoor room. The comparison between indoor illuminance level (floor area) and outdoor illuminance level (window area) at the overcast sky condition is shown in Figure 2.4. At tropical climate, the sky condition is mostly overcast sky, which means that at least 80% of sky dome is covered by the cloud.

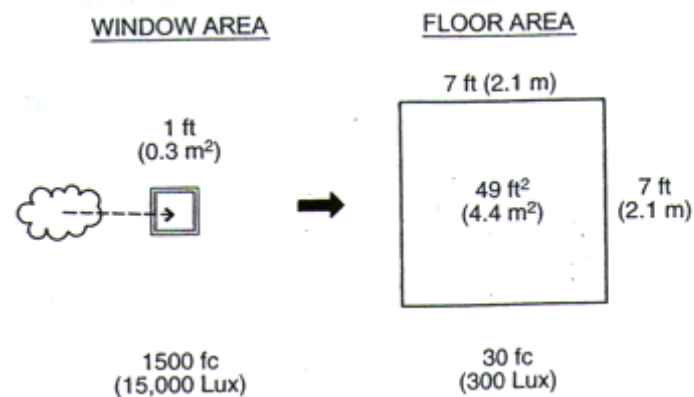


Figure 2.4 Comparison of Illuminance Level at Overcast Sky Condition (Lechner, 2014)

Aside from sunlight and skylight, light that is reflected from ground and other surrounding is another important daylight source. A white painted building can reflect light up to 80%, while grass ground cover can reflect approximately 10% of light. Referring to the explanation above, natural lighting or daylighting is a method of utilizing sunlight, skylight, and reflected sunlight and skylight during the day for building illumination to meet the needs of user activities (Gregg D. Ander, 2003). It changes due to the climate, season, and weather condition. The strategy of daylighting should consider that daylight has a dynamic characteristic, since it varies in light intensity. The strategy of daylighting should also consider heat and glare. Quantitatively, daylighting aims to provide adequate illuminance level to promote good visual performance. While qualitatively, daylighting aims to prevent glare, to provide uniform distribution and to bring the light to penetrate deeper into the building.

These quantitative and qualitative aims can be achieved by considering several daylighting design options as discussed below.

2.2.1 (a) Daylighting Design Options

Daylight can be introduced into a room through top lighting, side lighting, and combination of both (Lechner, 2014). Top lighting could be the most efficient one since it can distribute light evenly throughout the room. However, for buildings in the tropics, the use of top lighting should also consider the effect of heat because of the high solar radiation intensity. Side lighting seems to be the most common strategy to introduce daylight. The use of side lighting gives additional advantages such as providing access to outside view and natural ventilation. Hence, the placement in multiple orientations will provide a more evenly daylight distribution that enhance the daylighting performance (Lotfabadi & Hançer, 2023).

2.2.1 (a)(i) Top Lighting

Top lighting is a daylighting design option that promotes natural lighting through apertures located above ceiling line and usually replaces certain parts of building's roof (Gregg D. Ander, 2003). It gives advantage in terms of providing uniform distribution of daylight, but the application is usually limited to a large single-story building or the top floor of multistory buildings. Top lighting can be found in many options such as skylight (Lou et al., 2021; Marzouk et al., 2022; D. Wijaya et al., 2024), roof monitors and saw-tooth (Emmanuel Gift & Chinwennwo Philips, 2024), as well as light pipes (Sreelakshmi & Ramamurthy, 2024; Y. Wu, Jin, et al., 2024).

Skylight, an aperture that consist of horizontal glazing located in-roof, plays a significant role in daylighting as well as in building performance, affecting energy efficiency, and thermal comfort. To achieve the aims, a skylight should be properly designed, considering certain factors such as the geometry and the glazing system. In more detail, study on multi-objective optimization of skylight has found various

variables of skylight design, including skylight-to-floor ratio, clerestory geometry, and building materials (Fang et al., 2024).

Aside of skylight, top lighting can also be found in forms of roof monitor and saw-tooth. Gift and Philips (2024) described that a roof monitor is a construction of raised flat roof bay with vertical glazing enclosing both sides. While saw-tooth, involves a pattern of vertical or sloped glazing sections that is separated by sloped roofing materials. Similarly with skylight, saw-tooth could distribute natural light over relatively large floor plan. However, saw-tooth gives advantage in terms of minimizing excessive direct sunlight. Meanwhile, light pipes as another option of top-lighting, is now being recognized as a useful tool of daylighting, energy-saving, and comfort. Light pipes, that consist of light collector, hollow tube, and diffuser, could give better insulation performance and flexibility when it is compared to traditional skylights (Y. Wu, Jin, et al., 2024).

2.2.1 (a)(ii) Side Lighting

Greg. D Ander (2003) described that side lighting is a daylighting concept that uses building's wall as the aperture location. Providing natural light through side lighting will also give opportunity to users for access to outside view and natural ventilation. Side lighting could give adequate level of illuminance to spaces within building's perimeter. However, the level of illuminance will decrease as the distance from the perimeter increase. In more detail, the level of illuminance that is provided by side lighting within spaces is influenced by the depth of the field, the height of the building floor, the position of the building, and the condition of the sky (B. Wijaya et al., 2024). Greg D. Ander (2003) explained that side lighting varies in single sided (where natural lighting penetrates through an opening from a single wall) and multi sided openings (where natural lighting penetrates through openings from minimum two adjacent walls or from two walls located opposite one to another).

Examples of side lighting are clerestories and windows. In particular, clerestories are defined as an opening where the height of lower threshold is above

the human eye level, but the upper threshold is below the ceiling height. When it was compared to window within the same size, clerestories were found to be more effective (Treado et al., 1984). Hence, the study also found that south-facing clerestories and windows are more effective than north-facing ones.

2.2.1 (b) Daylighting Control Strategies

Daylighting gives benefits in terms of providing natural lighting to save electrical energy consumption in buildings. However, inappropriate daylighting design could lead to higher heat load, cause glare, or promote visual discomfort to the occupants. Its performance is influenced by different factors such as sky conditions, building geometry, orientation, and spatial layout (B. Wijaya et al., 2024). Considering the advantages, disadvantages, and the influencing factors, control strategies are then needed to provide appropriate lighting level. In general, architecture design should put concerns on the site development, building's layout, building's envelope, and development of building's interior (Heerwagen, 2003). Hence, in more detail, Greg D. Ander (2003) described that daylighting control strategies consist of control through external element, internal element, as well as roof and in-wall system.

2.2.1 (b)(i) Site Development

Heerwagen (2003) described that related to site development, access to sky dome is very important for daylighting. To provide optimum daylight condition, site development should provide un-interrupted visual line between room inside the building and the sky dome. To make the sunlight penetrates the building, there should be no obstruction on the visual line between the sun, the opening, and the surface that want to be illuminated by the sun. The site contour, vegetation, and surrounding buildings can be considered as an obstruction since they create shade and shadow on the building's opening and building's interior, as well as reduce diffuse daylight that is important for skylight and any other openings in overcast sky.

A previous study in residential developments found that obstructions by surrounding buildings can substantially reduce the available amount of daylight, that lead to poorly daylighted spaces, less healthy building, and higher electricity consumption (Šprah & Košir, 2020). This study used floor area ratio (FAR) and site coverage as the indicators of density on the site planning. Indoor daylight value according to EN 17037 is used as the parameter of permissible FAR and site coverage. The correlation on FAR, site coverage, and adequate daylight area within a room is presented in Figure 2.5. This study found that site coverage at the same FAR value has more significance impact on the average vertical daylight factor, compared to building typology and building placement. Within the specific context of the study, a FAR value of 0.93 is required to meet minimum daylight requirements. Buildings in higher densities area should consider shallower room and higher window-to-floor ratios (WFR).

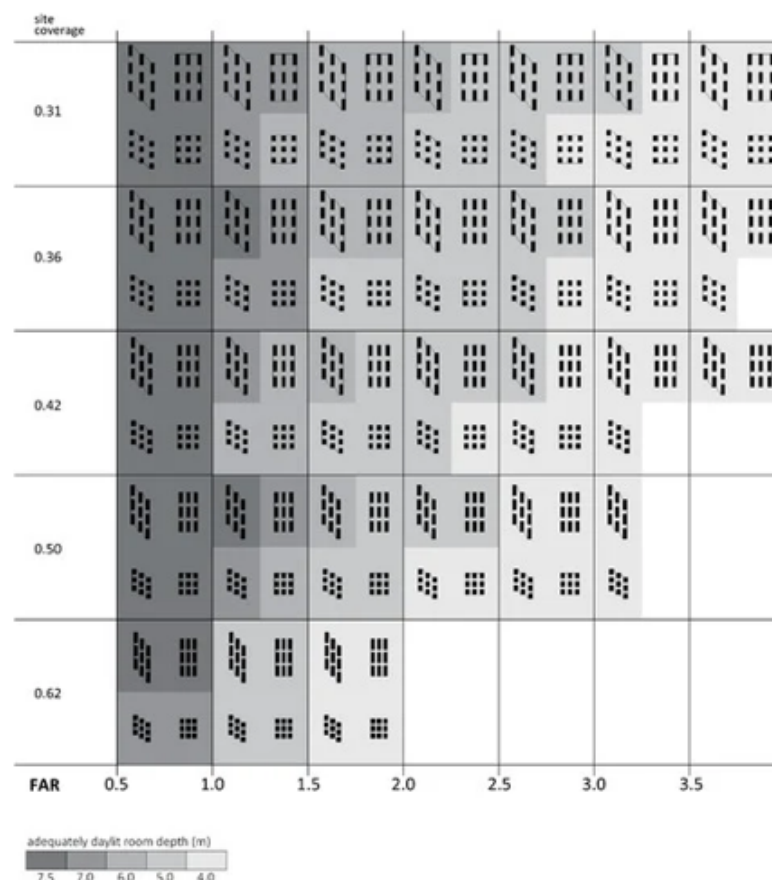


Figure 2.5 Correlation of FAR, Site Coverage, and Adequately Daylit Room Depth (Šprah & Košir, 2020)