Estimating Solar Energy Production in Urban Areas for Electric Vehicles

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The American University in Cairo
School of Sciences and Engineering
Environmental Engineering Program

Estimating solar energy production in urban areas for electric vehicles

BY

Shaimaa Ahmed

A thesis submitted in the partial fulfillment of the requirements for the degree of

Master of Science in Environmental Engineering

Under the Supervision of

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Fall 2022
Declaration of Authorship

I, Shaimaa Ahmed, declare that this thesis titled, “[Thesis title]” and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.

- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.

- Where I have consulted the published work of others, this is always clearly attributed.

- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.

- I have acknowledged all main sources of help.

- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed:

Shaimaa Ahmed

Date:

16 December
Abstract

Cities have a high potential for solar energy from PVs installed on buildings' rooftops. There is an increased demand for solar energy in cities to reduce the negative effect of climate change. The thesis investigates solar energy potential in urban areas. It tries to determine how to detect and identify available rooftop areas, how to calculate suitable ones after excluding the effects of the shade, and the estimated energy generated from PVs. Geographic Information Sciences (GIS) and Remote Sensing (RS) are used in solar city planning. The goal of this research is to assess available and suitable rooftops areas using different GIS and RS techniques for installing PVs and estimating solar energy production for a sample of six compounds in New Cairo, and explore how to map urban areas on the city scale.

In this research, the study area is the new Cairo city which has a high potential for harvesting solar energy, buildings in each compound have the same height, which does not cast shade on other buildings affecting PV efficiency. When applying GIS and RS techniques in New Cairo city, it is found that environmental factors - such as bare soil - affect the accuracy of the result, which reached 67% on the city scale. Researching more minor scales, such as compounds, required Very High Resolution (VHR) satellite images with a spatial resolution of up to 0.5 meter. The RS techniques applied in this research included supervised classification, and feature extraction, on Pleiades-1b VHR. On the compound scale, the accuracy assessment for the samples ranged between 74.6% and 96.875%.

Estimating the PV energy production requires solar data; which was collected using a weather station and a pyrometer at the American University in Cairo, which is typical of the neighboring compounds in the new Cairo region. It took three years to collect the solar incidence data. The Hay- Devis, Klucher, and Reindl (HDKR) model is then employed to extrapolate the solar radiation measured on horizontal surfaces $\beta =0^\circ$, to that on tilted surfaces with inclination angles $\beta =10^\circ, 20^\circ, 30^\circ$ and $45^\circ$. The calculated (with help of GIS and Solar radiation models) net rooftop area available for capturing solar radiation was determined for sample New Cairo compounds . The available rooftop areas were subject to the restriction that all the PVs would be coplanar, none of the PVs would protrude outside the rooftop boundaries, and no shading of PVs would occur at any time of the year; moreover typical other rooftop occupied areas, and actual dimensions of typical roof top PVs were taken into consideration. From those calculations, both the realistic total annual Electrical energy produced by the PVs and their daily monthly energy produced are deduced. The former is relevant if the PVs are tied to a grid, whereas the other is more relevant if it is not; optimization is different for both. Results were extended to estimate the total number of cars that may be driven off PV converted solar radiation per home, for different scenarios.
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# Contents

Declaration of Authorship .........................................................................................i

Abstract ..................................................................................................................... ii

Acknowledgments ..................................................................................................... iii

List of figures ............................................................................................................... VIII

List of tables ............................................................................................................... X

List of Maps ................................................................................................................ XIII

List of Abbreviations ................................................................................................ XVI

List of Symbols ............................................................................................................ XIX

Chapter 1 Introduction ................................................................................................. 1

1.1 General Introduction ........................................................................................... 1

1.2 Research Objectives: ......................................................................................... 3

1.3 Thesis Layout ...................................................................................................... 4

Chapter 2 Literature Review ....................................................................................... 5

2.1 Methods for Assessing Photovoltaics Potential on Roofs ..................................... 6

2.2 Studies Conducted on a Microscale ..................................................................... 7

2.3 Studies Conducted on the Mesoscale .................................................................. 14

2.4 Studies Conducted on the Meso Scale (Part of the City) ..................................... 16

2.5 Studies Conducted on a Macroscale (City) ........................................................ 18

2.6 Studies Conducted on Multiple Scales ................................................................ 27

2.7 Studies Conducted on Large-Scale (Territories) ................................................ 30

2.8 Studies conducted on a global scale .................................................................... 33

Chapter 3 Geographic Information Sciences, Remote Sensing, and Processed Maps .......... 34

3.1 Spatial Database .................................................................................................. 36

3.1.1 Online Spatial Databases ............................................................................ 36

3.1.2 Data from Remote Sensing Data .................................................................. 38
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2 GIS Approaches for PV Energy Estimation</td>
<td>38</td>
</tr>
<tr>
<td>3.2.1 GIS and Machine Learning</td>
<td>39</td>
</tr>
<tr>
<td>3.2.2 GIS and Three-Dimensional Models</td>
<td>39</td>
</tr>
<tr>
<td>3.2.3 GIS and Sampling Techniques</td>
<td>41</td>
</tr>
<tr>
<td>3.2.4 Geostatistics</td>
<td>42</td>
</tr>
<tr>
<td>3.3 LiDAR Data and Urban Mapping</td>
<td>45</td>
</tr>
<tr>
<td>3.4 Remote Sensing</td>
<td>46</td>
</tr>
<tr>
<td>3.4.1 Nadir Images</td>
<td>47</td>
</tr>
<tr>
<td>3.4.2 Oblique Images</td>
<td>47</td>
</tr>
<tr>
<td>3.4.3 Sensors</td>
<td>47</td>
</tr>
<tr>
<td>3.5 Sentinel-1</td>
<td>48</td>
</tr>
<tr>
<td>3.6 Application of GIS and RS to New Cairo City</td>
<td>49</td>
</tr>
<tr>
<td>3.6.1 Sentinel-1 or SAR Data Processing</td>
<td>49</td>
</tr>
<tr>
<td>3.6.2 Workflow of Sentinel-1 and Sentinel-2 Workflow</td>
<td>49</td>
</tr>
<tr>
<td>3.7 Optical Remote Sensing</td>
<td>57</td>
</tr>
<tr>
<td>3.7.1 Sentinel 2 images</td>
<td>58</td>
</tr>
<tr>
<td>3.7.2 Atmospheric Correction</td>
<td>60</td>
</tr>
<tr>
<td>3.7.3 Terrain Correction</td>
<td>60</td>
</tr>
<tr>
<td>3.7.4 Re-projection</td>
<td>60</td>
</tr>
<tr>
<td>3.7.5 Indices</td>
<td>60</td>
</tr>
<tr>
<td>3.7.6 Built-up Indices for Sentinel-2</td>
<td>61</td>
</tr>
<tr>
<td>3.7.7 Classification</td>
<td>63</td>
</tr>
<tr>
<td>3.7.8 Pléiades-1B</td>
<td>67</td>
</tr>
<tr>
<td>3.7.9 Segmentation</td>
<td>67</td>
</tr>
<tr>
<td>3.7.10 Image Extraction</td>
<td>67</td>
</tr>
<tr>
<td>3.7.11 Root Mean Square Error (RMSE)</td>
<td>68</td>
</tr>
<tr>
<td>3.7.12 Accuracy Statistics</td>
<td>68</td>
</tr>
<tr>
<td>3.8 Workflow for Feature Extraction Using OBIA</td>
<td>68</td>
</tr>
<tr>
<td>3.8.1 Compound-1</td>
<td>68</td>
</tr>
</tbody>
</table>
3.8.2 Compound-2 ........................................................................................................... 69

3.9 Supervised Classification for Pleadeas-1b ............................................................... 71

3.9.1 Compound-3 ......................................................................................................... 71

3.9.2 Compound-4 ......................................................................................................... 73

3.9.3 Compound-5 ......................................................................................................... 74

3.9.4 Compound-6 ......................................................................................................... 76

3.9.5 Available Areas ..................................................................................................... 77

Chapter 4 Solar Radiation Conversion ........................................................................ 78

4.1 Solar Radiation Measurements and Models ............................................................ 78

4.2 Hourly Global Solar Radiation on an Inclined Surface ........................................... 79

4.2.1 Calculating the Incident Solar Radiation on the PV Panel ................................. 79

4.2.2 Solar Radiation Angles ......................................................................................... 80

4.3 Sample of Calculations ............................................................................................ 82

4.4 Photovoltaic (PV) output ......................................................................................... 82

4.4.1 The Incident Solar Radiation on the PV Panel ..................................................... 83

4.4.2 Estimated PV Output for Differently Inclined Angle $\beta$ ....................................... 86

Chapter 5 Methods and Results .................................................................................. 96

5.1 Study Area .................................................................................................................. 96

5.2 Methodology ............................................................................................................. 97

5.2.1 Shadow Analysis Estimation .............................................................................. 97

5.2.2 Criteria for Arranging PVs .................................................................................. 98

5.3 Results ....................................................................................................................... 115

5.3.1 Estimated Upper & Lower Areas Available for PV Installation ....................... 115

5.3.2 Estimated Upper & Lower Electric Energy Produced ......................................... 115

5.3.3 Estimated upper & lower available sustainable mileage .................................... 120

Chapter 6 Conclusion and Recommendation Work ..................................................... 128

6.1 Conclusion ................................................................................................................. 128

6.2 Recommendation Work ............................................................................................ 129
References ........................................................................................................................................ 131
Appendix 1 Sentinel 2 after processing ........................................................................................ 152
Appendix 2 Input layers for classifications .................................................................................. 156
Appendix 3 Overall accuracy for different parameters in the RT model ....................................... 157
Appendix 4 comparison between RT and SVM overall accuracy for different compounds .......... 162
Appendix 5: Shadows analysis for building type 1 through December 2022 ......................... 164
Appendix 6: Shadows analysis for building type 1 through June 2022 ................................... 166
Appendix 7: Shadows analysis for building type 1 through March 2022 ............................. 168
Appendix 8: Shadows analysis for building type 2 through December 2022 ...................... 170
Appendix 9: Shadows analysis for building type 2 through March 2022 ............................. 172
Appendix 10: Shadows analysis for building type 2 through June and March 2022 ............ 174
Appendix 11 Pyrometer Specifications ....................................................................................... 178
Appendix 12 Weather Station Data Logger ................................................................................ 180
Appendix 13 Sample of Calculations ......................................................................................... 181
Appendix 14 PV Characteristics ................................................................................................. 185
List of figures

Figure 1. Thesis outline ........................................................................................................... 4
Figure 2 Hierarchical methodology for estimating Solar potential on roofs Izquierdo [54], Walch et al [55] ............................................................................................................. 6
Figure 3. Four existing housing blocks were selected for the model [63] ................................. 8
Figure 4. Solar potential assessment for different blocks [63] ................................................ 8
Figure 5. The model used by Alhamwi et al. [93] ................................................................ 19
Figure 6. This figure demonstrates the correlation between PVA, BFA, and Plot Area ........ 25
Figure 7. The framework of the renewable energy system, adapted from [138], [139] .......... 35
Figure 8. DEM, DTM, DSM, DHM an nDSM [154], [155], [156] ........................................ 40
Figure 9. Arial photos and orthophotos [155] ...................................................................... 41
Figure 10. The sensor collects two images of the exact location by adjusting its camera [157] ................................................................................................................................. 41
Figure 11. Specific spectral wavelengths of the electromagnetic spectrum and their properties and applications .................................................................................................................. 46
Figure 12. Observation geometry of a sensor triple mode [162] ........................................... 47
Figure 13. Forward, nadir, backward satellite images were taken by 3 line scanner [163] ...... 47
Figure 14. Nadir and oblique images [164] ........................................................................... 47
Figure 15. Passive and active sensors. [33] .......................................................................... 48
Figure 16. Work-Flow for Sentinel-1 and Sentinel-2 adopted from Clerici [35], and Valdiviezo-N [114] .......................................................................................................................... 50
Figure 17. Passive remote sensing [198] .............................................................................. 58
Figure 18. Sentinel-2 images contain 13 spectral bands ...................................................... 59
Figure 19 An image of the CMP10 pyrometer [240] ............................................................ 78
Figure 20 An image for the CR1000 data logger [241] ......................................................... 78
Figure 21 Different solar angles for an inclined surface [243] ............................................. 81
Figure 22 PVs arrangement on rooftops (a) $\beta = 30^\circ$ [246], and (b) $\beta = 0^\circ$ [247] ..... 84
Figure 23 Solar path diagram adopted from [248] ................................................................. 85
Figure 24. Single PV output on March day, $\beta=0$, $E=0.93$ kWh/m$^2$/d ................................ 87
Figure 25. Single PV output on June day, $\beta=0$, $E=1.33$ kWh/m$^2$/d .............................. 87
Figure 26. Single PV output on December day, $\beta=0$, $E=0.56\text{ kWh/m}^2\text{/d}$ ............................................. 88
Figure 27 Single PV output on March day, $\beta=10$, $E=1.00\text{ kWh/m}^2\text{/d}$ ......................................................... 89
Figure 28 Single PV output on June day, $\beta=10$, $E=1.30\text{ kWh/m}^2\text{/d}$ ............................................................. 89
Figure 29 Single PV output on December day, $\beta=10$, $E=0.66\text{ kWh/m}^2\text{/d}$ ......................................................... 89
Figure 30 Single PV output on March day, $\beta=20$, $E=1.04\text{ kWh/m}^2\text{/d}$ ............................................................. 90
Figure 31 Single PV output on June day, $\beta=20$, $E=1.25\text{ kWh/m}^2\text{/d}$ ............................................................. 90
Figure 32 Single PV output on December day, $\beta=20$, $E=0.74\text{ kWh/m}^2\text{/d}$ ......................................................... 91
Figure 33. Single PV output on March day, $\beta=30$, $E=1.05\text{ kWh/m}^2\text{/d}$ ............................................................. 92
Figure 34. Single PV output on June day, $\beta=30$, $E=1.16\text{ kWh/m}^2\text{/d}$ ............................................................. 92
Figure 35. Single PV output on December day, $\beta=30$, $E=0.80\text{ kWh/m}^2\text{/d}$ ............................................................. 93
Figure 36 Single PV output on March day, $\beta=45$, $E=1.04\text{ kWh/m}^2\text{/d}$ ............................................................. 94
Figure 37 Single PV output on June day, $\beta=45$, $E=0.99\text{ kWh/m}^2\text{/d}$ ............................................................. 94
Figure 38. Single PV output on December day, $\beta=45$, $E=0.86\text{ kWh/m}^2\text{/d}$ ............................................................. 95
Figure 39. Shadow analysis workflow ....................................................................................................................... 98
Figure 40. Shades of building type 1 at 5 pm, March 21, 2022.................................................................................... 99
Figure 41 Shades of building type 1 at 5 pm, June 21, 2022.................................................................................... 99
Figure 42 Shades of building type 1 at 5 pm, Dec 21, 2022 .................................................................................. 100
Figure 43 Shades of building type 2 at 5 pm, Dec 21, 2022 .................................................................................. 100
Figure 44. Shades of building type 2 at 5 pm, June 21, 2022................................................................................ 101
Figure 45 Shades of building type 2 at 5 pm, March 21, 2022............................................................................. 101
Figure 46 Upper limits of compound ..................................................................................................................... 104
Figure 48. Available daily electric energy produced by the PVs in kWh/m2/d in July .............................................. 116
Figure 49. Available daily electric energy produced by the PV in kWh/m2/d in December ........................................... 116
Figure 50. Daily average annual distance that can be traveled at different PV inclinations for the 6 compounds (km/day/house).................................................................................................................. 126
List of tables

Table 1. Comparison between different GIS methods for roof-PVs Gasser et al.[5] ...............43

Table 2. Inapplicability (N) and Applicability (Y) of GIS methods for assessing significant structures of roof-PV potential. Adopted from Gasser Gasser et al. [5].................................44

Table 3. Typical application modes for each application [172].................................................49

Table 4. Comparison of SENTINEL-2 with important heritage missions [201].........................59

Table 5. Sentinel-2 bands, their central wavelength, and resolution [202].................................60

Table 6. Accuracy report for Random forest classification, which produced 67.95 % overall accuracy .........................................................................................................................................66

Table 7. Pleiades-1B Satellite Sensor Characteristics [225]........................................................67

Table 8. Accuracy statistics for compound-3...............................................................................72

Table 9. SVM accuracy assessment for compound 4.................................................................74

Table 10. Accuracy assessment for compound 5 using SVM..................................................75

Table 11. Table for accuracy assessment for compound 6.........................................................77

Table 12 Table illustrates available areas for PVs installation for each compound....................77

Table 13 Sample measurements extracted from the weather station .....................................82

Table 14. PVs classification based on their basic physical configuration [5], [249], [250]........85

Table 15. Height of the PV array within maximum height restrictions .....................................103

Table 16 The maximum number of PVs for compound 6 at different PV inclination angles (β) ........................................................................................................................................103

Table 17. The lower limits for roofs of compound 6 at different PV inclination angles (β) ..103

Table 18. The utilizability ratio for compound 6 ......................................................................103

Table 19. The upper & lower utilizable areas for different PV inclination in m²......................103

Table 20. Available daily electric energy produced by the PV in kWh/m2/d .........................115

Table 21. The available daily electric energy produced by the PV for compound-1, during the month of July (kWh/d/house) ..................................................................................117

Table 22. The available daily electric energy produced by the PV for compound-1, during the month of December (kWh/d/house) ..............................................................................118

Table 23. The available daily electric energy produced by the PV for compound-2, during the month of July (kWh/d/house) ..................................................................................118
Table 24. The available daily electric energy produced by the PV for compound-2, during the month of December (kWh/d/house) ........................................................................................................ 118

Table 25. The available daily electric energy produced by the PV for compound-3, during the month of July (kWh/d/house) ........................................................................................................ 118

Table 26. The available daily electric energy produced by the PV for compound-3, during the month of December (kWh/d/house) ........................................................................................................ 119

Table 27. The available daily electric energy produced by the PV for compound-4, during the month of July (kWh/d/house) ........................................................................................................ 119

Table 28. The available daily electric energy produced by the PV for compound-4, during the month of December (kWh/d/house) ........................................................................................................ 119

Table 29. The available daily electric energy produced by the PV for compound-5, during the month of July (kWh/d/house) ........................................................................................................ 119

Table 30. The available daily electric energy produced by the PV for compound-5, during the month of December (kWh/d/house) ........................................................................................................ 120

Table 31. The available daily electric energy produced by the PV for compound-6, during the month of July (kWh/d/house) ........................................................................................................ 120

Table 32. The available daily electric energy produced by the PV for compound-6, during the month of December (kWh/d/house) ........................................................................................................ 120

Table 33. Daily distance that can be traveled for compound-1 per house, during the month of July l (km/day/house) ........................................................................................................ 121

Table 34. Daily distance that can be traveled for compound-1 per house, during the month of December l (km/day/house) ........................................................................................................ 121

Table 35. Daily average annual distance that can be traveled for compound-1, per house l (km/day/house) ........................................................................................................ 121

Table 36. Daily distance that can be traveled for compound-2, per house during the month of July l (km/day/house) ........................................................................................................ 122

Table 37. Daily distance that can be traveled for compound-2, per house during the month of December l (km/day/house) ........................................................................................................ 122

Table 38. Daily average annual distance that can be traveled for compound-2, per house l (km/day/house) ........................................................................................................ 122

Table 39. Daily distance that can be traveled for compound-3, per house during the month of July l (km/day/house) ........................................................................................................ 122

Table 40. Daily distance that can be traveled for compound-3, per house during the month of December l (km/day/house) ........................................................................................................ 123
Table 41. Daily average annual distance that can be traveled for compound-3, per house $l$ (km/day/house)..................................................................................................................................................123

Table 42. Daily distance that can be traveled for compound-4, per house during the month of July $l$ (km/day/house)..................................................................................................................................................123

Table 43. Daily distance that can be traveled for compound-4, per house during the month of December $l$ (km/day/house)..................................................................................................................................................123

Table 44. Daily average annual distance that can be traveled for compound-4, per house $l$ (km/day/house)..................................................................................................................................................124

Table 45. Daily distance that can be traveled for compound-5, per house during the month of July $l$ (km/day/house)..................................................................................................................................................124

Table 46. Daily distance that can be traveled for compound-5, per house during the month of December $l$ (km/day/house)..................................................................................................................................................124

Table 47. Daily average annual distance that can be traveled for compound-5, per house $l$ (km/day/house)..................................................................................................................................................124

Table 48. Daily distance that can be traveled for compound-6, per house during the month of July $l$ (km/day/house)..................................................................................................................................................125

Table 49. Daily distance that can be traveled for compound-6, per house during the month of December $l$ (km/day/house)..................................................................................................................................................125

Table 50. Daily average annual distance that can be traveled for compound-6, per house $l$ (km/day/house)..................................................................................................................................................125
List of Maps

Map 1. yearly solar irradiation for the campus of TU in Delft [65] ................................................................. 9
Map 2. Types of estimated energy savings for intervention in the Lombardy area (Scenario 1) [74] ................................................................. 11
Map 3. Sunlight hours on 21 December [84] .................................................................................................... 14
Map 4. Building suitability to PVs integrated installation [5]. ................................................................. 16
Map 5 Solar radiation of Concepción [96] ........................................................................................................ 20
Map 6. Overall radiation levels and zones .................................................................................................. 20
Map 7. A radiation map created by SimStadt to define optimal PV locations on a town scale [97] ................................................................................................................................. 21
Map 8. A map of all areas and available areas for rooftops, largest capacity for installation, and yearly energy generation likely for all governmental regions of Ibadan city .......... 23
Map 9. Yearly mean solar radiation on roofs for these scales (a) a building, (b) a neighborhood, and (c) a city. [110] .................................................................................................................. 26
Map 10. roof shapes examples [110] ............................................................................................................... 27
Map 11. Yearly daily irradiation for rooftops simulation at 90 meters resolution. [58] ................. 28
Map 12. Yearly daily irradiation for rooftops simulation at 55 cm resolution. [58] ................. 28
Map 13. Practical aspects of the selected site. [58] ......................................................................................... 28
Map 14. The best suitable areas of roofs for PV installation. [58] ................................................................. 28
Map 15. land cover Classification result [36] ................................................................................................. 29
Map 17. Solar resource potential [150] ......................................................................................................... 38
Map 18. City model[154] ......................................................................................................................... 40
Map 19. (A) Different perspectives for LiDAR data which represents a city [159] ............... 45
Map 20. (B) Different perspectives for LiDAR data which represents a city [159] ............... 45
Map 21. Example of LAS database that represents an airport [160] ......................................................... 46
Map 22. Sentinel-1 Satellite Image of the study location after applying subletting tool. ....... 51
Map 23. Sentinel-1 Satellite Image of the study area after applying orbit file. ................. 51
Map 24. Sentinel-1 Satellite image calibration for New Cairo City and the area around it. .... 52
Map 25. Sentinel-1 Satellite mage debuts for New Cairo City and the area around it. .......52
Map 26. Sentinel-1 Satellite Image after applying Multilooking. ........................................53
Map 27. Sentinel-1 Satellite mage radiometric correction ....................................................54
Map 28. Applying log scale to the image ............................................................................55
Map 29. Satellite image illustrating Vertical Horizontal Contrast .......................................56
Map 30. Satellite image illustrating Vertical-Vertical Contrast ...........................................56
Map 31. Satellite Image illustrating Vertical Vertical variance .............................................57
Map 32. An image illustrating BRBA built-up index for New Cairo ....................................62
Map 33. An image illustrating NBAI built-up index for New Cairo .....................................62
Map 34. An image illustrating BCI built-up index for New Cairo ........................................63
Map 35. Results from methodology figure 12. Yellow presents urban ................................65
Map 36. Segmentation parameters: Scale= 60 , Shape= 0.5, compactness =0.5..................69
Map 37 Maxim Pure Pixel Blue, Yellow areas are rooftops buildings after extraction. Condition
\[2904.95 \leq MaxPPBlue \geq 2270.69\] ........................................................................69
Map 38. The map illustrates rooms (beige color) on the rooftops, where
\[5024.2 \leq MaxGreen \geq 3417.96\] ........................................................................70
Map 39. Brown represents buildings, where \[13.54 \leq TexStdNIR \geq 5.5\] ....................71
Map 40. Final map for compound 3 ..................................................................................72
Map 41. Final map for compound 4 ..................................................................................73
Map 42. Final map for compound 5 ..................................................................................75
Map 43. Classification map for compound 6 ......................................................................76
Map 44. Land-use of the New Cairo City.[252] ..................................................................96
Map 45 layout of compound six, the map represents the lower limits at \(\beta=0^\circ\), green shaded
areas represent installed PVs..........................................................................................105
Map 46 layout of compound six, the map represents the upper limits at \(\beta=0^\circ\), green shaded
areas represent installed PVs..........................................................................................106
Map 47 layout of compound six, the map represents the lower limits at \(\beta=10^\circ\), green shaded
areas represent installed PVs..........................................................................................107
Map 48 ..............................................................................................................................107
Map 49 layout of compound six, the map represents the upper limits at \(\beta=10^\circ\), green shaded
areas represent installed PVs..........................................................................................108
Map 50 layout of compound six, the map represents the lower limits at $\beta = 20^\circ$, green shaded areas represent installed PVs.......................................................... 109

Map 51 Layout of compound six, the map represents the upper limits at $\beta = 20^\circ$, green shaded areas represent installed PVs.......................................................... 110

Map 52 Layout of compound six, the map represents the lower limits at $\beta = 30^\circ$, green shaded areas represent installed PVs.......................................................... 111

Map 53 layout of compound six, the map represents the upper limits at $\beta = 30^\circ$, green shaded areas represent installed PVs.......................................................... 112

Map 54 layout of compound six, the map represents the lower limits at $\beta = 45^\circ$, green shaded areas represent installed PVs.......................................................... 113

Map 55 layout of compound six, the map represents the upper limit at $\beta = 45^\circ$, green shaded areas represent installed PVs.......................................................... 114
### List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D</td>
<td>two dimensions</td>
</tr>
<tr>
<td>3D</td>
<td>three dimensions</td>
</tr>
<tr>
<td>4D</td>
<td>4 dimensions</td>
</tr>
<tr>
<td>Aa</td>
<td>the roof area that can be used for solar applications</td>
</tr>
<tr>
<td>Aa/ca</td>
<td>the available roof area per capita</td>
</tr>
<tr>
<td>AC</td>
<td>Alternating current</td>
</tr>
<tr>
<td>Ai</td>
<td>Roof print area</td>
</tr>
<tr>
<td>ANN</td>
<td>Artificial Neural Network</td>
</tr>
<tr>
<td>Aprojroof</td>
<td>the projected area included in the simulation</td>
</tr>
<tr>
<td>Apv</td>
<td>the suitable area selected for PV</td>
</tr>
<tr>
<td>Ar</td>
<td>The area within a built-up area.</td>
</tr>
<tr>
<td>ASR</td>
<td>Area Solar Radiation</td>
</tr>
<tr>
<td>Au</td>
<td>population and urban area</td>
</tr>
<tr>
<td>BCI</td>
<td>Biophysical Information Composition Index</td>
</tr>
<tr>
<td>Bd</td>
<td>building density</td>
</tr>
<tr>
<td>BFA</td>
<td>Building Footprint Area</td>
</tr>
<tr>
<td>BFA ratio</td>
<td>Area built/Area plot</td>
</tr>
<tr>
<td>Bgreen</td>
<td>Green Band</td>
</tr>
<tr>
<td>BHI</td>
<td>Beam Horizontal Irradiation</td>
</tr>
<tr>
<td>BRBA</td>
<td>Band Ratio for Built-up Area</td>
</tr>
<tr>
<td>Bred</td>
<td>Red Band</td>
</tr>
<tr>
<td>BSWIR</td>
<td>Band short-wave infrared</td>
</tr>
<tr>
<td>Bswir2</td>
<td>Band short-wave infrared 2</td>
</tr>
<tr>
<td>Cf</td>
<td>the facility coefficient</td>
</tr>
<tr>
<td>CS</td>
<td>which is the buildings’ voids, the shadowing coefficient</td>
</tr>
<tr>
<td>CSP</td>
<td>Concentrated Solar Plants</td>
</tr>
<tr>
<td>Cv</td>
<td>The void fraction coefficient</td>
</tr>
<tr>
<td>Db</td>
<td>building density</td>
</tr>
<tr>
<td>DBMS</td>
<td>database management system</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DEM</td>
<td>Digital Elevation Model</td>
</tr>
<tr>
<td>DHI</td>
<td>Diffuse Horizontal Irradiation</td>
</tr>
<tr>
<td>DHM</td>
<td>Digital Height Model</td>
</tr>
<tr>
<td>DL</td>
<td>Deep Learning</td>
</tr>
<tr>
<td>Dp</td>
<td>the population density</td>
</tr>
<tr>
<td>DSM</td>
<td>Digital Surface Model input</td>
</tr>
<tr>
<td>ELU</td>
<td>Existing Land Use</td>
</tr>
<tr>
<td>EV</td>
<td>Electric Vehicle</td>
</tr>
<tr>
<td>EW</td>
<td>the Extra Wide Swath</td>
</tr>
<tr>
<td>FLS</td>
<td>Full lambda schedule algorithm</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>FSO</td>
<td>Feature Space Optimization</td>
</tr>
<tr>
<td>GHI</td>
<td>Global Horizontal Irradiation</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographic Information Sciences</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>GRD</td>
<td>Ground Range Detention</td>
</tr>
<tr>
<td>GW</td>
<td>Giga Watt</td>
</tr>
<tr>
<td>H shading</td>
<td>fraction for shading</td>
</tr>
<tr>
<td>HB</td>
<td>the daily beam solar radiation incidence on a tilted surface, Wm(^{-2})</td>
</tr>
<tr>
<td>HD</td>
<td>the daily diffuse solar radiation incidence on a tilted surface, Wm(^{-2})</td>
</tr>
<tr>
<td>HDKR</td>
<td>Hay &amp; Device, Klucher and Reindl</td>
</tr>
<tr>
<td>HH</td>
<td>Horizontal- Horizontal</td>
</tr>
<tr>
<td>HR</td>
<td>High Resolution</td>
</tr>
<tr>
<td>HVAC</td>
<td>Heating, ventilation, and air conditioning</td>
</tr>
<tr>
<td>INS</td>
<td>Inertial Navigation System</td>
</tr>
<tr>
<td>ISR</td>
<td>Incident Solar Radiation</td>
</tr>
<tr>
<td>IWS</td>
<td>Interferometric Wide Swath</td>
</tr>
<tr>
<td>Kt</td>
<td>visibility index</td>
</tr>
<tr>
<td>LCLU</td>
<td>Land Change Land Use</td>
</tr>
<tr>
<td>LiDAR</td>
<td>Light Detection, and Ranging</td>
</tr>
<tr>
<td>Max_green</td>
<td>Maximum value for green band</td>
</tr>
<tr>
<td>Md</td>
<td>The monthly diffusion ratio.</td>
</tr>
<tr>
<td>ML</td>
<td>Machine Learning</td>
</tr>
<tr>
<td>MSAVI</td>
<td>Modified Soil Adjusted Vegetation Index</td>
</tr>
<tr>
<td>Mt</td>
<td>the monthly atmospheric transmittance</td>
</tr>
<tr>
<td>N</td>
<td>Number of municipalities in each RBT</td>
</tr>
<tr>
<td>NBAI</td>
<td>Normalized Built-up Area Index</td>
</tr>
<tr>
<td>NBEI</td>
<td>the New Built-up Extraction Index</td>
</tr>
<tr>
<td>NDBI</td>
<td>Normalized Difference Built-up Index</td>
</tr>
<tr>
<td>NDBRI</td>
<td>Normalized difference brick roof index</td>
</tr>
<tr>
<td>NDBSI</td>
<td>the normalized Difference Bare Soil index</td>
</tr>
<tr>
<td>NDDPI</td>
<td>Normalized Difference Dual Polarization Index</td>
</tr>
<tr>
<td>NDSI</td>
<td>Normalized Difference Soil Index</td>
</tr>
<tr>
<td>ndsm</td>
<td>normalized Digital Surface Model</td>
</tr>
<tr>
<td>NDVI</td>
<td>Normalized Difference Vegetation Index</td>
</tr>
<tr>
<td>NDWI</td>
<td>Normalized Difference Water Index</td>
</tr>
<tr>
<td>NEM</td>
<td>Net energy metering</td>
</tr>
<tr>
<td>NIR1</td>
<td>Near Infra-Red 1</td>
</tr>
<tr>
<td>NIR2</td>
<td>Near Infra-Red 2</td>
</tr>
<tr>
<td>NOCT</td>
<td>normal operating cell temperature ((^{\circ})C)</td>
</tr>
<tr>
<td>OBIA</td>
<td>Object-based image analysis</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>Pb</td>
<td>the fraction of surface area occupied by buildings within the urban area</td>
</tr>
<tr>
<td>$P_{\text{cloudy}}$</td>
<td>the proportion of cloudy days in a month</td>
</tr>
<tr>
<td>PEG</td>
<td>potential energy generated/m²/year</td>
</tr>
<tr>
<td>PR</td>
<td>performance ratio</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaics</td>
</tr>
<tr>
<td>PVA</td>
<td>Photovoltaic Available Roof Area</td>
</tr>
<tr>
<td>PVA ratio</td>
<td>$\text{PV area}/\text{BFA}$</td>
</tr>
<tr>
<td>RBT</td>
<td>Representative Building Typology</td>
</tr>
<tr>
<td>RF</td>
<td>Random Forest algorism</td>
</tr>
<tr>
<td>RGB</td>
<td>Red Green Blue</td>
</tr>
<tr>
<td>Rpv</td>
<td>$(\text{Apv})<em>{\text{site}}/(\text{Aprojroof})</em>{\text{site}}$</td>
</tr>
<tr>
<td>RS</td>
<td>Remote Sensing</td>
</tr>
<tr>
<td>SAR</td>
<td>Synthetic Aperture Radar</td>
</tr>
<tr>
<td>SDI</td>
<td>Spectral Discrimination Index</td>
</tr>
<tr>
<td>SEG</td>
<td>Solar Exposure Graph</td>
</tr>
<tr>
<td>SLC</td>
<td>Level-1 Single Look Complex</td>
</tr>
<tr>
<td>SM</td>
<td>The Stripmap mode</td>
</tr>
<tr>
<td>SRTM</td>
<td>Shuttle Radar Topography Mission</td>
</tr>
<tr>
<td>Ssa</td>
<td>shadow width obstructed along the azimuth of the sensor by a building in the sensor's field of view</td>
</tr>
<tr>
<td>Ssu</td>
<td>sun azimuth</td>
</tr>
<tr>
<td>SVMs</td>
<td>support vector machines</td>
</tr>
<tr>
<td>Tex_St11_NIR</td>
<td>Texture of the NIR</td>
</tr>
<tr>
<td>TIN</td>
<td>Triangular irregular networks</td>
</tr>
<tr>
<td>TopSAR</td>
<td>Terrain Observation with Progressive Scans SAR</td>
</tr>
<tr>
<td>VH</td>
<td>Vertical -Horizontal</td>
</tr>
<tr>
<td>VHR</td>
<td>Very high resolution</td>
</tr>
<tr>
<td>VV</td>
<td>Vertical -Vertical</td>
</tr>
<tr>
<td>W peaked</td>
<td>peaked rooftops are used for mixed purposes</td>
</tr>
<tr>
<td>WV</td>
<td>Wave mode</td>
</tr>
<tr>
<td>WV2</td>
<td>Worldview-2</td>
</tr>
</tbody>
</table>
# List of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_0$</td>
<td>Eccentricity correction factor</td>
</tr>
<tr>
<td>$ET$</td>
<td>Equation of time</td>
</tr>
<tr>
<td>$H_b$</td>
<td>Beam radiation on a horizontal surface</td>
</tr>
<tr>
<td>$H_b\beta$</td>
<td>Daily beam radiation on an inclined surface</td>
</tr>
<tr>
<td>$H_d$</td>
<td>Diffuse radiation on a horizontal surface</td>
</tr>
<tr>
<td>$H_d\beta$</td>
<td>Daily diffuse radiation on an inclined surface</td>
</tr>
<tr>
<td>$H_H$</td>
<td>Daily global radiation on a horizontal surface</td>
</tr>
<tr>
<td>$H_r$</td>
<td>Daily reflected radiation on an inclined surface</td>
</tr>
<tr>
<td>$H\beta$</td>
<td>Daily global radiation on an inclined surface</td>
</tr>
<tr>
<td>$I_b$</td>
<td>Hourly direct beam solar radiation on a horizontal surface</td>
</tr>
<tr>
<td>$I_bN$</td>
<td>Hourly direct average beam radiation on a horizontal surface</td>
</tr>
<tr>
<td>$I_b\beta$</td>
<td>Hourly direct beam solar radiation on an inclined surface</td>
</tr>
<tr>
<td>$I_d$</td>
<td>Hourly diffuse solar radiation on a horizontal surface</td>
</tr>
<tr>
<td>$I_d\beta$</td>
<td>Hourly diffuse solar radiation on an inclined surface</td>
</tr>
<tr>
<td>$I_H$</td>
<td>Hourly global solar radiation on a horizontal surface</td>
</tr>
<tr>
<td>$I_o$</td>
<td>Hourly extraterrestrial solar radiation on a horizontal surface</td>
</tr>
<tr>
<td>$I_r$</td>
<td>Hourly ground reflected radiation on an inclined surface</td>
</tr>
<tr>
<td>$I_{sc}$</td>
<td>Solar constant</td>
</tr>
<tr>
<td>$I\beta$</td>
<td>Hourly global solar radiation on an inclined surface</td>
</tr>
<tr>
<td>$K_t$</td>
<td>Daily clearness index</td>
</tr>
<tr>
<td>$LL$</td>
<td>Longitude of the location under study in degrees</td>
</tr>
<tr>
<td>$Ls$</td>
<td>Standard meridian for a local zone</td>
</tr>
<tr>
<td>$LT$</td>
<td>Local standard time</td>
</tr>
<tr>
<td>$m$</td>
<td>Air mass</td>
</tr>
<tr>
<td>$M_t$</td>
<td>Hourly clearness index</td>
</tr>
</tbody>
</table>
n \quad \text{The number of the day in the year}

P1 \quad \text{Vicinity of the sun’s disc}

P2 \quad \text{Sky radiation from the region near the horizon}

ws \quad \text{Sunrise hour angle}

ws \quad \text{Sunset hour angle}

Z \quad \text{Correcting factor}

\beta \quad \text{Tilt angle}

\gamma \quad \text{Solar azimuth angle}

\delta \quad \text{Declination angle}

\varepsilon \quad \text{The function of hourly diffuse radiation}

\theta \quad \text{The angle of incidence for a surface facing the equator in degrees}

\theta z \quad \text{Zenith angle}

\varphi \quad \text{Latitude}

\omega \quad \text{Hour angle}

\Gamma \quad \text{The day angle in radians}
Chapter 1 Introduction

1.1 General Introduction

Geographic Information Sciences (GIS) and Remote Sensing (RS) are being used to overcome the negative impact of climate change and to achieve sustainable development goals such as cheap, clean energy for all (goal 7) [1]. GIS and RS are used to identify suitable areas for Concentrated Solar Plants (CSPs) in the Middle East and North Africa (MENA) [2]. Many different platforms support CSPs, such as International Renewable Energy Agency (IRENA) [3] and the Solaris platform [4]. In addition, GIS and RS are used to identify suitable areas for PVs on rooftops in Europe and North Africa as demonstrated by Gasser et al. [5]. However, very few detailed studies use GIS and RS to map suitable areas for PV installation in cities in the MENA region as Skaher et al. [6] did. Many studies investigated the potential for employing solar energy for charging Electric Vehicles (EVs) or storing this energy in EVs’ batteries. These studies are conducted mainly in the west such as studies conducted by Kawamura and Muta [7], Mouli et al. [8], Aljohani et al. [9], Vermeer et al. [10], Ghotge et al. [11], Mohammad et al. [12], but there are very few studies that are conducted in the MENA area Alsomali et al. [13] or in Egypt, such as Hassan et al. [14] and Allam et al. [15]. There is an urgent need to fill the research gap in using energy generated from PVs to charge EVs in Egypt as mentioned in the Egyptian media [16] and [17], this is because of the recent Egyptian policy towards EVs, which increases EV usage and import [18], El-Dorghamy [19] and Graditi et al. [20] and manufacture Egyptian EVs as demonstrated by El-Dorghamy [19] and other Egyptian media [21], [22]. For these reasons, this research aims to map suitable areas for PV rooftops to charge EVs and to estimate the electrical energy generated from PVs installed on the rooftops. The study is conducted on a compound scale in New Cairo City.

One major cause of climate change is the increase of CO₂, a product of human activities such as construction and transportation. Based on “our world in data” website [23], the transportation sector is responsible for 24% of CO₂ production worldwide. In addition, road transport produces 75% of transport emissions and 15% of total CO₂ emissions. According to Central Agency for Public Mobilization and Statistics [24], the number of cars in Egypt increased to 9.9 million in 2017, and it is expected to grow. The demand synchronizes with fuel’s price increase. Thus, there are more economic burdens on people who use conventional cars. The decreasing amount of CO₂ slows climate change, possibly by incorporating renewable energy, especially in the transportation sector. Egypt has a high potential for solar energy and is developing mega CSP projects to attract international businesses and achieve economic development goals [25]. Egypt’s interest in Electric Vehicles (EVs) has been increasing over time [26]. EVs are reducing CO₂ emissions, and this is a mitigation opportunity Shalaby et al. [27] to overcome climate change. The Egyptian Ministry of Trade and Industry allows importing used EVs to promote environmentally friendly cars [28]. This development creates a market niche for international EV vendors to sell EVs and build EV charging stations [29], [30], [31]. Egyptians can charge their EV and decrease their expenses when they use solar energy.
to charge their EV. Using Photovoltaics (PVs) installed on house roofs to charge EVs is a good solution for Egyptians to decrease fuel bills, especially in new cities. The suggested project gives opportunities to decrease CO$_2$ and improve the Egyptians’ environment and health. In addition, EV batteries could be utilized to save energy generated by PVs, which decrease the cost of installing PV systems.

According to Gasser et al [5], GIS and RS are used to map suitable rooftop areas. GIS is a set of data, concepts, and processing technologies used to model earth in computers [32]. RS is the science that allows researchers to collect data about an object (earth) from a distance as written on NASA website [33]. Many GIS and RS studies used Sentinel-2 satellite images with a spatial resolution equivalent to 20 m as the research conducted by Halder [34] and Sentinel-1 satellite images to map urban areas with a spatial resolution equal to 10 m as demonstrated by Clerici et al. [35]. Some studies also fuse Sentinel-1 and Sentinel-2 satellite images to map land-cover land-use areas, and the resulting spatial resolution equals 10 m [35]. In addition, very high-resolution satellite images, for example, worldview-2 as demonstrated by Zhou et al. [36] and Pleiades -1 as demonstrated by Zylshal et al. [37], are used to get accurate areas of rooftop PVs, and these images have a resolution of less than 10 m. Feature extraction and classification are the most critical concepts in rooftop extraction on city and compound scales. According to the website of harrisgeospatial company [38], feature extraction could be defined as isolating objects from the satellite image representing different urban elements such as buildings, streets, and green areas. According to Ela and O. Claire [39], classification could be defined as creating samples, identifying them, and combining them into groups with labels to train the embedded algorithm in the GIS software to learn how to identify urban elements on its own.

This research is distinguished by accurate hourly solar radiation data collected at the American University in Cairo. It was not derived from generic climate models and satellite images with less accuracy [40]. The calculated energy is used to charge Electric Vehicles as demonstrated by Bhatti et al. [41], a new trend in Egypt [26]. This research is confined to compound scales so as to yield results of higher accuracy than if it was extended to city scales, similar to other Egyptian researchers such as Shaker et al. [6], Taha et al. [42] amd Muhammed[43]. This thesis investigates the fusion of Sentinel-1 and Sentinel-2 in a desert city, and very few studies have used these technologies in desert areas, such as Eddahby et al.[44] and Sinergise [45]. The suggested approach for this research is an interdisciplinary approach that combines solar energy, urban planning, GIS, and RS in Egyptian urban areas, which is a unique approach. Calculations of the area of buildings in compounds were processed on the cloud, a new technology for GIS and RS processing [46]. The suggested research can assist policymakers in improving their policies for solar energy planning and including urban areas in their goals. The results of this research could advance and promote EV planning policies.

This research highlights the need for PV and EV manufacturing, management, and installation, which creates job opportunities. Accordingly, there could be economic development on the country scale. Finally, by achieving the affordable clean energy goal, it is possible to achieve other sustainable development objectives such as good health
and wellbeing (goal 3), economic growth (goal 8), industry, innovation and infrastructure (goal 9), and sustainable cities (goal 11). The study has six limitations: (1) the applied method — on the city scale — cannot be applied for all geographic locations because the environment and weather affect the results. (2) built-up indices used in the method — for New Cairo City — are not sensitive enough to distinguish between soil and man-made features (buildings, roads, etc.). (3) due to technical limitations, applying segmentation step for New Cairo City is not possible. (4) the accuracy of supervised classification could be improved by adding more digitized features (buildings, green areas, etc.), which is costly, and adding Ground Control Points (GCPs), which is not possible in Egypt.

The present study is a multidisciplinary research that integrates GIS, RS, town planning, and solar energy engineering. Therefore, the thesis outline (Figure 1) is designed for researchers in these disciplines. The outline introduces previous studies (chapter 2) and solar energy (chapter 4). Since GIS and RS are space technologies that are not as known as other engineering fields, there is a focus on their concepts and technologies in chapter 3. The output of chapter 3 and chapter 4 are combined and are used as inputs in the methods and results (chapter 5).

1.2 Research Objectives:

The main objectives of this study is to demonstrate the use of solar radiation measurements and models combined with GIS data to make reasonably accurate estimates of the potential electrical energy produced from roof mounted PV modules, taking into account all practical aspects. This includes having all PV coplanar to avoid PVs shading each other at some time of the day or year as well as shading by nearby obstacles, not allowing any protrusion of the rectangular shape of the PV outside the actual plan profile of the roof, and taking into consideration the actual house plans and orientations with respect to the cardinal directions. Previous studies assumed adhoc ratios or very rough assumptions of the useful area of the roof, whereas we strive here to deduce a justifiable ratio which is a more accurate tradeoff between generality and accuracy.

To this end the model has been employed to 6 different Villa compounds in New Cairo. The reason for selecting this area is that it is a suburb of Cairo where the buildings in each compound have the same height, have typically the same designs (ground floor plus first floor plus roof with one or two rooms) and are fairly geometrically uniform.

Inhabitants of those compounds are typically middle class and own cars which they need to drive to work, shopping and other commuting needs, for lack of suitable public transport. Hence one of the objectives of the research is to investigate whether inhabitants of those compounds can achieve complete sustainable mobility or not, through charging their future Electric vehicles employing rooftop PV generated electricity.
1.3 Thesis Layout

The thesis consists of seven main chapters. Chapter 1 is the introduction, providing a general over-view, thesis objectives, and a summary of the contents. Chapter 2 presents a literature review of GIS and RS models and their applications. It includes studies on extracting rooftops and estimating potential solar areas according to different planning scales. Chapter 3 introduces the GIS and Remote Sensing (RS) procedures, which includes the primary GIS and RS concepts and structure of different data types documented in the literature review. In addition, chapter 3 contains processed maps and calculated suitable PV areas among rooftop areas. Chapter 4 is dedicated to solar data and models for extracting horizontal measurements to inclined surfaces. Chapter 5 presents the methodology and results. This chapter includes the main methods used to achieve the study’s objectives. It contains data, software, and workflow diagrams. It consists of the results obtained from GIS and RS analysis (chapter 3). In addition, more processing is applied to the output of chapter 3 and chapter 4 and combined to get the final result. The discussion and conclusion in chapter 6 demonstrates the similarity and differences between the obtained results and the results of other studies and states the main conclusion of the research. Chapter 7 suggests future research work.

Figure 1. Thesis outline
Chapter 2 Literature Review

The literature review within the scope of solar energy planning in urban areas in desert cities had gaps related to the planning scale, solar data sources, and creative energy storage solutions. Previous studies focused on one planning scale, which is demonstrated in this chapter. Previous research in desert areas did not include creative solutions that use solar energy, such as charging EVs or storing solar energy in their batteries. More importantly, the literature review showed that most research solar data is derived from remote sensing models and extrapolated solar data. Addressing this research gap is vital because many big establishments exist in the Egyptian desert, such as the new administrative capital, the six of October city, and New Cairo. Desert cities can be energy self-sustained, and this could save electricity generated from the high dam, which can be used for other development projects. In addition, saved electricity decreased electricity bills for Egyptian citizens. Solar energy generated from PVs could create job opportunities, especially in post COVID economy as demonstrated by Tian et al. [47], [48], [49], Bjerde [50], and it could assist in solving the energy problems due to the Ukrainian crisis as demonstrated by Tollefson [51], Mcphie [52] and Florizone [53]. The literature review chapter includes the main concepts of planning scales, and different studies are categorized based on their planning scales. Their methods and actual results are included.

Conducting solar energy studies using Geographic Information Sciences (GIS) and Remote Sensing (RS) includes several variables, which are available roof areas, shades, topography, time of the year, efficiency, performance, PVs specifications, and solar radiation models as demonstrated by Izquierdo [54], and Walch et al. [55]. According to Taherzadeh et al. [56], detection of roofs in urban regions was challenging due to their heterogeneous nature that combines impervious surfaces such as roads, parking, and rooftops and landscape feature such as gardens and water fountains [56]. Field survey that is used to detect rooftop materials and their areas is costly. It takes a long time and is challenging to implement due to buildings’ security: therefore, remote sensing data is crucial to provide information about the spatial distribution of manmade elements such as buildings and roads. Researchers can use their results to choose PV specifications that satisfy the electricity demand in the study area. In addition, extracting areas for PV installations requires understanding different concepts and definitions from other science disciplines. For example, Sharifi [57] demonstrated that it is vital to choose the urban scale, which may be macro, miso-scale, or micro-scale, when research is conducted in a city. There is a need to understand GIS concepts, such as 2.5 dimensions, three dimensions, Light Detection and Ranging (LiDAR), and the Hillshade tool.

According to Sharifi [57], researchers use three scales in studying cities: macro, miso, and micro. The macro-scale study of the city’s construction and its present and future positions concerning other cities’ networks. Macro-scale elements and aspects are the city's size, development type, people’s distribution pattern, clustering degree, and connectivity of landscape elements. The mesoscale focuses on the layout and structure of neighbors, streets, open spaces, blocks, and lots. The micro-scale studies the
construction and design of buildings and the location of the attached structures, paths, and spaces. Meso-scale features and aspects are the neighborhood's shape and design, the district's density, land use mix, size, and the form of spaces. The mesoscale analysis achieves a more comprehensive and context-specific understanding of urban arrangement and its features. In addition, it enables observing how different urban elements interact. The mesoscale is the minimum scale to consider the interactions among inhabitants between themselves and their environment. Usually, developers designed algorithms for rooftop PVs for macro and micro scales, but they forgot about the mesoscale in the middle. The selected algorithm is intended for a specific site with specific requirements. Therefore, a successful simulation depends on (1) calculating the solar vector; (2) the Digital Surface Model input (DSM); and (3) the shading and irradiation model as demonstrated by Nguyen and Pearce [58]. After selecting the scale of the analysis, researchers must choose suitable methods and data types to capture the urban scale.

2.12 Methods for Assessing Photovoltaics Potential on Roofs

Hierarchical methods for assessing Photovoltaics potential on buildings' roofs were suggested by many studies such as Izquierdo [54], where (A) the physical potential, which includes the total solar energy; (B) topographical potential, which limits the places for capturing solar energy; and (C) the technical potential, which includes the technical features of the tools utilized for converting the solar energy into electrical energy. This is shown in Figure 2 Hierarchical methodology for estimating Solar potential on roofs Izquierdo [54], Walch et al [55].

According to Izquierdo [54], the calculation of the technical potential includes (i) the radiation on the tilted roofs and the measure of diffuse, direct, and surface-reflected radiation influences. (ii) the PV efficiency that is a function of incident irradiance, the ambient temperature. (iii) the space required between modules to avoid shades (min shades in the winter solstice) and the radiation reaching tilted PVs has three parts, which
are direct, diffuse, and ground-reflected. Erbs’ relation [59] is utilized to compute the monthly diffuse part from the clearness index and horizontal irradiation. Then, it is likely to compute hourly direct & diffuse horizontal modules. This data is utilized to calculate the irradiance on a tilted PV using the isotropic Liu-Jordan model[60]. The computed hourly data were aggregated to get yearly results. The economic potential includes cost and social constraints, lifetime and interest rates, and government regulations. Since there is high uncertainty in the decision-making process and factors affecting the project, economic potential is considered beyond the project’s scope.

2.2 Studies Conducted on a Microscale

Mastrucci et al. [61] introduced a bottom-up statistical method that depends on GIS energy-consuming estimating housing stocks in a city. They used a multiple linear regression model for the electricity and gas utilization downscaling from the aggregated post-code to single dwellings, based on different factors, for example, the dwelling type, construction duration, floor area, and the number of inhabitants. Consumption of energy is assigned to diverse end-usages and adjusted for meteorological conditions. Later, they estimated the potential of saving energy by accounting for the application of refurbishment procedures. The findings are aggregated for a city to design evidence-based decision support for planning sustainable cities. In addition, these results were used to prioritize the execution of energy retrofit processes for the building stock in the town of Rotterdam. The method can be applied to other contexts. Future studies could be based on analyzing energy usage by applying geo-statistics to get enhanced forecasts at a smaller scale. The statistical method is applied to the website (iGUESS), which is part of the Project “MUSIC” to be used for more cities. The city’s zones could be the following GIS planning scale.

In their study, Chen and Hong [62] assessed the effects of three zoning methodologies and floor multipliers utilization on the modeled energy usage in three environmental zones utilizing energy savers for buildings. The first method uses the building’s footprint to create one thermal zone/floor. The second method uses the perimeter and core zones. The third method uses the shapes of building prototypes which are available from the U.S. Energy Department. Their study illustrated that zoning methodologies significantly affect the modeled energy usage of building energy models on the urban scale. They recommended using the method and floor multiplier to get precise results while considering the modeling time for city-scale building energy modeling. In addition, planning for energy modeling could be on a building’s scale, and this requires taking the roofs into account.

Tian et al. [63] studied the impact of computed morphological variables on generating solar energy potential for housing areas in Wuhan, China. The morphological plan of the residential block includes building type, height, usage, number of floors, size, and max house density – spacing between PVs changes due to shades from nearby buildings with taller heights. Radiation simulations were conducted as the followings: 1. importing the historical climate data into the Rhinoceros Software. 2. creating the three-dimensional
The model of the block. The model of Perez scattered radiation was used in the radiance system. The Perez model estimates diffuse irradiance on the tilted surface of all directions for different insolation scenarios, relying on the direct & global irradiance data [64]. The model of the block’s solar radiation was completed using Ladybug and Honeybee software, and the findings of the solar radiation intensity spreading of houses’ facades were visualized. The simulation cycle was 12 months, and the surface area of buildings was split into a grid of 4m² to compute the yearly accumulative solar radiation of all samples. Furthermore, radiance uses composite light tracking processes based on the light’s behavior in the three-dimensional model; therefore, it can calculate radiation on both roofs and the building’s façade. It was found that the area ratio of the floor, density of the building, building’s mean elevation, and interval strongly affect the solar potential for the housing block. The correlation was between 71% and 78%.

Zhou et al. [65] aimed to create a large-scale urban Photovoltaic modeling system using the minimum input databases. They conducted their studies at the Delft University of Technology. They used LiDAR data, building footprint, ArcGIS pro software, and the original model to reconstruct a new 3-d building model. Then, they used the latest model to create an annual solar irradiation map by integrating bar centric coordinate system and simplifying the skyline-based model. They also used the new building model to create a yearly DC yield map and annual DC yield on roofs by using MATLAB to model the panel fitting on roofs, simplifying the skyline-based model, and specifying the yield> 650 kWh/kWp. The annual DC yield on roofs was used to create a specific yield of PV systems which led to roof classes. In addition, the annual DC yield on the roof was used to develop Sandia National Laboratories (SNL) model. SNL model was used to create the annual AC yield on roofs and the annual AC yield map. Since shades decrease the power, they installed PVs in the urban context through Digital Surface Model. The selected PV
modules were: Solarge SOLO and Solarge DUWO solar PVs. Both modules provide the same peak power of 365 Wp. The measurement of Solarge SOLO is 2.066×0.997m², and Solarge DUWO is 2.021×0.997m². The tilt angle equals 12°.

Machete et al. [66] used 2.5 and 3 dimensions data and three solar radiation tools for a city block in Lisbon for summer and winter. In the 2.5D, each x and y coordinates holds one z-value for modeling across continuous planes, and it does not consider complicated geometries. The 2.5 D solar radiation prototype used the Area Solar Radiation extension, employed in ArcGIS, and Incident Solar Radiation and Solar Exposure Graph, which was included in ECOTECT software for the 3D model. The study demonstrated that the 3D method could assess solar accessibility in urban areas. Moreover, researchers can combine 3d and energy simulation and object image analysis for PVs and other usages on rooftops. They found that 30% of the city’s block potential to generate energy is affected by the built-up areas and topographic relief surrounding these blocks. Their studies used 3D GIS to build blocks and their surrounding area.

Jo et al. [67] used GIS, RS, and solar energy simulation to calculate the possible benefits of PV applications. They assessed the rooftop’s PV potential and advantages on an urban area scale. The model predicted the potential energy generated from roof areas that can
be used to meet the requirements of solar energy generation in Arizona. It was found that Photovoltaics can generate ten percent of the total electricity demand. This method may not be applied to other residential places in Arizona since buildings’ structures are sloped and have small roofs. Therefore, the residential area offers various settings for solar system applications. It is essential to assess the energy usage of different tech (ex: green roofs, cool-roofs, and solar thermal) s. The technology of green roof enhance buildings’ energy efficiency; therefore, it is implemented as a strategy for demand-side administration. These approaches decrease people’s vulnerability to excessive heat stress by improving the structure of the building surface. Finally, Jo et al. [67] suggested that combining cool- roof and PV systems could maximize the benefits and reduce the impact of urban areas in the hot and arid desert region. Other models can get accurate results on different city scales.

Hofierka [68] assessed the potential of PVs using a three-dimensional city model and solar radiation tools, the r.sun model, and PVGIS on a city in eastern Slovakia. GIS was used to construct a database that includes building data. The city is divided into different urban zones categorized by various functionality and morphology. PVs’ potential was evaluated using the PVGIS estimation tool. The result showed a high possibility that it could meet the need of 2/3 of electricity consumers.

Nevertheless, this potential exhibits significant temporal and spatial differences because of local & global causes. Hofierka [68] showed that national PVs’ potential assessments could be enhanced by extrapolating the local calculations using cities’ GIS databases. Hofierka [68] recommended applying a complete 3d model that considers the building’s surface facades, trees, infrastructure, demographic, and statistics about power intake to better represent the properties of different intra-urban structures. If shades are included in the study, it is crucial to work on a suitable scale and have new variables.

Boz et al. [69] created a model using LiDAR data, buildings footprints, and ArcGIS software to automatically identify rooftop segments suitable for PVs. Three key constraints are considered: slope (tilt), aspect (azimuth), and shades. Shadow analysis was performed utilizing Area Solar Radiation (ASR) and ArcGIS. Digital Surface Model (DSM) was developed from LIDAR data. Data inputs are latitude and longitude values for Philadelphia. Thus the shading times relate only to Philadelphia. Inputs to the ASR model are The DSM, a particular time, time interval for computations, and latitude and longitude functions as parameters. Outputs are direct and diffuse irradiation levels and the number of sun hours as shown by Machette [70] and in the solar analyst manual created by ESRI [71]. The model was used for all hours through a day representing each month (21st day was selected for this study). Outputs were reclassified to a file containing the time duration. Later, this file was reclassified again, and these conditions were applied. If the 0 =< time duration = 0.5 hours, it gets a zero value (shades). If hour >= duration> 0.5 hours, it is assigned a value of one (no shades). Criteria for areas without shades for PVs installations are: no shades from 9 am to 3 pm in summer, and no shades between 10 am to 2 pm in the winter. GIS analysis was done using shadows conditions and other conditions related to slope, and aspect to extract suitable roofs for PVs, such as 135 ≤Aspect≤ 225 or Flat, and 20m²≤Area≤ 100m² for residential PV system.
Cecconi et al. [73] used GIS, open data, and Artificial Neural Networks (ANN) to assess the potential of saving energy for an Italian school in Lombardy. They aimed to support energy policies on a regional scale. They used 8 Neural Networks to calculate how much power is saved in 3 retrofit situations. They created different scenarios for retrofit interventions for schools in the study areas, and they considered the entire retrofit, roof and walls, windows and walls, windows and ceilings, only walls, only windows, and only rooftops. They calculated Whole savings [MWh/y] for each scenario and Average savings [kWh/y]. For example, design one had a total energy consumption before-retrofit: of $8.9712 \times 10^5$ MWh/y; whole energy consumption post-retrofit: $5.25874 \times 10^5$ MWh/y; and a total saving of $3.57953 \times 10^5$ MWh/y for 1,216 refurbished schools. For all schools, a saving of 294.370 MWh/y was calculated. Later, researchers linked their findings to GIS maps. They found out that GIS is an essential system for creating energy policies.

Taha et al. [44] automatically extracted urban areas from Pleiades satellite images for the Marina area in Egypt. The need for automated extraction increases due to the high demand for fast-updating GIS databases for cities and touristic site improvement. They compared the performance of different Machine learning (ML) algorism: random forest, maximum likelihood, Support Vector Machines (SVM), and backpropagation neural networks. These algorisms were used to classify Pleiades' image and to obtain urban and non-urban area classes. Next, they applied opening and closing morphological

[Map 2. Types of estimated energy savings for intervention in the Lombardy area (Scenario 1) [74]]
operations or grid filters [74], and Sobel edge detection was utilized to enhance the connectedness of the result. Finally, they converted the edge image to vector data and performed quality analysis, including completeness, correctness, and quality. It was found that random forest has the highest overall accuracy, and it is equal to 97%, maximum likelihood (95%), SVM (93%), and backpropagation (92%). Researchers encouraged using ML algorithms to extract urban areas from high-resolution images.

Zylshal et al. [37] studied National Monument Park in Kuala Lumpur, Malaysia. They classified one Pleiades image using SVM and applied expert knowledge refinement. To improve the classification, they derived and included the Normalized Difference Water Index (NDWI), Normalized Difference Vegetation Index (NDVI), and Modified Soil Adjusted Vegetation Index (MSAVI). Two land cover classes were created, representing “urban green” and “non-urban green.” The visual interpretation and site dimensions as reference data were used for overall accuracy. The suggested segmentation and classification still need further study to understand their effectiveness in different cities with various land use.

Aerial photography can add value to GIS-Solar energy studies. Aerial photography is photos taken using a camera on an airplane and improves the data quality of low-resolution satellite images. For example, Bunme et al. [75] used an aerial photo image to increase the quality and precision of the Digital Surface Model (DSM) and its resolution from low to high. These maps were created using Area solar radiation functions in ArcGIS software, extracting solar radiation from a satellite image[76]. In addition, the digital surface model, digital elevation model, and spatial analysis were used to estimate the tallness of buildings and trees that cause shade. After comparing the aerial photos and low and high-resolution images, it is easy to identify shadows and houses. They estimated solar power using solar radiation data from GIS. They applied this solar radiation map and actual power consumption information to an accurate distributed system model in Kitakyushu, Japan. They investigated the influence of high setting-up rates of PVs in residential areas. They considered the impact of shades caused by clouds on the voltage variations in the supply system model by using a GIS algorithm that simulated cloud movement. It was found that cloud shades movements obstructed the power generation, which caused voltage variations of the supply approach on both the housing side (100–127 Volt ) and among buses (6.6 kV). They recommended planning a supply system with many PVs to overcome the negative impact of cloud movement in generating solar energy power. Solar energy projects are not limited to residential areas but could also be implemented in service buildings.

Airports are good service utilities that could benefit from solar energy. For instance, Jiang et al. [77] judged the potential of solar power & associated economic performance of airports by implementing GIS. The Hourly PV output (kWh), which is equal to the PV area * hourly global incident solar radiation (kWh/m²)*PV efficiency* the balance of system efficiency [78]. The sum of electricity generated in the life span of the PV system (kWh) = 25 years* yearly production of the PV system (kWh)* the yearly degeneration rate of the PV panels. They did not consider shades in this study. They found that the potential capacity of PV in the Chinese airports equals 2.50 GW. It is possible to satisfy
the yearly electrical request of the aviation industry in eight provinces in China by generating solar energy from the airports’ rooftops. The economic analysis demonstrates that all airports’ PV systems benefit when applying investment strategies. In addition, integrating a Photovoltaic system with a noise barrier could be a new source to generate solar energy when there are no buildings or enough land.

Moreover, PVs could be built on vertical and light elements such as noise barriers. For example, Zhong et al. [79] created a computational system to calculate the solar potential of Photovoltaic noise barrier systems based on both present and planned sites for noise. They made a surface model using ArcGIS and calculated the shades caused by buildings using the ArcGIS Mountain shadow tool. Determining the shade’s effects on the structures on the PVs potential, researchers overlaid the shadow layer with the barriers layer. It was found that no shades covered the noise barriers. Monthly solar data for 2019 were downloaded from CAMS Radiation Service [80], which contains Global Horizontal Irradiation (GHI), Beam Horizontal Irradiation (BHI), and Diffuse Horizontal Irradiation (DHI). This data was used to predict solar PV potential. The system identifies a suitable area for PV installation. They used deep learning to identify onsite noise barriers using images from street view and added new noise barrier sites from existing urban policies. It was found that the yearly solar potentials from PVs in 2019 were 29,137 MWh for existing sites and 113,052 MWh for planned sites. The potential Photovoltaic noise barrier could reach up to 14.26 MW for present locations, and 57.24 MW for future planned sites.

Montealegre et al. [81] conducted a multi-criteria criteria analysis using GIS to map suitable roofs for Food, Energy, Water, and (FEW) purposes. The study area was the district of El Rabal in Spain. They used LiDAR data and houses footprints to calculate the slope (tilt), aspect (azimuth), shades, and solar radiation reaching the rooftops. This method has excellent accuracy for studies conducted on district or city scales because it considers the building’s type, the hourly position of the sun, the slope and orientation of the roof, and the effects of shades. Digital Surface Model was used as the topographic input to calculate the roof’s tilt, azimuth, shades, and solar radiation. Simulation captured the shades’ seasonal variation by using the Hillshade tool in ArcGIS software. The model was used for four days: the 21st day of March, June, September, and December 21. Hillshade is a tool that uses the altitude and azimuth of the sun, which were downloaded from the Solar Energy Services for Professionals (SODA) [82]; this was hourly data for the 2019 year. The classification criteria were selected based on the FEW system requirements. To identify the area covered by shades, a binary raster image that represents Shades was created to represent the shades based on the position of the Sun.

Pixel values range from 0, when shades completely cover the area, to 255, when there are no shades. Criteria or conditions used in the multiply criteria analysis are 1 ≤ Shading raster image ≤ 255: reclassify shading raster image where = suitable = 1, unsuitable = 0.68. On flat roofs, avoiding self-shading required calculations of the reduction coefficient for \( P \). The value equals 0.43. The annual electricity (kWh) = global annual irradiance in kWh/m²y for energy calculation *0.16* Area available for PVs*losses coefficient, PVSuitable = Reclassified shading raster x Areas losses due to tilt and azimuth.

Ibrahim et al. [83] developed a new Worldview-2 image’s built-up index using ENVI
software for the University Putra Malaysia campus in Malaysia. Researchers used particle swarm optimization to choose the most valuable bands from the Worldview-2 satellite image to extract buildings, and then these bands were used for creating the built-up index. It was found that the most relevant bands to extract built-up area are the yellow (band 4) and Near Infra-red 1 band (band 7). A normalized band ratio was developed using these two bands as follows: the spectral index $BSI = (\text{Yellow} - 2 \times \text{NIR1})/ (\text{Yellow} + 2 \times \text{NIR1})$. The overall accuracy of this index was (0.76). Since the validation was applied to the image used to create the index, it was recommended that future studies enhance the index and other optimization techniques.

2.3 Studies Conducted on the Mesoscale

Demonstrating renewable energy studies on more minor scales, such as the miso scale, requires using administrative and governmental data, such as cadastral data. For example, Beltran-Velamazan et al. [84] used GIS cadastral data to create a 3D model with available 2D data automatically and in neighborhoods and cities and investigate the model’s practicality in solar analysis by evaluating the results in comparison to a hand-built prototype. Data sources are available from the regular cadaster in Spain and the Spanish INSPIRE cadaster. They used the “3D_Model” algorithm and Auto LISP programming language, which make it possible to conduct solar analysis with other tools, such as Ecotect Analysis 2011, and to consider the effect of building shading. Rooftops were simplified by assuming that all roofs are flat, and the terrain model and tree shades were not considered in this study. It was demonstrated that the accuracy difference in assessing solar accessibility for pedestrian spaces and the hand-made model is 3.4 percent, and the accuracy difference between the automatic solar potential on rooftops and the hand-made model is 2.2 percent. The mechanical model was fifty times faster than the hand-made model for a neighborhood of 400 000-meter square. It was recommended to use this method for solar access evaluation in pedestrian spaces and rooftops’ solar potential where the effects of trees and the terrain are not significant and where the majority of roofs are flat in neighborhoods and city scales.
Adding new variables to the model can improve the results. For example, Assouline et al. [85] used SVM and GIS to calculate the solar PV potential for urban spaces at the smallest governmental division in Switzerland. They added new variables that were not used before. They added the available roof area and the technical capacity of roof PV electricity generation. To create the solar model, they used monthly global tilted solar radiation on tilted sites and the Hillshade function in ArcGIS to simulate the shade effects. Hillshade maps are derived from Digital Orthophoto [86]. The technical potential was estimated, and this includes the production of electricity from the rooftop solar based on this equation:

“The technical potential, that is, the PV electricity production, in each commune j, in GW h per year or kWh per month = geographical potential × average PV panel efficiency (%) × PR is the performance ratio.”

This study illustrated the considerable PV rooftop potential in Switzerland, and the results can be used for providing the future Switzerland grid. They recommended adding new variables in future studies for quantifying the potential rooftop PV energy, such as the future design of the grid, the changes in the grid’s capabilities and ability to get extra power, and the contribution of rooftop PV for deployment in the grid. Their results demonstrated that 81% of all buildings’ ground floor area could be used as the existing rooftop area for installing PVs.

Groppi et al. [5] Worked on urban cells in two urban cells in the Ladispoli municipality area. Urban cells are the minimum foundation of the larger city’s model. In this research, both urban cells had between 2000 and 6000 inhabitants and were designed based on defined land use, urban design, and building typology. They obtained solar data from the meteorological station of Torre Flavia [87]. They assumed that the overall PV nominal efficiency of 10%. They used a complete census for two cities that included cities’ roofs, slopes, the orientation of roofs, and the yearly expected solar radiation. They concluded that “Urban cells” can be used to assess the usable solar energy potential in various urban contexts. PV systems would save more energy than the solar thermal newly built
suburban district. PVs reduce the electricity demand in non-efficient houses. Solar thermal systems have more impact on improving the efficiency of thermal energy in houses than the one caused by PV systems in the electricity sector in the study area. Rooftops availability is the controlling parameter for historic buildings, which leads to the possibility of hosting solar thermal systems, not PV systems. Policies for energy efficiency on recent constructions are insufficient to decrease consuming energy of one urban cell; it is recommended that these policies contain the restoration of existing buildings to reduce a city’s energy consumption.

![Map 4. Building suitability to PVs integrated installation [5].](image)

2.4 Studies Conducted on the Meso Scale (Part of the City)

GIS-renewable energy research could be conducted on a region of the city. For example, Muhammed et al. [43] studied part of Madinati City in Egypt, where they Extracted buildings’ rooftops for (PVs) potential through two steps. First, the pre-processing step, which includes gamma correction, vegetation and shadow masking, k-means, one of many clustering algorithms as explained by Dahmane et al [92], and connected features, and an ML algorithm, or SVM, was applied on a satellite image to detect rooftops. Second, to evaluate the method, PVGIS, and Solar Analyst Software. The source of the image was google earth pro, and digitized buildings were used as samples to teach the algorithm. Building shadows were removed by creating the shadow index = (pixel value in the blue band - pixel value in the green) / (pixel value in the blue band + pixel value in the green). The SVM’s accuracy assessment was 95%, and the precision was 90%.
The number of detected roofs was 112 rooftops, with an area of 26 m². Using the suggested tool, they projected the yearly PV potential to be between 9.3 and 8.7 MWh/year. Muhammed et al. [43] suggested that using PVGIS updated solar database produced more accurate results and that Solar Analyst produced less accurate results because it depended on the 30 m resolution - digital elevation model. The title angle of PVs is 30 degrees, which is the latitude of the study area. Moreover, PVs should face true south to get the maximum annual solar energy generation. They deducted the area of the elevator room from the total area, but the room's shadows were not considered. The gross area was estimated to be 54000 m², and the estimated usable space is 26131 m², equaling 48.4% of the gross area. The yearly PV potential ranged between 9.3 to 8.8 MWh/year. The energy estimation was calculated using the Solar Analyst ArcGIS tool and PVGIS. The CO₂ percentage and energy were compensated by a yearly mean value of 48% for utilizing PVs instead of the old-fashioned energy sources.

Taherzadeh et al. [56] studied a part of Kuala Lumpur, and they aimed to identify the materials of rooftops, especially concrete tile using a WorldView-2 satellite image. They used the Object-Based approach to extract and integrate spatial, spectral, and texture information. This approach was used to remove any misclassification produced by spectral similarity and challenge the weakness of spectral data. They applied pansharpen and geometric correction before using the feature extraction module in ENVI software. They applied the edge method and merging in segmentation to convert the pixel classification to an object-based approach. As Hamedianfar et al demonstrated [88], the segmentation scale must be defined to decrease or eliminate any errors in classification. They used to scale and merge levels, which were chosen at 30 and 80, correspondingly, and they defined the rule used to extract the concrete roof from spectral, spatial, texture, and color information. Researchers extracted fourteen spatial and four spectral attributes and calculated four characteristics for all types of remaining info, such as color and texture. A standard confusion matrix evaluated the classification after collecting data to calculate the accuracy of the classification. After applying rule-based classification on Worldview-2 satellite image, the results demonstrated that it has good possibility to detect concrete roofs with accuracy equals to 85%.

Bachofen et al. [89] identified the building footprints using multispectral statistics and stereo-derived elevations of Pleiades tri-stereoscopic images in the City of Kigali. They created Digital Surface Model (DSM) and performed image analysis to get the basic geometries and useful variables used as inputs for ML classification, or SVM. The DSM assisted in discriminating between buildings and bare ground. The topographic position index was helpful in some areas but could not be valuable enough when the buildings were built on steep slopes. Roofs of rusty corrugated metal were challenging to be mapped since they have the same spectral properties of surrounded soil. Since both corrugated roofs and ground were adjacent, the segmentation was not entirely correct, and there were misclassifications. Dark asbestos roofs had the same spectral reflectance as vegetation. Authors recommended including a remote sensing sensor with a higher spectral resolution, like WorldView-3, which distinguishes better between roof materials.
Tian et al. [90] fused the height and spectral information of 2 intersecting WorldView-2 stereo-pairs of a part of Munich to extract rooftops. First, they generated the digital terrain model (DTM) and applied a step-edge approach to obtain the normalized Digital Surface Model (nDSM). Second, they derived the initial boundaries of the building and roofs. Third, they adapted and implemented the edge-based active contour model to get refined roofs. This approach exploited the 3-D information from stereoscope images to develop extract rooftops. This approach can get more accurate results since it uses the edge information from the panchromatic image.

Shaker et al. [6] assess a method that uses IKONOS stereo images to estimate the buildings’ elevation and accurate location in dense housing areas. The methodology was examined in 3 locations in a region covered by two overlapping IKONOS satellite images of around 97%. The method used Ground Control Points (GCPs) in rational function models to orient the images. Digital Surface Model (DSM), obtained from the two photos and its spectral properties, was used by a designed algorism to identify the buildings. Building heights were calculated using a digital terrain model and the DSM. Location accuracy and sizes of buildings were assessed using corner coordinates obtained from surveyed building elevations and maps. It was found that the mean percentage of building identifications for the samples was 82.6%. The horizontal accuracy or the Root Mean Square Error (RMSE) for the Northern =2.42 and RMSE for the easting = 2.39 m were achieved when the imagery rational polynomial coefficients were utilized to create the photo model. When GCPs were added to the model, the results enhanced to the sub-meter level. Changes between elevations of buildings were obtained from the image model, and their equivalent heights were acquired from civil surveying and had an RMSE of 1.05 m.

Bouroubi et al. [91] used a stereo pair of WorldView-3 to extract the roofs of buildings in I Da Nang City. The panchromatic band was added for the pan-sharpen processing. The stereo pairs were preprocessed geometrically. Later ML was applied to the pair to detect and extract rooftop, shadow, rooftop height, slope, and aspect. Dahmane et al. [92] adopted the DL method to classify roofs based on their shapes and inclined angle (ex: flat with 10 to 30 % obstacles, flat with ≥ 30% obstacles, and two-sided. Using Digital Surface Model, the sun’s position every month, and the time between sunrise and sunset, shades were calculated using a GIS. Samples of suitable roofs were used in the site survey for confirmation. The results demonstrate that there is a high potential for producing energy from PV when they are installed on roofs. The results can assist leaders in planning and creating solar energy. However, very high-resolution images- such as WorldView3- is costly to be used on a large-scale area, especially in developing countries.

2.5 Studies Conducted on a Macroscale (City)

Alhamwi et al. [93] Studied how planners can integrate GIS flexibilization (for example, storage in advocating greater autarky levels in cities) in urban areas and how this is applied in the acquisition and processing of energy in urban regions. Alhamwi et al. [93] used data from Oldenburg city and the locations of renewable generation from EnergyMap.info data which is available online. In addition, they assessed and analyzed
open-source GIS-based flexibilization. Their model is a GIS-based system for optimizing town flexibility options (FlexiGIS). Their model integrates energy planning on a spatial and temporal scale. The integration was done by coupling electricity’s microgeneration with suggested and future flexibilization options. They combined open data, GIS, and models to replicate urban energy systems. This GIS model assists stakeholders in understanding and demonstrating the relation between various geographic information like buildings, administrative units, and energy systems and temporal ones such as generating and consuming energy. Thus, GIS plays a vital role in promoting roof PV and applying energy flexibilization possibilities, for example, demand-side administration and storage. Understanding how to estimate solar energy produced by PVs using GIS is essential.

![Diagram of the model used by Alhamwi et al.]

Figure 5. The model used by Alhamwi et al. [93]

Jamali et al. [94] used R programming language and SVM and Random Forest (RF) to classify one Sentinel-1C Synthetic Aperture Radar (SAR) to obtain urban areas of Shiraz city in Iran. The preprocessing workflow was as follows: 1. reading the file, 2. Apply orbit file, 3. Calibration, 4. Speckle filter, and finally, ellipsoid correction. They compared eight variables to get the best combinations for extracting urban areas. It was found that SVM did better than RF, where the overall SMV accuracy was 91.76, and the overall RF accuracy was 88.83. The best performance for SVM was with VV, VH, (VV+VH).

Holobâcă, et al. [95] studied Cluj-Napoca, in Romania and Wroclaw, in Poland. They combined two polarized Sentinel-1 images, one from an ascendant and the other from a descendant orbit, to extract urban areas. They used sentinel-1 A and Sentinel 1 B from the ground range detected type in the C. The used bands were (VV and VH) in the wide interferometric mode. The preprocessing included applying radiometric correction,
range-Doppler Terrain correction, and Speckle Divergence. The classification was done using texture analysis, including spectral signature and separation threshold on four backscattering, primary texture bands, and 12 secondary bands. Then they compared the results with other studies, and it was concluded that the suggested method had the best overall accuracy among them, and it was equal to 95. In contrast, other studies achieved overall accuracy (88, 89, and 93). The main advantage is the clear separation between classes that usually have problems in radar and optical systems, for example, bare soil and urban surface.

The workflow of Wegezhangrtseder et al. [96] was based on five steps for assessing solar potential in Concepción. First, creating the solar profile, they used direct and diffuse radiation over hourly data for one day for each season. They got the weather data from a typical meteorological year database. Second, They used the Hillshade-GIS tool, URBES, and Cercasol software to calculate the percentage of radiation loss due to shades caused by topography and nearby buildings. They created a solar radiation map at an urban scale with hourly time and season-time resolution. Third, ArcGIS software was used to classify and identify the building typology using morphological conditions, floor area, height, density, and building area to map the distribution of residential typologies in the city. Fourth. They calculated the energy consumption pattern by creating a dynamic simulation of each typology for each representative day and determining consumption ranges (population density and level of socioeconomic status), and they used design builder software. The result of step 4 was a map of solar potential per residential unit with season-time resolution. Fifth, ArcGIS was used again to do the last step for the solar collector system. The total solar potential (3883 GWh) exceeds the city’s energy demand (3180 GWh).

Romero Rodríguez et al. [97] estimated the PV potential by using urban simulation to compute the potential of PVs in Ludwigsburg city in Germany. All buildings were simulated using CityGML [98], which contains more details than other 3D city models,
allowing the city model to adjust to building parameters. The study was applied on urban and regional scales. Researchers investigated technical and economic potential through two PV efficiency cases, including the area of rooftops and insolation thresholds. Identifying the electricity demand fraction that could be met in all municipalities was possible. In addition, it was feasible to calculate the investment’s profitability and select the optimal places. They assessed emissions and developed an economic analysis. SimStadt software was used to estimate the total available roof area [m2] and to determine the yearly insolation of PV units' surface [kW h/m2 year] [99]. SimStadt software has two radiation models, which are simplified radiosity algorithm, and INSEL model, which is depending on the Hay sky model for calculating diffuse irradiance.

The study applied the INSEL model without shades because of the significant number of studied buildings. The shades effect is considered through a reduction coefficient. The technical PV potentials are the result of multiplying: PV area, PV modules efficiency, losses for temperature and irradiance, incoming solar energy in PV modules surfaces, and performance ratio, which includes distribution losses due to dust, inverter efficiency, and losses due to orientation. The workflow of PV potential is as follows: importing the CityGML file into the city doctor model to create the SimStadt model, processing both the weather and building geometry to obtain the radiation model then applying the reduction coefficient to generate the PV potential. The results demonstrated the possibility of reaching high yearly electricity needs rates in many towns and getting more than 100% in more or fewer situations. Utilizing the whole rooftop area will cover 77% of the district’s electricity consumption and 56% as a financial possibility if only high-irradiance roofs are used. This method should help policy-making procedures and communicate the rewards of distributed generation and solar energy systems in buildings to managers, academics, and concerned citizens.

Map 7. A radiation map created by SimStadt to define optimal PV locations on a town scale [97]
Ayodele et al. [100] investigated the likelihood of satisfying the energy demands of Ibadan city in Nigeria by using the energy generated from PV installed on the rooftop. They aimed to calculate suitable rooftops for PV. Thus, they used ArcGIS, google earth, samples from the population, and the reduction factor in calculating the suitable area. They considered the roof’s orientation, shading, and other usages. They used daily mean horizontal global solar radiation info from 2008 to 2018, and they considered the visibility index $K_t$. Irradiation on tilted surfaces (HT) = HB + HD + HR, “where: HB is the daily beam solar radiation incidence on a tilted surface, Wm$^{-2}$; HD is the daily diffuse solar radiation incidence on a tilted surface, Wm$^{-2}$; and HR is the daily reflected solar radiation on a tilted surface, Wm$^{-2}$”. Roof print area (Ai) was obtained by digitizing the 24 wards samples, Area of roof per capita = Ai / present ward population i. The mean area of rooftops per capita for the research area is calculated as demonstrated in equation (2-1)

$$\frac{\sum_{i=1}^{24} A_{\text{roof/cap}(i)}}{N=24}$$

(2-1)

The whole area of a roof at any location in the study area = the mean rooftop area per capita for the study region* the population of any location within the study region. Fraction of correctly oriented rooftop = (T peaked* W peaked) + (T flat* W flat), where their values are from predefined surveys as Khan[101] and Mijinyawa [102] selected. Area for PV = Area roof * H shading* Oriented roof, H shading = 0.35 from Khan [101] and Wiginton [103]. Where H shading is the fraction for shading, W peaked is peaked roofs are used for many usages, peaked rooftops usually are lesser in height and are less exposed to shades. Orientation affects these roofs with 50% south-facing area (T peaked= 0.50). Buildings with flat roofs are not affected by house directions, T flat = 1, and W flat = 0.16. Ayodele, et al. [100] concluded that the total rooftop area in the town is 49.5 km$^2$, and the available area of roof PV is 7.54 km$^2$ with a max capacity of 1734.8 MWp, at a fixed tilt of 11. This setting generates 6.67 TW h per annum. Ayodele et al. [100] chose SW280 mono black c-Si as a PV unit. Preventing panels shades required this inter-panel specification, the tilt angle is 11 degrees, PV Width, pw= 1001 millimeters, the difference between heights, a = 191 millimeters, Horizontal gap, and b = 154 millimeter, and Pitch, d = 1137 millimeter.
Map 8. A map of all areas and available areas for rooftops, largest capacity for installation, and yearly energy generation likely for all governmental regions of Ibadan city.

Gómez-Navarro et al. [104] studied the likelihood of meeting the electric request of Valencia city with PVs- rooftops. Suitable types of buildings based on the demand and generating/consumption model. The potential energy generation for Valencia is projected to meet the demand for house electricity. Solar Radiation was downloaded from PVGIS [105]. Selected buildings did not have shades or obstacles to solar radiation. Cloudy days are modeled by Homer and include data from PVGIS statistics. The available area for computing the potential energy generation is a measured value multiplied by 0.5, and it considers other usages of the roofs or shades. The potential energy generated/m²/year (PEG) equals to mean value for Valencia city, at zero degrees panel * efficiency × factor for all the losses = 4960Wh/m²-day×0.15×0.8 = 592.2Wh/m²-day = 217.25kWh/m²-year.

The simulated PV systems are economically profitable for tall residential buildings. The single-family houses could sell their extra electricity production. That sale is most advantageous when it applies the market price (20.85 €/kWh). The roofs can produce up to 99% of the needed electricity by the housing division by PV power systems and 37% of the whole demand. There is a need for consumer schemes such as Net energy metering (NEM). Incorporating renewable distributed production systems in the grid has problems, such as synchronization and issues related to power quality. They
recommended a NEM program for consumers and developed a framework for energy supply projects (private ownership or partnership with the government). They created websites for the self-design of PV-Grid electric systems and virtual markets for prosumers with simulated power plants, where consumers and producers work together—in addition to supporting the adaptation of rooftops and initiating projects for prosumers.

Singh and Banerjee [106] used free high classified land-use and sample satellite images. They analyzed these images by GIS image analysis techniques and other models and simulations to calculate values of the Building Footprint Area (BFA) and PVs available Roof Area (PVA). Later, they compared the results with other published research results. To estimate rooftop areas, researchers obtained detailed categorized and sub-categorized land-use types from the municipal company of Greater Mumbai. The City area has been classified into 24 wards with complex land use analysis, and it contains land use types such as educational, commercial, residential, and other land use categories. For each land use, building footprint area (BFA) was calculated as BFA ratio = Area built/Area plot, where Area Built is the total area roofed by built-up structure and Area Plot is the plot area of the building. Researchers used Google Earth satellite images and GIS packages to calculate the BFA ratio to create data samples. On a city level, the BFA ratio (aggregate) = sum Area built/Sum Area plot. BFA ratio (aggregate) is required because The Existing Land Use (ELU) is used for various land use, but it did not demonstrate the percentage of the used area. The actual area for each building is estimated by taking samples of satellite images of limited buildings for each land use class and using GIS SW to map them. The data source is derived from the engine google earth and GeoEye’s GE-2 satellite, which has a resolution equal to 50 cm. It is georeferenced using Quantum GIS (QGIS) 1.8.0. Five control points were chosen for each image to ensure higher accuracy. QGIS’s function to measure the Area has been used for calculating and estimating the BFA Ratio, resulting in 0.05. After estimating the BFA, researchers estimated the total Footprint area under the land used subcategories of municipal wards of Mumbai, which are suitable for installing of PVs roofs. The following formula was used for this estimation:

$$BFA = \sum_{j=1}^{m} \sum_{i=1}^{n} A_{ij} \cdot b_{i}$$

(2-2)

Where the building footprint proportion of land use is represented by bi, the land use area in the district is described as Aij. In addition, building density was calculated as Db = BFA/total area, and population density for Mumbai was calculated as DP = No of inhabitants/Area in HA. The third step for calculating PV area is estimating BFA for spaces under the special planning authority (SPA). The researcher correlated the primary land use type of each of the SPA areas to that of at least one of the twenty-four municipal zones of Mumbai. Every SPA region is assigned a Db value illustrating its building density shape. The final step of estimating rooftop areas is analyzing BFA ratio results by aggregating BFA concerning land-use types. The PVA ratio was defined as PVA ratio = PV area/BFA. Researchers defined PVA Ratio because the total roof area cannot be used entirely to install PV systems. There is a decrease in suitable roofs area for PV
because of shades from other surrounding buildings, various uses of rooftop areas, and restrictions due to the unevenness of the roof area.

![Diagram of PVA, BFA, and Plot Area]

**Figure 6.** This figure demonstrates the correlation between PVA, BFA, and Plot Area.

The researchers summarized different PVA from different studies. For example, PVA = 0.4, according to the International Energy Agency [107], which is applicable everywhere on earth, and researchers applied this value to their research. Other researchers estimated that PVAs are measured locally for study areas [108], [109]. To design the optimum solution for the tilt angle, researchers used the Liu Jordan transposition model and data for climate design in 2009 to assess the plane-of-array insolation. Effective sunshine hours were done using micro-level simulations in PV Syst. The installed capacity, daily and yearly production profiles, and capacity factor were assessed for PVs with various rated solar modules' efficiency and power temperature coefficient. Results showed that Mumbai city has the potential of producing 2190 MW with median efficiency panel at a yearly mean capacity factor of 14.8%. PVs installed on roofs can produce between 12.8 to 20% of the mean daily demand and 31 to 60 of the monthly peak demand in the morning. Since the built-up structure is low-height and more horizontal across the country, there is a high potential for solar photovoltaic electricity based on the rooftops. Therefore, there is a need to develop a case study for estimating and quantifying the rooftops' potential to be used as a guide for large-scale deployment.

Mohajeri et al. [110] ranked rooftop forms depending on Geneva city's solar potential. They used free yearly mean solar radiation data. GIS data was the small resolution LiDAR point data created by SITG | Le territories generous à la carte [111]. They used GIS solar radiation tools and Matlab software to develop the solar potentials on roofs (levels of the building, district, and city) on various scales. They used SVM and GIS to develop and categorize Geneva buildings' roofs, relying on solar energy. They ranked shapes that receive solar energy in Geneva, and they used urban scale rooftops form and SVM to classify shapes of roofs. The classification correctly identified six forms of roof shapes in 66% of buildings: flat & shed, gambrel, gable, hip, and complex roofs.
The yearly average solar radiation (GWh/year) database was estimated using Cadaster Solaire Du Canton De Geneve [112] with mean efficiency (20%) and the 79% performance ratio for PV panels [111], and they used Shades co-efficient for direct and diffuse radiation from database developed by Desthieux [112]. They showed how the monthly and annual solar radiations as functions of the slope and aspect of the roof. They found a tilt angle within 30 or 40, an ideal rooftop slope for PV installation in Switzerland. Mohajeri et al. [110] concluded that solar roof-shape classification offers essential data for creating new constructions, modification on roofs, and efficient solar incorporation on the tops. Results demonstrated that the heights roofs to receive mean annual solar radiation are the flat & shed roofs (809 kWh/m²). This method may not be suitable for other places since the roofs' structure, and shapes are unique.

Map 9. Yearly mean solar radiation on roofs for these scales (a) a building, (b) a neighborhood, and (c) a city. [110]
2.6 Studies Conducted on Multiple Scales

Luca [113] used fractal dimension and geospatial metrics to assess how dynamic and interactive generative modeling could be used to simulate urban areas and different processes. The core of their system was built on micro-dynamics, which is the interaction between the local and the global actors. Researchers used databases on urban and regional scales. The electronic platform reads and correlates data obtained from various authorities. They worked in the city of Torino in Italy and focused on solving problems related to the relation among regional infrastructures and house clusters. They concluded that dynamic generative modeling is a powerful tool for planners, societies, and policy-makers. The complicated social systems could be affected by access to data. Thus, they recommended integrating urban and regional “knowledge” in the design and planning processes through interactive modeling.

To demonstrate all city planning scales and incorporating shades, Nguyen et al. [58] represented an interdisciplinary approach that combines GIS, remote sensing, and solar energy engineering on different urban scale types: macro, meso, and micro urban scales—integrated the Light Detection and Ranging technology (LiDAR) within simulations for solar irradiation on a large scale to detect the suitable roof facades for PV application, and calculated the shadows losses that these PVs could lose using Hillshade. They did the simulation during the summer because losses in the summer reduce the suitability of roofs for PVs. Therefore, analyzing shading hourly for the mean monthly days from May to August provides enough understanding of the development of the
shades on the rooftops. They used GHI resulting from r.sun, r. horizon to compute the hourly shadows, and used the SOLPOS calculator to calculate the sun's position and intensity. The ration \( r_{pv} = \frac{A_{pv}}{A_{projroof}} \) site = 0.30–0.33 was used to get the actual area and it was selected from Wiginton [103]. Where \( A_{projroof} \) = the projected roofs are used in the modeling, and \( A_{pv} \) = the actual area which is suitable for installing PV.

Zhou et al. [36] applied Object Oriented Classification on worldView-2 satellite images to map urban areas in Szekesfehervar, Hungar. They conducted segmentation on a multiply scale level, selected and extracted features, and used the rule set for process creation. They assessed the accuracy and classification of the results. They found that the overall accuracy of 9 classes was 79.4%. Achieving these results required orthorectification of the topographic map with a scale of 10000 and DEM with a scale of 50000.

In addition, the WorldView2 image was converted to the 8-bit unsigned image after resampling. They used the Fractal Net Evolution algorithm for segmentation in
eCognition. They used a segmentation method that uses the bottom-up zone growing method that starts with image objects in one pixel’s size which increases by merging nearby objects. Object integration relies on the mean heterogeneity of the building weighted by its size and stops when the designed criteria by the researcher are reached. Since the size of segmentation depends on the scale at which they are generated, objects with different sizes and varying homogeneity are produced when the scale parameter changes. Therefore, there is a hierarchy among other classes. They created a model for the land cover. The model has multiple scales to represent different levels of this structure, and the objects in the previous level of the [36] hierarchy are dependent on and nested into their parent object in the last level. Based on trial and error analysis, Zhou et al. [36] created two level object layers according to the size of patches of the land cover classes. The object layer for level 1 has a weight of 1 for eight bands; the scale parameter is 30, the color is 0.9, and the compactness is 0.5. This level is suitable for extracting buildings, roads, trees, shadows, and grass according to the object's size. The level 2 object layer was derived from the previous layer by merging objects in the level 1 object layer by changing the scale to 350, and this change allowed the researchers to extract forest, crops, arable land, and water-based on the object size. They analyzed spectral mean curve based on samples to use the spectral features in worldview-2, and they created normalized difference indices, including the normalized Difference Bare Soil index (NDBSI), Normalized Difference Water Index NDWI, Normalized difference index vegetation index (NDVI), Forest and crop Index, Normalized difference brick roof index NDBRI. To select features used Feature Space Optimization (FSO) tool to for distinguishing between different classes, FSO indicates the separation distances that a user can use to spread between different objects.

Map 15. land cover Classification result [36]

Valdiviezo-N [114] studied several urban area indices for sentinel-2 satellite images. He compared built-up indices using the Spectral Discrimination Index (SDI) while focusing on
soil and urban areas using sentinel-2 satellite images. SDI is the difference between the mean values of two classes separated by the sum of their standard deviation as shown by Valdiviezo-N [114]. It was found that these built-up indices achieve the highest SDI: Band Ratio for Built-up Area BRBA (1.47), and Normalized Built-up Area Index NBAI (1.26), Biophysical Composition Index BCI (1.2) have the highest SDI to differentiate between soil and built-up zones. It is concluded that the resolution, seasonality, and location quickly impact built-up indices. Many indices cannot distinguish between surfaces of urban areas, bare soil, and barren land cover.

2.7. Studies Conducted on Large-Scale (Territories)

Estimating PVs’ potential in central and eastern Europe was possible by applying the r.sun model to terrain data [117]. R.sun model uses all relevant parameters to enable calculations for significant areas with mixed terrain. The overcast radiation was calculated from clear-sky data and a clear-sky index. The map of the clear-sky index was calculated by applying a multivariate interpolation, and terrain effects were considered by including interpolation parameters. Terrain data improved the spatial pattern of the model output and decreased the model’s error for estimating radiation. After comparing the results with the European solar radiation atlas dataset, it is found that a combination of the r.sun model and the GIS interpolation Software can be helpful for higher resolution info and regions that do not have ground measurements.

Izquierdo et al. [54] assessed the technical potential of PV-roof in Spain. The method uses available data representing the uses of the urban area and population and building densities on urban areas’ samples. The technique was hierarchal, consisting of the physical potential or the solar energy received in the study area and the geographical potential, excluding the regions that do not get the solar area. In addition, the techniques included the technical potential, including the technical characteristics such as the PV’s performance and the equipment used to transform the solar energy into electrical energy. The sampling process is based on applying specific building typologies representing all the study area’s urban areas. The physical and geographical potential is an indicator for the maximum energy limits, which is evaluated like horizontal irradiation, and computed using fixed processes[118]: (a) monthly extraterrestrial radiation is calculated depending on the geometry of the sun–earth system; (b) a monthly clearness index is calculated for hourly meteorological values obtained from metrological stations; (c) maps for monthly irradiation are developed by ordinary Kriging on a 200m×200m grid of the clearness indexes (d) hourly shades impact on monthly values are calculated geometrically with a digital terrain model.

Clerici et al. [123] used sentinel-1 data for Colombia’s lower Magdalena region. They performed pre-processing data of level-1 Single Look Complex (SLC) image using the SNAP sentinel application toolbox. They performed calibration, thermal noise removal, Terrain Observation with Progressive Scans SAR de-burst or TopSAR de-burst, mosaicking, and resampling data to 10 *10 m² spatial resolution. In addition, they executed multitask parameterization for VV & VH polarization images. They used an advanced Lee-low-pass filter to compensate for Speckle effects, characteristic of radar
affecting the radiometric information. Moreover, they developed Ground Range Detention (GRD) from (SLC) level 1 image. Atmospheric and Terrain correction of Sentinel-2A top of atmosphere level 1C image were performed using ESA SEN2COR software to create a level-2A BOA reflectance image. All used bands from Sentinel-1 and Sentinel-2 were resampled to achieve a resolution of 10 m, and Terrain correction was applied for all images using the DEM of 30m. All maps were projected to the required projection. Researchers performed texture calculation of bands (VV&VH, variance, and contrast images) for Sentinel-1, and vegetation indices were calculated for Sentinel-2. Resulted from, maps were combined in the layer stacking to perform segmentation, classification, and accuracy assessment. It was found that the overall accuracy was 88.75%, and for built-up areas, it was 100% in the user accuracy category. The benefits of this method are the speed and reliability of pre-processing. The integration between Sentinel-1 and sentinel-2 produces very satisfactory accuracy results for all the Land Change Land Use or (LCLU) classes with spatial resolution equals to 20 m [35], [119], [120].

Semenzato et al. [121] applied the semiautomatic method to extract urban footprint from Sentinel-1 data IW Level-1 SLC products for Veneto Region in Italy. They used supervised and unsupervised classification and multitemporal analysis of interferometric coherence. The overall accuracy was between 85% and 90%. Halder [34] extracted impervious regions using multiple normalized indices and regression modeling from the Sentinel-2A dataset of Delhi, and they achieved overall accuracy equals to 87%. They used numerous normalized indices to obtain better classification results. They computed the Normalized Difference Vegetation Index (NDVI), a standardized vegetation index, and the Normalized Difference Water Index (NDWI), which captures water features. The Normalized Difference Soil Index (NDSI) distinguishes the minor line between built-up and bare soil in an urban area. The Normalized Difference Built-up Index (NDBI) gives the best result illustrating the density in built mass. Stacked multiple normalized images produced better classification results in compression to the typical band.

Adeniyi et al. [122] studied Pretoria, Gauteng Province, South Africa. They tested the Built-up Extraction Index (NBEI) for enhancing manufactured structures' mapping materials regardless of the type or material. The index was developed from the red edge, green, Near Infra-Red 1 (NIR1), and Near Infra-Red 2 (NIR2) bands, which greatly clarify the variation in built-up areas on WorldView-2 (WV-2) image. The developed index, NBEI = [(NIR2 +NIR1) – (green + red edge)]/ [(NIR2 +NIR1) + (green + red edge)]. The result demonstrated that NBEI enhances the extraction of built-up areas with high accuracy equal to 0.82 compared to the other built-up area indexes, where accuracy equals 0.73. The performance of NBEI is not material-specific and could be used in other study areas. [122] According to Adeniyi et al. [122], built-up indices for high-resolution images are specific. They may not be accurate because they are designed for specific man-made materials in the urban landscape. An impervious material is defined by its age, color, and thickness.

Neupane et al. [123] analyzed solar energy’s spatial & financial potential at the sub-
national level in Nepal. The method is based on spatial energy modeling, including mechanical, geographical & economic suitability criteria. Estimating the potential of solar energy required using SolarGIS [124]. The solar resource map has a resolution of 250m and contains global horizontal irradiance (GHI). The suitable locations should receive GHI greater than 4.1 kWh/ (m²·day). The installed capacity of solar PV systems equals the surface area * efficiency of land-use (or 30 MW/km²)* land-use discount factor. The discount factor of land-use is part of the land that would not be used in the actual plant. The land-use discount factor could be zero or 75 % discount factor. Neupane et al. [123] considered shades by using a PV availability ratio (PVar) of 0.4 based on data created by the international agency for energy database [107]. PV systems' performance and efficiency rely on the tilt angle and direction in which it is faced, and the tilt angle must be equal to the location's latitude [125].

Neupane et al. [123] applied these criteria. The suitable sites for built-up areas were selected from areas with an average GHI equal to or greater than 4.1 kWh/ (m²·day). Since the grid size equals 30 m x 30 m, researchers used built-up areas where the surface area equals to or is more than 900 m². Installed Capacity of PV system =the total built-up areas in km²×mean power density of the roofs PVs, which was assumed to be 150 W/m²× the rooftop available factor (0.507) × building footprint area ratio (0.5) [106] × the PV availability ratio MW (0.4) [107]. About 47,628 MW of solar energy could be harnessed in Nepal. Karnali and Gandaki regions have the most significant solar energy potential because of the enormous suitable locations with excellent resource quality. It is projected that the 10th percentile of the Levelized cost of electricity production of 91 USD/MWh for solar energy.

Mishra et al. [126] used RS and GIS to study the potential of solar energy on roofs in Uttarakhand state India. The hierarchical physical, geographic, and potential technical framework were applied. They applied statistical clustering to compute the areas of roofs in thirteen districts. Roofs on hills receive higher solar insolation than those in plain areas. Installed PVs on a hill’s horizontal roofs could solve its irregular topography. Based on the state’s geographic location, the slopes’ north sides are shaded, and their southern side is tilted toward the sun, allowing more solar radiation exposure. According to Mahatta et al., Gastli and Charabi [128], the The efficiency of the PVs module is calculated from equation (2-3)

\[
E = (G) \cdot r \cdot PR \cdot TH
\]

Where E = Energy (kWh), r = solar panel efficiency (range between 15 and 18% default value used = 15%) [129], [130]

Mishra et al. [126] approximated used area equals 25% of the available space, the calculated average solar radiation = 5.6 kWh/m²/day = 0.233 kWh/m²/h, data used are mean monthly sunshine hours, solar panel efficiency = 15%, temperature and irradiance losses = 10%, performance ratio = 75%. It was found that the potential of solar energy in the hill region was 9.1 GWh from Janto Mar, 12.7 GWh from Apr to June, 12.4 GWh from July to Sept, and 7.7 GWh from Oct to Dec. If all available rooftops with high solar
radiation are used, it provided around 57% of the state electricity consumption.

### 2.8 Studies conducted on a global scale

Joshi et al. [131] created a high-resolution worldwide measurement of roof-PVs utilizing big data, ML, and spatial analysis. They divided the land into a Fishnet Grid (FN) covering 3,521,120 unique 10 km², where each FN has an id and is attributed to one country. Roof Solar photovoltaics potential assessment requires datasets of houses footprints, solar insolation mapping, and PV information such as panel size, system losses, and conversion efficiency, which can obtain from the global PV power potential by Country [132]. Researchers assumed general assuming to keep the calculations uniform. It is assumed that the estimated footprints represent the available roof area; in other words, the whole estimated whole roof area is suitable for installing PVs. The PS’s slope is assumed to represent the optimum angle for each latitude. PVs face the sun without shadows to create maximum electricity production. Roofs are flat, and their design leads to the total usage of the rooftop for PV installation. The technical solar potential is computed for global FNs for a year as the following:

Technical solar potential equals the calculated area for the roof in m² * conversion factor for a month for FN cell * number of days in a month/365

Joshi et al. [131] used the area of the global land surface (130 million km²) to calculate the rooftop area (0.2 million km²). It was found that this area can generate 27 PWh yr⁻¹ of electricity, and it may cost between 40–280 $ MWh⁻¹. It was found that: 10 PWh yr⁻¹ can be achieved with less than 100 $ MWh⁻¹. In addition, the global potential is as follows Asia (47%), North America (20%), and Europe (13%). The lowest cost of achieving India’s PV solar potential (66 $ MWh⁻¹) and China (68 $ MWh⁻¹), and the USA (238 $ MWh⁻¹). Limitations of the methods are due to the accuracy of maps which is 100 m, which could overestimate the built-up area, and there is misclassification in different classes, including build-up areas, streets, and parks. The study’s assumption concerning the roofs, their areas, and having no shades added more limitations to the study.
Chapter 3 Geographic Information Sciences, Remote Sensing, and Processed Maps

The purpose of this chapter is to present an introduction to the geospatial sciences for readers who do not have a scientific background in geospatial sciences. This chapter consists of two parts. The first is a review of Geographic Information Sciences (GIS) and Remote Sensing (RS) data, definitions, concepts, and tools employed in this study. The second part of this chapter introduces the application of GIS and RS for New Cairo City on a city scale using sentinel-1 and sentinel-2 satellite images and selected compounds extracted from the Pleadeas-1B satellite image. Moreover, the second part includes a scientific explanation of the workflow used in the research methods. Only the image analysis results and their overall accuracy are presented here, and the estimated area is presented in Chapter 5.

Geographic Information Sciences (GIS) was used in many cities’ urban studies and solar energy. GIS is designed to capture, store, analyze, and manage spatial or non-spatial data [133], [134]. In addition, GIS is an organized set of structured data stored in a computer system called a database, managed by a database management system (DBMS) [135]. The database consists of tables with columns and rows containing data types such as numbers and strings. The National Renewable Energy Laboratory (NREL) [136] is an excellent example of a tabular database with helpful information for professionals working in the discipline of renewable energy [137]. The critical difference between databases and GIS is that GIS can analyze non-spatial and spatial data using the earth as a model [134]. For example: Finding the best location for electric vehicle charge stations requires non-spatial data, such as data about people who may have Electric Vehicles (EVs), their socio-economic data, and population density. This non-spatial data could be combined with spatial data such as the geographic location of available land areas that could be used for charging EVs, their characteristics (size, cost, and land topography), and roads (length and finishing materials).
Figure 7. The framework of the renewable energy system, adapted from [138], [139].

Planners use GIS to analyze digital urban models (height, shape, and orientation) at different levels and create 2D and 3D/4D images for buildings as demonstrated by Luca [113]. Therefore, GIS was used for renewable energy modeling, such as selecting the best location for wind and solar farms or evaluating biomass availability for energy generation [140], [141]. In addition, GIS was used for saving, managing, examining, and predicting extensive databases for both temporal-spatial and non-spatial data. For example, The German Aerospace Center (DLR)[142] published a study about suitable areas for Concentrated Solar Plants (CSP) in which they used GIS and various planning criteria to create a regional concept about solar resources and land availability in the Mediterranean area. Working with GIS requires understanding the different types of GIS data.
3.1 Spatial Database

There are two approaches to getting GIS data. The first approach is downloading data that can be used immediately from the internet (online spatial database), some databases are up-to-date [144], and others are not updated. Most online databases demonstrate solar resources, and few provide GIS data about streets and buildings [145]. European CORINE databases provides GIS data about urban areas, which includes shape, space, and orientation [146]. The second method is downloading and processing remote sensing data before using them in the project.

3.1.1 Online Spatial Databases

A. NASA’s prediction of worldwide energy resources is an online spatial database that
provides data extracted from remote sensings such as solar and climate data. This data is used for the energy efficiency of buildings and renewable energy estimation. The database includes functional parameters for previous usages on different time scales for the whole globe from 1981 to 2020 [144]

B. The International Renewable Energy Agency (IRENA) provides statistics that are required for evaluating and monitoring the policies and deployment of renewable energy policies on the country's scale. It also provides financial data for public investment and country per area. The database provides yearly information about installed electricity capacity (MW), Technology, and connection to the grid. [147]

C. Google used Artificial Intelligence (AI) and remote sensing to estimate areas of buildings in Africa, and these databases only provide (x, y coordinates) and places in m², but they do not contain any GIS files. The data can be downloaded using Africa’s Buildings Database [148]

D. Open streets mapping is an open source for street download, and it is based on volunteering activities [145]

E. European Organization for the Exploitation of Meteorological Satellites (EUMESAT) delivers data produced by Copernicus Information Services for Climate and Marine (CISCM) purposes. It derives its data from the Sentinel-3 satellite, which monitors the ocean and other international space missions such as the Jason-3 satellite [149]

F. Coordination of information on the environment’s land cover database provides 44 classes for land cover. It uses 25 ha as the minimum mapping unit for areal features and a minim of 100m for linear features. The database is produced from satellite images, GIS data, and national in-situ data [146]
3.1.2 Data from Remote Sensing Data

Many remote-sensing images have different spatial and temporal scales and different bandwidths. Sentinel-1 and sentinel-2 have a medium spatial scale which ranges between 10m and 20m, while WorldView-2 and Pleadeas-1 B have higher spatial resolutions up to a few meters. These different satellite images have their limits, for example, when two landcover classes overlap, such as soil and urban areas or shadows and water ponds. Results may be affected due to the topography or geography of the study location.

3.2 GIS Approaches for PV Energy Estimation

According to Kawamura and Muta [7], there are four approaches for PV energy estimation that uses GIS. They are machine learning, modeling (2D and 3D GIS models), geostatistical, and sampling. Each approach has pros and cons regarding performance and applicability in computing and evaluating the PV systems’ potential on rooftops. The sampling approach uses extrapolation to determine the roofs’ PV energy potential at many urban scales. The geostatistical procedure executes spatial analyses and predicts
the distribution of solar radiation [5]. GIS and 3D models are used to compute the PV energy and received solar energy. It simulates the effect of shadows and trees on the rooftop. Support Vector Machines (SVMs), decision trees, and linear regression statistics are integrated with GIS to detect and assess the PV systems and solar radiation on roofs.

3.2.1 GIS and Machine Learning

Artificial intelligence (AI) is used in GIS and RS and contains Machine Learning (ML) and Deep Learning (DL). ML is the latest technology in GIS, including supervised and unsupervised classification and reinforcement learning [151]. The GIS-ML can gain knowledge through repetitive observed conditions and builds a model that could be used in new situations. Algorithms of DL and ML are used to detect and classify objects, pixels, and cloud points [152]. DL is a subfield of machine learning, and it is based on the concept of artificial neural networks, an algorithm designed as one of the brain’s structures and functions [153]. DL was used to manage energy-related problems at mega-city scales [152]. In addition, the GIS platform can be incorporated with data-driven methods, such as multivariate clustering, image segmentation, Random Forests (RFs), multiple regression, and artificial neural networks. GIS-ML could be used to support energy policy on different scales. Based on the methods, approaches, and GIS data, results can be duplicated in some areas and conditions, but the results cannot be duplicated in other regions and on different scales.

3.2.2 GIS and Three-Dimensional Models

City planners can work with PV components, solar energy estimation, and 3D models on different city scale levels. The three-dimensional modeling approach uses the correct values for rooftop features, and then GIS identifies the suitable areas. GIS can calculate the roofs' slope, azimuth, shape, and footprint area [5].

A Digital Surface Model (DSM) describes the elevation above sea level of the ground and all objects or structures on it [154], and it is developed from georeferenced gridded surface elevation raster data [155]. This data includes: (1) a Digital Height Model (DHM), which shows the elevation of the upper surface of the land above a vertical datum representing the tops of trees and buildings, (2) a Digital Terrain Model (DTM), which only displays the elevation of the ground surface above a vertical datum [155], or it describes the ground elevation above sea level [154], (3) a Normalized Digital Surface Model (NDSM), which shows the calculated elevation of objects above the normalized terrain and is developed by subtracting DTM heights from DHM heights [155].
DSMs of urban areas are vital for city planning because they can be used to quantify solar insolation for PVs, air quality analyses, and 3D visualization, enhancing the mapping of the urban area [154].

DSMs could be created using: (1) optical data by matching stereo image pairs or shadow analysis of objects on the surface to estimate height, (2) Light detection and ranging (LiDAR) by generating accurate DSMs from pulsed lasers, which measure the distance to structures by time-of-flight, (3) Synthetic Aperture Radar (SAR) [154].

Aerial photos offer a perspective view, which has a changing scale and distortion
unsuitable for GIS applications. This happens because the distance between the viewpoint and objects changes. An orthographic view is a view after distortion, which fits the photo into a DSM and projects it on a horizontal reference datum, as shown in Figure 9 [155].

![Figure 9. Aerial photos and orthophotos][155]

Stereoscopic images are created from two photos of the exact location taken from different angles. The best DEMs are created from stereoscopic imagery collected by WorldView-1, WorldView-2, and WorldView-3 satellite images, as shown in Figure 10 [157].

![Figure 10. The sensor collects two images of the exact location by adjusting its camera][157]

### 3.2.3 GIS and Sampling Techniques

Other GIS methods use the sampling approach, which relies on calculating the variables and selected samples and using suitable methods to extrapolate the variables for the whole region [5]. The sampling process depends on a set of average building typologies used in the stratification process, representing all urban areas in the study region. The
methodology is characterized by its scalability and potential to be utilized on regional and continental scales. Researchers can obtain consistent estimates of variables and lower the computational requirements. The sampling approach has been used in significant regional areas to calculate the available roof area. There are three sampling techniques: simple, multivariate sampling, and complete census approaches. The simple sampling estimates the available area of rooftops in a specific area and extrapolates this data to the study area. The multivariate approach calculates the relationship between the available space of rooftops and the density. The complete census method calculates the whole roof area in the study region by utilizing existing statistical info for the building data [5].

3.2.4 Geostatistics

Geostatistics is a branch of statistics used to study and forecast the values linked to spatial to describe spatial shapes and interpolate values for places where samples were not taken. Geostatistics tools can measure uncertainty for missing values [158]. Geostatistics methods include statistical clustering, convolution kernel, Fuzzy membership, clustering methods, and spatial statistics [5].

Geostatistical procedures to estimate the PV energy generation of roofs use the total received solar energy from Sun. Thus, these methods provide precise probabilistic results that consider diffuse radiation on tilted roofs, the distribution map of solar radiation on the roof, and energy potentials. However, Geostatic methods require heavy calculations, especially for the large-scale study area. These methods cannot be used successfully to identify the roof characteristics, such as calculating the available roof areas, classifying roof types, and determining the effects of shading factors and the roof slope [5].
<table>
<thead>
<tr>
<th>Method</th>
<th>Benefit</th>
<th>Weakness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geostatistics-based</td>
<td>Results are probabilistic</td>
<td>Not easy to identify many features</td>
</tr>
<tr>
<td></td>
<td>Clear examples of the whole study area</td>
<td>Intensive Computation</td>
</tr>
<tr>
<td></td>
<td>It is possible to establish a good theory</td>
<td>Not scalable</td>
</tr>
<tr>
<td>Sampling-based</td>
<td>Built on actual data and extrapolation</td>
<td>Reasonable extrapolation is not guaranteed.</td>
</tr>
<tr>
<td></td>
<td>Scalable and not expensive</td>
<td>Performance varies</td>
</tr>
<tr>
<td></td>
<td>Probabilistic results</td>
<td></td>
</tr>
<tr>
<td>Modeling-based</td>
<td>Accuracy is good</td>
<td>Time-consuming</td>
</tr>
<tr>
<td></td>
<td>Precise details</td>
<td>Demanding computation</td>
</tr>
<tr>
<td></td>
<td>The opportunity for automation in many areas</td>
<td>Hard to scale up</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Know-how is needed</td>
</tr>
<tr>
<td>ML- base</td>
<td>High performance and precise results</td>
<td>Works with only big data</td>
</tr>
<tr>
<td></td>
<td>It can take many feature types as input</td>
<td>some models can be hard to be trained</td>
</tr>
<tr>
<td></td>
<td>Adaptable and flexible</td>
<td>It needs experience</td>
</tr>
<tr>
<td></td>
<td>Easily scalable</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vector and raster data</td>
<td></td>
</tr>
</tbody>
</table>
Table 2. Inapplicability (N) and Applicability (Y) of GIS methods for assessing significant structures of roof-PV potential. Adopted from Gasser Gasser et al. [5].

<table>
<thead>
<tr>
<th>Method</th>
<th>Mapping of solar radiation</th>
<th>Tilted radiation</th>
<th>Area availability</th>
<th>Shades</th>
<th>Aspect and slope</th>
<th>Types of roofs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geostatistics-based</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Sampling-based</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Modeling-based</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Machine learning-based</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>
3.3 LiDAR Data and Urban Mapping

This data type is used to build high-resolution ground elevation with an accuracy of ten cm. An airplane carries Lidar apparatus, a Global Positioning System (GPS), an Inertial Navigation System (INS), and a laser scanner. The laser scanner spreads pulses of light to Earth. The travel time of the reflected or scattered pulses is used to compute the space between the scanner & Earth. LiDAR is collected as a “point cloud” of separated points reflected from all landscape elements, including buildings and green areas. LiDAR data is an example of data that can produce very accurate results, but it is a very complex and expensive technology. Raster data types can be used to improve results from extracting rooftops.

Map 19. (A) Different perspectives for LiDAR data which represents a city [159]

Map 20. (B) Different perspectives for LiDAR data which represents a city [159]
3.4 Remote Sensing

Remote Sensing (RS) is obtaining information from a long distance. Satellites are used to observe Earth and planets via remote sensors that sense and save reflected or emitted energy. Remote sensors illustrate collective understanding and rich data about Earth systems, allowing decision-makers to decide based on the most advanced technology [161]. There are different orientation types for a sensor, which results in various kinds of images, such as Nadir image and oblique images.

Figure 11. Specific spectral wavelengths of the electromagnetic spectrum and their properties and applications
3.4.1 Nadir Images

A Nadir image is an image that was taken while the camera is positioned perpendicular to the scene.

3.4.2 Oblique Images

It is an image that was taken at an angle other than a Nadir angle, and it could be taken before the satellite reaches the target, and it is called a forward image, or it could be taken after the satellite left the location and it is called backward image.

Satellite images are classified based on the spatial resolution into three categories:

- Low resolution: sixty meters per pixel
- Medium resolution: ten to thirty meters per pixel
- High to very high resolution: thirty cm to 500 cm per pixel.

The spatial resolution is the pixel size on the ground. A pixel is the tiniest 'dot' that builds up satellite imagery and defines how complete a picture is [165]. Low-resolution image has 60m per pixel, and medium-resolution images have between 10m to 30m per pixel. It is not possible to differentiate between tiny details in using these resolutions. However, they cover more extensive areas of the earth. Sentinel is considered a low- and medium-resolution imagery. Several applications use low and medium-resolution images, for example, agriculture, urban development, construction, disaster mitigation, and managing water resources. It is possible to detect more details using high-resolution photos. High-resolution images can calculate the number of trees in a field and precise agriculture. In addition, they can be used to conserve forests by identifying endangered species and diagnosing diseases that affect trees [166].

3.4.3 Sensors

Sensors on satellites utilize the sun as a source of lighting or their lighting source,
collecting reflected energy from Earth. Sensors that use sun’s energy are named passive sensors, and those that send their energy source are called active sensors. Active sensors have varieties of radio detection and ranging radar sensors. Active sensors function in the electromagnetic spectrum's microwave band, enabling them to pierce the atmosphere under all atmospheric circumstances. Active sensors assess the vertical profiles of aerosols, winds, forest structures, and precipitation [33]. Passive sensors have devices that can sense, measure, and investigate the reflected electromagnetic radiation from the earth. Passive systems work in the electromagnetic spectrum's visible, infrared, thermal, and microwave portions. Passive systems measure the land surface’s temperature, vegetation, and clouds’ properties. These systems have limitations because they cannot pierce dense cloud cover.[33]. An example of an active sensor is the Sentinel-1 satellite [167], and an example of a passive sensor is the Sentinel-2 sensor [168], [169]

![Passive Sensors and Active Sensors](image)

**Figure 15.** Passive and active sensors. [33]

### 3.5 Sentinel-1

Sentinel-1 or Synthetic Aperture Radar (SAR) is an active sensor that functions in the electromagnetic spectrum's microwave band. SAR can penetrate the atmosphere in most circumstances. [33]. There are any satellites use SAR, such as Sentinel-1 and India Risat-1 [170]. Radar remote sensing can be used in almost all weather conditions, day or night, it can penetrate through the soil, and the atmosphere has little impact on it. Radar remote sensing is sensitive to the water dielectric properties, it can sense liquid and frozen water, and it is sensitive to the structure. However, SAR is difficult to interpret, topography affects SAR and its images have graininess [171].

According to the European Satellite Agency [172], sentinel-1 and its product type acquisition modes are designed to serve specific applications, as shown in Table 3. Typical application modes for each application [172]. There are four modes for SAR[173]. The first mode is the Stripmap mode (SM)[174], the second mode is the Extra Wide Swath (SW), the third mode is the wave mode (WV)[175], and the fourth mode is the (IWS) mode [176].

![Diagram of different SAR modes](image)
Table 3. Typical application modes for each application [172]

<table>
<thead>
<tr>
<th>Application</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SM</td>
</tr>
<tr>
<td>Arctic and sea-ice</td>
<td>X</td>
</tr>
<tr>
<td>Open ocean ship surveillance</td>
<td>X</td>
</tr>
<tr>
<td>Oil pollution monitoring</td>
<td>X</td>
</tr>
<tr>
<td>Marine winds</td>
<td>X</td>
</tr>
<tr>
<td>Forestry</td>
<td>X</td>
</tr>
<tr>
<td>Agriculture</td>
<td>X</td>
</tr>
<tr>
<td>Urban deformation mapping</td>
<td>X</td>
</tr>
<tr>
<td>Flood monitoring</td>
<td>X</td>
</tr>
<tr>
<td>Earthquake analysis</td>
<td>X</td>
</tr>
<tr>
<td>Landslide and volcano monitoring</td>
<td>X</td>
</tr>
</tbody>
</table>

3.6 Application of GIS and RS to New Cairo City

This section introduces Sentinel-1 and Sentinel-2 Satellite images and their processing workflow.

3.6.1 Sentinel-1 or SAR Data Processing

SAR processing aims to rebuild the scene from the different pulses echoed by all targets, reached by the antenna, and recorded in memory [177]. SAR processing demands much computation [177]. In order to understand SAR processing, its workflow is introduced in Figure 16. The detailed SAR data pre-processing steps produced by the European Space Agency [178], [179] were used in the workflow of Figure 16, and satellite images resulted from the processes are included.

3.6.2 Workflow of Sentinel-1 and Sentinel-2 Workflow

The fusion of Sentinel-1 and Sentinel-2 is illustrated in Figure 16, followed by explaining each step for non-GIS specialists. Firstly, RS techniques were applied on a sentinel-1 satellite image for the region of the New Cairo city. Secondly, RS techniques were applied to Sentinel-2 satellite image. Finally, the results of processed Sentinel 1 and Sentinel-2 are combined or fused on a stack. The slack is used in supervised classification to classify the bands of New Cairo into buildings and non-buildings categories. The detailed processing for Sentinel-1 and sentinel-2 are adopted from Clerici [35], and Valdiviezo-N [114]

The processing of Sentinel-1 was created using SNAP software, which is an open
software developed by the European Space Agency. The processing includes satellite image subset in Section Subset, apply Orbit file in Section Apply Orbit File, thermal noise removal in Section Thermal Noise Removal Calibration in Section 3.6.2.4., Sentinel-1 TOPSAR deburst in Section Sentinel-1 TOPSAR Deburst, resampling 10m x 10m in Section Resampling 10 m x 10 m Speckle filtering in Section Speckle Filtering Multi-look parametrization in Section Multi-look Parametrization and Radiometric correction in Section Radiometric Correction, and projecting to Egypt’s projection. Finally, the processing includes creating Vertical-Vertical (VV) and Vertical-Horizontal (VH) components and textural calculations, as shown in Section Texture Calculations).

The Sentinel-2 outputs from the preprocessing are band 2 to band 8a, band 11, band12 and developed built-up indices, as shown in Section Built-up Indices. Bands of Sentinel-2 were resampled and corrected for the atmosphere and terrain, as shown in Section Atmospheric Correction and Section Terrain Correction. In addition, they were re-projected to the Egyptian projection. Later, the built-up indices were created using the band calculator in SNAP software. The whole process is shown in Figure 16.

![Figure 16. Work-Flow for Sentinel-1 and Sentinel-2 adopted from Clerici[35], and Valdiviezo-N [114]](image-url)
3.6.2.1 Subset

The subset is the process of subtracting the study area from the satellite imagery scene to save time and space on the computer memory.

![Map 1A, 7B. Satellite image before and after subsetting. [180].](image)

Map 1A, 7B. Satellite image before and after subsetting. [180].

Map 22. Sentinel-1 Satellite Image of the study location after applying subletting tool.

3.6.2.2 Apply Orbit File

SAR’s orbit files are not precise and can be corrected by using the precise orbit files after the satellite image download. The orbit file has the accurate location of the satellite and its velocity and is used to update the sentinel-1 file. [181]

![Map 23. Sentinel-1 Satellite Image of the study area after applying orbit file.](image)

Map 23. Sentinel-1 Satellite Image of the study area after applying orbit file.

3.6.2.3 Thermal Noise Removal

According to ESRI company [182], the Sentinel-1 Level-1 image has a noise look-up table (LUT) file for all measurement databases. The de-noise LUT has values represented in linear power and is utilized to originate calibrated noise profiles identical to the calibrated original data. Bilinear interpolation is used for pixels included in the LUT [182] [183].
3.6.2.4 Calibration

SAR calibration aims to produce an image in which the pixel values can be directly associated with the radar backscatter of the sight [183]. Calibration is the process that is used to convert pixel values to radiometrically calibrated SAR backscatter. The required information is stored as a calibration vector incorporated as an annotation in Sentinel 1 image, which converts image intensity values into sigma-naught values[179].

Map 24. Sentinel-1 Satellite image calibration for New Cairo City and the area around it.

3.6.2.5 Sentinel-1 TOPSAR Deburst

According to the European Space Agency [181], the IW product contains an image per swath per polarization. IW images have three swaths, and each sub-swath photo consists of a sequence of bursts, where each burst is processed as a separate image. Images for all bursts in all sub-swaths of an IW image are re-sampled to a mutual pixel spacing grid in range and azimuth.

Map 25. Sentinel-1 Satellite mage debuts for New Cairo City and the area around it.

3.6.2.6 Resampling 10 m* 10 m

According to Gurjar et al [184], resampling is an image processing technique that changes the image’s resolution or orientation

3.6.2.7 Speckle Filtering

SAR images have noise that appears as “salt and pepper,” called a speckle. This noise results from interference many scattering echoes within one cell [185]. Speckle grants SAR images a grainy appearance with random spatial variations.[186], and it is a general phenomenon in SAR [187]. The speckle decreases the reparability of the various land use classes; therefore, it is vital to remove the speckle to advance the possibility of land use classes’ separation with minimal loss of information. [188], [189]. Speckle filters decrease the total of speckles at the cost of blurred elements or reduced resolution [190]. Examples of speckle filtering types are: refined Lee filter low-pass filter with 5*5 Kernel that
Averages the photos while maintaining feature edges [35], [191]

3.6.2.8 Multi-look Parametrization

Smoothing out the speckle could be achieved by averaging independent measurements of the same target. This procedure could be done by splitting the SAR into lesser sub-apertures; they are named "looks," and each is processed and averaged. The various looks are averaged to decrease the grey-level random variations provoked by speckles [188].

3.6.2.9 Terrain Correction, or Radiometric Terrain Flattening (RTF)

"RTF uses a Digital Elevation Model (DEM) to delete geometry-dependent radiometric distortions; normalizes measured backscatter for terrain slope."[179]

Map 26. Sentinel-1 Satellite Image after applying Multilooking

3.6.2.10 Radiometric Correction

It is required to perform radiometric correction to SAR because the pixel values characterize the radar backscatter of the reflecting plane. Radiometric correction is needed to compare SAR images and images obtained from other sensors or the same
sensor at various times, in different modes, or processed by multiple processors [183], [183, p. 1].

Map 27. Sentinel-1 Satellite mage radiometric correction
3.6.2.11 Texture Calculations

The texture is the spatial variation of brightness in a satellite image at a specific scale, and it is used to differentiate between objects in a satellite image [192]. Texture statistics gives colors or concentrations for an image [193], and calculating them is helpful in image classification [194]. Texture statistics are entropy, energy, contrast, homogeneity, correlation, average, and variance [195].

Contrast image measures the neighborhood variations represented in a satellite image. When there is a significant quantity of variation, the contrast is high [193], and the proceeding maps are the Vertical- Horizontal (VH) contrast map, as shown in Map 29.

Map 29. Satellite image illustrating Vertical Horizontal Contrast. Another map is produces, which is the Vertical-Vertical (VV) contrast map, as shown in Map 30. Satellite image illustrating Vertical-Vertical Contrast. The variance is the amount of the spreading of the gray-level changes at a known distance, and the processed map is the Vertical-Vertical (VV) variance, and it is shown as Map 31. Satellite Image illustrating Vertical Vertical variance [193].
Map 29. Satellite image illustrating Vertical Horizontal Contrast

Map 30. Satellite image illustrating Vertical-Vertical Contrast
3.7 Optical Remote Sensing

Optical RS is a passive procedure for observing the earth that depends on solar light [196] and measures energy reflected from Earth[33]. A raster image pixel contains multiple values at a precise wavelength interval of the electromagnetic spectrum with a specific intensity [197].
3.7.1 Sentinel 2 images

Sentinel-2 is a high-resolution satellite, and it has an optical apparatus that models 13 spectral bands: 4 bands at 10m, six bands at 20m, and three bands at 60m spatial resolution.[199]

The goals of Sentinel-2 images are obtaining high-resolution, multispectral images with high revisit occurrence for Earth and observing and recording new data for maps of land-cover land-change and geophysical elements. In addition, Sentinel-2 images are used for studies related to climate change and emergency management. [200]
Table 4. Comparison of SENTINEL-2 with important heritage missions [201]

<table>
<thead>
<tr>
<th>Mission Lifetime</th>
<th>LANDSAT 1-7</th>
<th>SPOT</th>
<th>SENTINEL-2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1972 - present</td>
<td>1986 - present</td>
<td>See Copernicus pages</td>
</tr>
<tr>
<td>Instrument principle</td>
<td>Scanner</td>
<td>Pushbroom</td>
<td>Pushbroom</td>
</tr>
<tr>
<td>Repeat cycle (days)</td>
<td>16</td>
<td>26</td>
<td>5*</td>
</tr>
<tr>
<td>Swath width (km)</td>
<td>185</td>
<td>2 x 60</td>
<td>290</td>
</tr>
<tr>
<td>Spectral bands</td>
<td>7</td>
<td>4</td>
<td>13</td>
</tr>
<tr>
<td>Spatial resolution (metres)</td>
<td>30, 60</td>
<td>2.5, 10, 20</td>
<td>10, 20, 60</td>
</tr>
</tbody>
</table>

Figure 18. Sentinel-2 images contain 13 spectral bands.

These thirteen bands have three spatial resolutions (ten, twenty, and sixty meters pixel size) extending from the visible (VIS) part to the Short-Wave Infrared (SWIR) part of the electromagnetic spectrum[180]
Table 5. Sentinel-2 bands, their central wavelength, and resolution [202]

<table>
<thead>
<tr>
<th>Sentinel-2 Bands</th>
<th>Central Wavelength (μm)</th>
<th>Resolution (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band 1 - Coastal aerosol</td>
<td>0.443</td>
<td>60</td>
</tr>
<tr>
<td>Band 2 - Blue</td>
<td>0.490</td>
<td>10</td>
</tr>
<tr>
<td>Band 3 - Green</td>
<td>0.560</td>
<td>10</td>
</tr>
<tr>
<td>Band 4 - Red</td>
<td>0.665</td>
<td>10</td>
</tr>
<tr>
<td>Band 5 - Vegetation Red Edge</td>
<td>0.705</td>
<td>20</td>
</tr>
<tr>
<td>Band 6 - Vegetation Red Edge</td>
<td>0.740</td>
<td>20</td>
</tr>
<tr>
<td>Band 7 - Vegetation Red Edge</td>
<td>0.783</td>
<td>20</td>
</tr>
<tr>
<td>Band 8 - NIR</td>
<td>0.842</td>
<td>10</td>
</tr>
<tr>
<td>Band 8A - Vegetation Red Edge</td>
<td>0.865</td>
<td>20</td>
</tr>
<tr>
<td>Band 9 - Water vapour</td>
<td>0.945</td>
<td>60</td>
</tr>
<tr>
<td>Band 10 - SWIR - Cirrus</td>
<td>1.375</td>
<td>60</td>
</tr>
<tr>
<td>Band 11 - SWIR</td>
<td>1.610</td>
<td>20</td>
</tr>
<tr>
<td>Band 12 - SWIR</td>
<td>2.190</td>
<td>20</td>
</tr>
</tbody>
</table>

3.7.2 Atmospheric Correction

Atmospheric correction is a process that converts the top-of-atmosphere radiance to surface reflectance [203].

3.7.3 Terrain Correction

Topographic correction is essential in pre-processing images and is performed to remove any topographic effects. The satellite image's topographic effect is varied illumination produced by viewing angle, terrain slope, and solar incidence [204].

3.7.4 Re-projection

Re-projection is transferring the projection of an image to another projection [205].

3.7.5 Indices

Extracting land covers from a satellite image requires environmental indices for each land cover type. For example, Normalized Difference Vegetation Index (NDVI) had been developed to detect the greenness of plants [206], and the Normalized Difference Water Index (NDWI) had been developed to obtain water properties [207]. Although there are built up indices to extract built-up areas, it is still challenging to discriminate between bare land and built-up areas due to their similarity of spectral response patterns [208], [209].
3.7.6 Built-up Indices for Sentinel-2

Remote sensing Index-based methods use spectral bands to exact land cover types and resample their highest and lowest reflectance values among a multispectral database [210]. The spectral index uses bands that resemble the green, red, near-infrared (NIR), and short-wavelength infrared (SWIR) [114]. Built-up indices are spectral indices that are used to map urban areas. Spectral indices are used in modeling surface developments. Indices are obtained from different combinations of spectral bands [211]. An online database defines spectral indices from different satellite images for applications such as agriculture and urban mapping [212].

In this research, BRBA is calculated from equation (3-1), NBAI is calculated from equation (3-2) and these equations are explained in Valdiviezo-N [114], and Waqer et al [115]. In addition, BCI is calculated from equation (3-3) and this is demonstrated in Valdiviezo-N [114], and Deng and Wu [116]

\[
BRBA = \frac{B_{\text{red}}}{B_{\text{SWIR}} - B_{\text{SWIR2}}} \\
NBAI = \frac{B_{\text{green}}}{B_{\text{SWIR2}} + B_{\text{SWIR}}} + \frac{B_{\text{SWIR2}}}{B_{\text{green}}} \\
BCI = \left( \frac{TC_{1} + TC_{3}}{2} \right)^2 \left( \frac{TC_{1} + TC_{3} + TC_{2}}{2 + 2TC_{2}} \right) \]

\( B_{\text{red}} \) is the red band, \( B_{\text{green}} \) is the green band, \( B_{\text{SWIR}} \) is the band short-wave infrared, and \( B_{\text{SWIR2}} \) is the short-wave infrared2. Tasseled Cap (TC) transform compresses spectral information from multiple rounds into fewer space scenes, illustrating spectral characteristics of different land cover [114]

According to IDB database [213], TC1 is Brightness, TC2 is Greenness, and TC3 is Wetness.

According to to IDB database [214], the wetness TC3 =

\[
0.1509*B2 + 0.1973*B3 + 0.3279*B4 + 0.3406*B8 - 0.7112*B11 - 0.4572*B12 \quad (3-4)
\]

According to to IDB database [215], the brightness formula TC1 =

\[
0.3037*B2 + 0.2793*B3 + 0.4743*B4 + 0.5585*B8 + 0.5082*B10 + 0.1863*B12 \quad (3-5)
\]

The greenness formula TC2 =

\[
-0.283*B3 - 0.660*B4 + 0.577*B6 + 0.388*B9 \quad (3-6)
\]

B2 is Band 2, B3 is band 3, B4 is Band 4, B8 is band 8, B11 is band 11, and B12 is band 12.

, as shown in Table.1.
Map 32. An image illustrating BRBA built-up index for New Cairo

Map 33. An image illustrating NBAI built-up index for New Cairo.
3.7.7 Classification

Mapping urban areas require classifying the satellite image. The advantages of classifying high-resolution images for urban areas' purposes include their availability, improved land use of impervious surfaces, and obtaining high spatial resolution maps up to a few meters [39]. However, the challenges of classifying urban features include: firstly, one land use class has an increased spectral variation as Yang and He [216] demonstrated in their research. Secondly, land-use types have reduced spectral reparability [217], and thirdly, shadow obscuring land-use features, especially in high-density areas or with tall buildings as demonstrated by Myeong et al. [218]. In addition, the urban landscape is developed constantly, allowing a new mix of artificial, such as asphalt and concrete, and natural features, such as grass and soil, to mix in unexpected arrangements as shown by Sande et al [219] in their research. The classification of the pixel-based techniques for urban areas gets complicated when the landscape is rich with different features. The complex landscape shapes of urban complicate the usage of the pixel-based classification method as shown by Mesev [220]. There are different approaches to categorizing land use, such as using fine-resolution images as shown by Lu et al. [221], aerial orthoimage as demonstrated by Mhangara and Odindi [222], and LiDAR data as shown by Yan [217]. The inclusion of LiDAR data solves challenges related to using high-resolution multispectral images, such as shades [217]

3.7.7.1 Unsupervised Classification

According to Jensen [223], the GIS software analyzes the image automatically without
adding or editing sample classes. The computer decides which pixels belong to a class or numbered classes based on specific techniques. The user can choose which algorithm to use and the number of output classes. Later, the GIS software label classes with numbered categories based on the software’s spatial intelligence.

### 3.7.7.2 Supervised Classification

According to Jensen [223], users can select and identify sample pixels in an image representing different classes, such as urban areas, streets, green areas, and bare land. The user defines these training samples and associated categories to the image processing software for classifying all pixels in the image. Models are selected based on the user’s knowledge of the studied area. Support Vector Machine (SMV) and Random Tree (RT) are examples of algorithms used in supervised classification.

In this research, supervised classification is applied to the maps resulting from the fusion of Sentinel-1 and Sentinel-2, as shown in Figure 1. Random Trees (RT) algorithm was applied to a set of images that consists of different bands of sentinel-2, The images are included in Appendix 1. In addition, the dataset includes a Vertical-Horizontal Contrast image, as shown in Map 29. Satellite image illustrating Vertical Horizontal Contrast a Vertical-Vertical Contrast image, as shown in Map 30. Satellite image illustrating Vertical-Vertical Contrast, Vertical- Vertical variance image, as shown in Map 31. Satellite Image illustrating Vertical Vertical variance and BRBA built-up index for New Cairo, as shown in Map 32. An image illustrating BRBA built-up index for New Cairo Moreover, it includes NBAI built-up index for New Cairo (and BCI built-up index for New Cairo), as shown in Map 33 and Map 34.

Training the RT algorithm required vector layers and samples of soil, green areas, urban areas, and streets, as shown in Appendix 2. The model was run several times until the highest % prediction accuracy was achieved. Different results are included in Appendix 3. The highest prediction accuracy was 67.95%, and the most critical variables by top rankings were BRBA, BCI, NBAI, Vertical-Vertical Variance, Vertical-Horizontal Variance, Vertical-Vertical Contrast, Vertical-Horizontal contract, and Band 12, as shown in Table 6. Since the highest prediction accuracy was 67.95%, which is not good enough for PVs planning. The city planning scale was not included for further analysis.
The total area of New Cairo city is 142 km². The total area of the urban region is 49 km², and it has 67.9% correct predictions. Yellow is the urban area, and brown are other landscape elements.

**3.7.7.3 Classification Accuracy Report**

The classification module in SNAP software produces a report with the overall accuracy of the map, as shown in Table 6. The report contains the number and names of classes (buildings, soil, streets, and green), the percentage of corrected prediction, total samples used in the classification, the Root Mean Square Error (RSME), bias in sampling, the distribution of classes among the sample, and the top-ranked features (bands) that contributed the most in classifying the image. Since the Random Forest module was tested several times, the highest percentage of correct prediction is included in table 6 and the other results for the same classifiers are included in Appendix 3 Overall accuracy for different parameters in the RT model.
Table 6. Accuracy report for Random forest classification, which produced 67.95% overall accuracy

Cross Validation

Number of classes = 4

<table>
<thead>
<tr>
<th>class 0.0: Buildings</th>
<th>accuracy = 0.8350 precision = 0.6459 correlation = 0.6510 errorRate = 0.1650</th>
</tr>
</thead>
<tbody>
<tr>
<td>TruePositives = 1881.0000 FalsePositives = 1031.0000 TrueNegatives = 6469.0000 FalseNegatives = 619.0000</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>class 1.0: Soil</th>
<th>accuracy = 0.8872 precision = 0.7480 correlation = 0.7419 errorRate = 0.1128</th>
</tr>
</thead>
<tbody>
<tr>
<td>TruePositives = 2064.0000 FalsePositives = 692.0000 TrueNegatives = 6008.0000 FalseNegatives = 436.0000</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>class 2.0: Streets</th>
<th>accuracy = 0.7935 precision = 0.5956 correlation = 0.5892 errorRate = 0.2065</th>
</tr>
</thead>
<tbody>
<tr>
<td>TruePositives = 1355.0000 FalsePositives = 920.0000 TrueNegatives = 6580.0000 FalseNegatives = 1145.0000</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Class 3.0: Green</th>
<th>accuracy = 0.8433 precision = 0.7268 correlation = 0.7268 errorRate = 0.1567</th>
</tr>
</thead>
<tbody>
<tr>
<td>TruePositives = 1405.0000 FalsePositives = 562.0000 TrueNegatives = 6938.0000 FalseNegatives = 1805.0000</td>
<td></td>
</tr>
</tbody>
</table>

Using Testing dataset, % correct predictions = 67.9500

Total samples = 20000

RMSE = 1.058560275882641

Bias = -0.1523000000000001

Distribution:

<table>
<thead>
<tr>
<th>class 0.0: ClassificationBuildings</th>
<th>5000 (25.00000%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>class 1.0: Classificationsoil</td>
<td>5000 (25.00000%)</td>
</tr>
<tr>
<td>class 2.0: Classificationstreets</td>
<td>5000 (25.00000%)</td>
</tr>
<tr>
<td>class 3.0: Classificationgreen</td>
<td>5000 (25.00000%)</td>
</tr>
</tbody>
</table>

Testing feature importance score:

Each feature is perturbed 3 times and the % correct predictions are averaged

The importance score is the original % correct prediction - averaged score

<table>
<thead>
<tr>
<th>rank</th>
<th>feature</th>
<th>score</th>
<th>accuracy</th>
<th>precision</th>
<th>correlation</th>
<th>errorRate</th>
<th>cost</th>
<th>GainRatio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>feature 2</td>
<td>0.0456</td>
<td>0.2284</td>
<td>0.0.4097</td>
<td>0.4356</td>
<td>0.2284</td>
<td>-0.3262</td>
<td>0.1425</td>
</tr>
<tr>
<td>2</td>
<td>feature 4</td>
<td>0.0.3728</td>
<td>0.1864</td>
<td>0.3551</td>
<td>0.3617</td>
<td>0.1864</td>
<td>-0.7759</td>
<td>0.1304</td>
</tr>
<tr>
<td>3</td>
<td>feature 3</td>
<td>0.0.2220</td>
<td>0.1145</td>
<td>0.2226</td>
<td>0.2493</td>
<td>0.1145</td>
<td>-0.3516</td>
<td>0.1065</td>
</tr>
<tr>
<td>4</td>
<td>feature 8</td>
<td>0.0.2118</td>
<td>0.1055</td>
<td>0.2027</td>
<td>0.2365</td>
<td>0.1055</td>
<td>-0.3050</td>
<td>0.0177</td>
</tr>
<tr>
<td>5</td>
<td>feature 6</td>
<td>0.0.1965</td>
<td>0.0903</td>
<td>0.1539</td>
<td>0.1899</td>
<td>0.0903</td>
<td>-0.2458</td>
<td>0.0140</td>
</tr>
<tr>
<td>6</td>
<td>feature 7</td>
<td>0.0.1811</td>
<td>0.0006</td>
<td>0.1759</td>
<td>0.2021</td>
<td>0.0006</td>
<td>-0.2600</td>
<td>0.0094</td>
</tr>
<tr>
<td>7</td>
<td>feature 5</td>
<td>0.0.0453</td>
<td>0.0227</td>
<td>0.0450</td>
<td>0.0551</td>
<td>0.0227</td>
<td>-0.0444</td>
<td>0.0113</td>
</tr>
<tr>
<td>8</td>
<td>feature 1</td>
<td>0.0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
</tbody>
</table>
3.7.8 Pléiades-1B

According to the website of harrisgeospatial [224], Pléiades-1B is a commercial sub-meter resolution satellite, and it was launched in 2011. Its characteristics are shown in Table 7.

Table 7. Pléiades-1B Satellite Sensor Characteristics [225]

<table>
<thead>
<tr>
<th>Products</th>
<th>• Panchromatic: 50cm • Multispectral: 2m • Colour: 50cm (merge) • Bundle: 50cm panchromatic; 2m multispectral</th>
</tr>
</thead>
<tbody>
<tr>
<td>Revisit rate</td>
<td>• Daily (constellation)</td>
</tr>
<tr>
<td>Swath width</td>
<td>• 20km</td>
</tr>
<tr>
<td>Tasking</td>
<td>• Work plan updated every 8 hours</td>
</tr>
<tr>
<td>Processing levels</td>
<td>• Primary (1A), Ortho (automatic), or Tailored Ortho</td>
</tr>
</tbody>
</table>

3.7.9 Segmentation

According to Hossain [226], segmenting an image is vital in Object-Based Image Analysis (OBIA), and it impacts the results from feature extraction and classification workflows [226]. Segmentation has been utilized in satellite image managing since the beginning of the Landsat-1. Since operating the high-resolution IKONOS, analyzing images analysis changed from pixel-based to object-based. Therefore, the goal of segmentation is object identification rather than pixel labeling. The main challenge in segmenting an image is to select the best fit of factors and algorithms which create image objects corresponding to the equivalent geographic feature. According to Lucchese and Mitra [227], the aim of segmentation is to separate an image into a set of disjointed zones that are different according to certain characteristics such as size, color texture, shape, and gray level. Image segmentation identifies areas based on their properties, such as texture, color, and smoothness. Segmentation is a set of sub-processes that build, change, grow, unite, cut, or shrink objects as demonstrated by Baatz et al. [228]. Examples of segmentation methods are region growing and edge detection. The Full lambda schedule (FLS) algorithm also uses spatial and spectral information to segment an image as demonstrated by Robinson et al. [229]. The algorithm uses each pixel as an isolated or independent region. Then, neighboring elements are fused based on combining the spectral and spatial information as shown by Liu et al. [230]. Varies weights can be given to spectral and spatial items to segment an image. The segmentation’s accuracy increases when researchers use spectral and textural properties as shown by Ryherd and Woodcock [231].

3.7.10 Image Extraction

High-resolution satellite images of built-up regions have noises, such as shades which decrease the accuracy of elements extraction [247]. Roofs are visible in high-resolution photos, and they are used to identify and extract rooftops using “feature extraction” techniques as shown by Xiang et al [234]. According to Jayasekare [232] and Angiati et al [233], different subclasses can be identified writing one class. For example, identifying...
different types of roofs materials or identifying specific properties for buildings, such as spatial and textural variations, which are used in determining the building’s boundaries.

### 3.7.11 Root Mean Square Error (RMSE)

According to Franczyk [235], “Root Mean Squared (RMS) Error equals the difference between the chosen output GCP coordinate (reference) & the actual output coordinate (source) for the same point after transformation.”

\[
\text{RMS error} = \sqrt{(x_r - x_i)^2 + (y_r - y_i)^2}
\]

(3-7)

Where:
- \(x_i\) and \(y_i\) are the input source coordinates
- \(x_r\) and \(y_r\) are the retransformed coordinates

### 3.7.12 Accuracy Statistics

After classifying the image, accuracy statistics are created and include overall accuracy, overall kappa statistics, user’s accuracy, and producer’s accuracy, as shown in Table 8. Producer’s Accuracy is the accuracy from the map maker’s viewpoint. This refers to features omitted from their classes in the classified map. The User’s Accuracy is the map’s accuracy from the user’s viewpoint. This accuracy tells how often the class on the map was present on the site. Kappa statistics assess the classification’s accuracy and how well the classification is achieved when compared to random value [236].

### 3.8 Workflow for Feature Extraction Using OBIA

#### 3.8.1 Compound-1

A feature extraction tool was used to extract rooftops in compound 1 [237] from Pleadeas-1B satellite image, and the segmentation process was applied to the compound where the scale = 60, the shape = 0.5, and the compactness = 0.5, as shown in Map. 36, later, different attributes were calculated. Since the material of the spectral reflectance of rooftops was different from the material of other surroundings, it was easy to use the feature extraction tool, which is based on OBIA. It was found that the maximum value of the Pure Pixel in the blue band could be used to extract the rooftops, as shown in Map. 37. According to Sharifahmadian [238], pure pixel includes a single surface material, and the condition that allowed extracting the rooftops is shown in equation (3-8)

\[
2904.95 \leq \text{Max}_{PP_{Blue}} \geq 2270.69
\]

(3-8)

Where Max_PP_Blue is the maximum value for the pure pixel of the blue band.
Map 36. Segmentation parameters: Scale = 60, Shape = 0.5, compactness = 0.5

Map 37 Maxim Pure Pixel Blue, Yellow areas are rooftops buildings after extraction.
Condition $2904.95 \leq Max_{PP_{Blue}} \geq 2270.69$

3.8.2 Compound-2

Since the material of additional rooms on the roofs of compound-2 has different spectral reflectance than other materials of the landscape elements, it was possible using a feature extraction tool [237], and the maximum value of the green band was used to extract these roofs, as shown in Map. 38.
Using ruled-based extraction to extract rooms, the extraction equation is (3-9):

\[ 5024.2 \leq MaxGreen \geq 3417.96 \]  

(3-9)

Where MaxGreen is the maximum value of the green band.

Map 38. The map illustrates rooms (beige color) on the rooftops, where \( 5024.2 \leq MaxGreen \geq 3417.96 \).

In addition to extracting additional rooftops by max value for the green band through a feature extraction tool, it was also possible to extract the whole rooftops of buildings using texture attributes, as shown in Map.39. According to Doma and Amer [239], an Image’s texture could be defined as a recurring pattern of its local variants that is very small to be recognized as single items at the studied resolution. Therefore, a linked group of pixels fulfilling a certain gray-level property that frequently happens in an image’s area represents a textured region. The roofs are mostly extracted using equation (3-10):

\[ 13.54 \leq TexStdNIR \geq 5.5 \]  

(3-10)

Where TexStdNIR is the texture standard deviation of the Near Infra-Red Band.
Other compounds have many similar finishing materials, which did not make it easier to extract rooftops using feature extraction tools. This is because of the overlap of spectral reflectance. Therefore, supervised classification was used, and SVM and RT algorithms were applied for Compound-3 to compound-6. After comparing the overall accuracy of SVM and RT for each compound, it was found that SVM achieved better accuracy than RT, Appendix 4 demonstrates the comparison between RT and SVM accuracy for different compounds.

3.9.1 Compound-3

Compound 3 had rooftops with two different finishing materials, which appeared brown and beige. In addition, the compound had green areas, streets, shades, and ground areas or bare areas, as shown in Map. 40., and the overall accuracy achieved up to 96.87%, as shown in Table 8.
Map 40. Final map for compound 3

Table 8. Accuracy statistics for compound-3.

<table>
<thead>
<tr>
<th>Class</th>
<th>Producer's 95% Confidence Interval</th>
<th>User's 95% Confidence Interval</th>
<th>Kappa Statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>shades</td>
<td>[100.000% (97.059% 100.000%)]</td>
<td>[94.444% (81.085% 100.000%)]</td>
<td>0.9243</td>
</tr>
<tr>
<td>street</td>
<td>[84.615% (61.156% 100.000%)]</td>
<td>[100.000% (95.155% 100.000%)]</td>
<td>1.0000</td>
</tr>
<tr>
<td>Green</td>
<td>[100.000% (93.750% 100.000%)]</td>
<td>[100.000% (93.750% 100.000%)]</td>
<td>1.0000</td>
</tr>
<tr>
<td>ground</td>
<td>[100.000% (97.222% 100.000%)]</td>
<td>[94.797% (82.065% 100.000%)]</td>
<td>0.9260</td>
</tr>
<tr>
<td>roof 2</td>
<td>[100.000% (91.667% 100.000%)]</td>
<td>[100.000% (91.667% 100.000%)]</td>
<td>1.0000</td>
</tr>
<tr>
<td>Roof1</td>
<td>[100.000% (75.000% 100.000%)]</td>
<td>[100.000% (75.000% 100.000%)]</td>
<td>1.0000</td>
</tr>
</tbody>
</table>

Quantity Disagreement: 3.125%  Allocation Disagreement: 0.000%
3.9.2 Compound-4

Compund-4 was classified as roof type 1, roof type 2, shades, trees, pedestrians, vegetation, and water, as shown in Map 41. The overall accuracy = 74.6\%, as shown in Table.9

Map 41. Final map for compound 4
Table 9. SVM accuracy assessment for compound 4

<table>
<thead>
<tr>
<th>Class</th>
<th>Producer's 95% Confidence Interval</th>
<th>User's 95% Confidence Interval</th>
<th>Kappa Statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>roof</td>
<td>85.71% (52.64% 100.00%)</td>
<td>75.00% (38.74% 100.00%)</td>
<td>0.7188</td>
</tr>
<tr>
<td>vegetation</td>
<td>75.00% (46.33% 100.00%)</td>
<td>69.23% (40.29% 98.16%)</td>
<td>0.6199</td>
</tr>
<tr>
<td>roof</td>
<td>83.33% (58.08% 100.00%)</td>
<td>90.00% (69.37% 100.00%)</td>
<td>0.8877</td>
</tr>
<tr>
<td>streets</td>
<td>80.00% (34.93% 100.00%)</td>
<td>50.00% (9.10% 89.8%)</td>
<td>0.4569</td>
</tr>
<tr>
<td>pedestrians</td>
<td>16.66% (0.00% 54.32%)</td>
<td>100.00% (50.00% 100.00%)</td>
<td>1.0000</td>
</tr>
<tr>
<td>shades</td>
<td>88.89% (62.60% 100.00%)</td>
<td>80.00% (50.20% 100.00%)</td>
<td>0.7667</td>
</tr>
<tr>
<td>trees</td>
<td>81.81% (54.45% 100.00%)</td>
<td>75.00% (46.33% 100.00%)</td>
<td>0.6971</td>
</tr>
<tr>
<td>water</td>
<td>0.00% (0.00% 0.00%)</td>
<td>0.00% (0.00% 0.00%)</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

Quantity Disagreement: 11.11% Allocation Disagreement: 14.28%

3.9.3 Compound-5

In compound 5, the roofs are not finished, and their spectral reflection is similar to the unfinished areas and streets around them. In addition, the side façade is visible, and it has the same finishing materials, which may decrease the accuracy of extracting rooftops. Map 42 shows the extracted roofs in beige, and its accuracy is 83.3%, as shown in Table 10.
Map 42. Final map for compound 5

Table 10. Accuracy assessment for compound 5 using SVM

<table>
<thead>
<tr>
<th>Class</th>
<th>Producer's 95% Confidence</th>
<th>User's 95% Confidence</th>
<th>Kappa Statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Streets</td>
<td>100.000% (75.000% 100.000%)</td>
<td>100.000% (75.000% 100.000%)</td>
<td>1.0000</td>
</tr>
<tr>
<td>Ground</td>
<td>100.000% (75.000% 100.000%)</td>
<td>100.000% (75.000% 100.000%)</td>
<td>1.0000</td>
</tr>
<tr>
<td>Buildings</td>
<td>100.000% (50.000% 100.000%)</td>
<td>100.000% (50.000% 100.000%)</td>
<td>1.0000</td>
</tr>
<tr>
<td>Shades</td>
<td>0.000% (0.000% 0.000%)</td>
<td>0.000% (0.000% 0.000%)</td>
<td>0.0000</td>
</tr>
<tr>
<td>Room</td>
<td>0.000% (0.000% 0.000%)</td>
<td>0.000% (0.000% 0.000%)</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

Quantity Disagreement: 16.567% Allocation Disagreement: 0.000%
3.9.4 Compound-6

Compound-6 had many finishing materials for its rooftops, and some materials are classified as the ground. Roofs are brown, beige, and yellow, gardens are green, and streets are black, as shown in Map 43. The overall accuracy of SVM is 82.76%, as shown in Table 2.

Map 43. Classification map for compound 6
Calculating available areas for PV installation require GIS data with higher accuracy. Thus roofs of the six compounds are digitized and included in table 12. Shadow analysis should be conducted to get suitable areas for PVs, and designing criteria should be included for each compound. Since shadow analysis is time-consuming, one shadow for one compound is analyzed in Chapter 5.

Table 12 Table illustrates available areas for PVs installation for each compound

<table>
<thead>
<tr>
<th>Compound number</th>
<th>Area in m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10090</td>
</tr>
<tr>
<td>2</td>
<td>25331</td>
</tr>
<tr>
<td>3</td>
<td>56832</td>
</tr>
<tr>
<td>4</td>
<td>19041.6</td>
</tr>
<tr>
<td>5</td>
<td>4191.2</td>
</tr>
<tr>
<td>6</td>
<td>27367</td>
</tr>
</tbody>
</table>
Chapter 4 Solar Radiation Conversion

This chapter is concerned with the presentation of the solar radiation models, measurements, equipment characteristics, and calculating procedures employed to estimate the electricity generated from the home rooftops. The measurements are performed using a weather station at the American University in Cairo, Egypt, located at latitude and longitude angles of 30° and 31.5°, respectively.

4.1 Solar Radiation Measurements and Models

The total irradiance, $G$, on a horizontal surface is measured every hour, in W/m$^2$, using a pyrometer, model CMP10, and manufactured by KIPP & ZONEN [240]. The pyrometer specifications are presented in 0. An image of the pyrometer is shown in Figure 19. An image of the CMP10 pyrometer [240]

![Image of CMP10 pyrometer](image19.png)

Figure 19 An image of the CMP10 pyrometer [240]

The pyranometer is connected to a data logger, model CR1000 and manufactured by Campbell Scientific [241]. The data logger also collects data from wind speed and direction sensors. Specifications of the data logger are included in the Appendix 12 Weather Station Data Logger. An image of the data logger is shown in Figure 20. An image for the CR1000 data logger [241]

![Image of CR1000 data logger](image20.png)

Figure 20 An image for the CR1000 data logger [241]

The weather data for the period from November 2018 to January 2022 are recorded and
utilized for the analyses. Since the solar radiation measurements are collected for horizontal surfaces, solar radiation models are used to extrapolate solar radiation on tilted surfaces; the model applied here is Klucher and Reindl and Hay and Davies [242] model, which is the measurements available for the global radiation on the horizontal surface; to deduce the diffuse component from it the Erbs' model [59] is employed.

### 4.2 Hourly Global Solar Radiation on an Inclined Surface

The global solar radiation incident on an inclined plane consists of beam radiation ($I_b$), reflected radiation, and diffuse radiation ($I_d$). The reflected radiation is the fraction of reflected radiation by the ground [243]. While the diffuse solar radiation is a portion of the sunlight that goes through the atmosphere and is scattered or reflected, and it cannot be focused.

Diffuse radiation models for inclined surfaces are isotropic and anisotropic models. Isotropic models assume distribution uniformity of diffuse radiation intensity over the sky. Anisotropic models contain suitable components for regions representing elevated diffuse radiation [244]. An example of isotropic models is the Liu and Jordon's model. An example of the anisotropic model is the HDKR model [242].

#### 4.2.1 Calculating the Incident Solar Radiation on the PV Panel

To estimate the hourly irradiation on the PV, the HDKR model [242] is utilized to calculate the hourly irradiation on a tilted surface in kWh/m², $I_T$, as shown by Eq. **Error! Reference source not found.**. The surface is south facing and tilted at slope $\beta = 30^\circ$ from the horizontal.

\[
I_T = (I_b + I_dA_t)R_b + I_d(1 - A_t)\left(\frac{1 + \cos \beta}{2}\right)^3 + I_d\rho_g\left(\frac{1 - \cos \beta}{2}\right)^2
\]  

(1)

$I_d$ is the hourly diffuse irradiation in kWh/m², calculated using Eq. (2, Erbs’ model [59].

\[
\frac{I_d}{I} = \begin{cases} 1 - 0.09k_T & \text{for } k_T \leq 0.22 \\ 0.9511 - 0.1604k_T + 4.388k_T^2 - 16.638k_T^3 + 12.336k_T^4 & \text{for } 0.22 < k_T \leq 0.80 \\ 0.165 & \text{for } k_T > 0.8 \end{cases}
\]

(2)

where $k_T$ is the hourly clearness index defined as the ratio of the hourly global (beam and diffuse) irradiation, $I$, received on a horizontal surface to the hourly radiation that would be received on a parallel extraterrestrial surface, $I_o$, as shown by Eq. (3 [243].
The global irradiation, $I_o$, is calculated by integrating the total irradiance, $G$, over an hour. The hourly values of the total irradiance, $G$, on a horizontal surface are available from the pyranometer measurements. While $I_o$ is the integration of the solar radiation incident on a horizontal plane outside of the atmosphere, $G_o$, over an hour calculated according to Eq. (4 [242]).

$$G_o = G_{sc} \left( 1 + 0.033 \cos \frac{360n}{365} \right) \cos \theta_z \quad (4)$$

where $G_{sc} = 1.367 \text{ kW/m}^2$ is the solar constant, $n$ is the day of the year and $\theta_z$ is the zenith angle.

In Eq. Error! Reference source not found., the hourly beam irradiation $I_b$ in kWh/m$^2$, is the difference between the hourly global irradiation, $I$ received on a horizontal surface and the hourly diffuse irradiation, $I_d$.

In Eq. Error! Reference source not found., $f$ is a modulating factor defined as $\frac{\sqrt{I_b}}{I}$, is the view factor for the tilted surface to the sky, and $I_o \frac{(1+\cos \beta)}{2}$ is the view factor for the tilted surface to the ground [242]. $\rho_g = 0.2$, is the ground albedo. $R_b$ is the ratio of beam radiation on the tilted surface $G_{b,T}$ to that on a horizontal surface $G_b$ at any time, as defined by Eq. (5 [242])

$$R_b = \frac{G_{b,T}}{G_b} = \frac{G_{b,n} \cos \theta}{G_{b,n} \cos \theta_z} = \frac{\cos \theta}{\cos \theta_z} \quad (5)$$

Where $\theta$ is the angle of incidence, and $\theta_z$ is the zenith angle, both angles are presented in section 4.2.2.

Finally, $A_i$ is the anisotropy index, which is a function of the transmittance of the atmosphere for beam radiation? It determines portion of horizontal diffuse which is to be treated as forward scattered; it is incident at the same angle as beam radiation. Under clear conditions, $A_i$ is high and most of diffuse is forward scattered; when sky is totally overcast, $A_i = 0$ and diffuse is isotropic. $A_i$ is calculated as in Eq. (6 [242])

$$A_i = \frac{I_{b,n}}{I_{o,n}} = \frac{I_b}{I_o} \quad (6)$$
4.2.2 Solar Radiation Angles

4.2.2.1 The Angle of Incidence $\theta$

It is the angle between the normal to the collector surface and the sun’s direct beam, as shown in Figure 21. It can be calculated as presented by Eq. (7) [243]

$$\cos \theta = \sin \delta \sin \phi \cos \beta - \sin \delta \cos \phi \sin \beta \cos \gamma + \cos \delta \cos \phi \cos \beta \cos \omega + \cos \delta \sin \phi \sin \beta \cos \gamma \cos \omega + \cos \delta \sin \beta \sin \gamma \sin \omega$$

Where $\phi$ is the latitude, which is the angular location north or south of the equator. $\gamma$ is the surface azimuth angle, which is the deviation of the projection on a horizontal plane of the normal to the surface from the local meridian. $\omega$ is the hour angle, which is the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15° per hour. Finally, $\delta$ is the declination, which is the angular position of the sun at solar noon, defined as shown by Eq. (8) [243]

$$\delta = 23.45 \sin \left(360 \frac{284 + n}{365}\right)$$

4.2.2.2 The Solar Zenith Angle $\theta_z$

It is the angle between the solar beam and the vertical direction. It is the angular
displacement from the south of the beam radiation projection on the horizontal plane, defined as shown by Eq. (9) [243]

\[
\cos \theta_z = \cos \phi \cos \delta \cos \omega + \sin \phi \sin \delta
\]  
(9)

### 4.3 Sample of Calculations

In this section, a sample of calculations during the time period from 9:00 AM to 10 AM for the month of July is presented. A sample of relevant data extracted from the weather station is shown in Table 13. This is for July 17th, 2019, the average day of July. Details of the calculation are presented in Appendix 13 Sample of Calculations.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Total irradiance, (G), on a horizontal surface (W/m²)</th>
<th>Air average temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7/17/2019</td>
<td>12:00:00 AM</td>
<td>0</td>
<td>34.9</td>
</tr>
<tr>
<td>7/17/2019</td>
<td>1:00:00 AM</td>
<td>0</td>
<td>35.32</td>
</tr>
<tr>
<td>7/17/2019</td>
<td>2:00:00 AM</td>
<td>0</td>
<td>35.11</td>
</tr>
<tr>
<td>7/17/2019</td>
<td>3:00:00 AM</td>
<td>0</td>
<td>34.83</td>
</tr>
<tr>
<td>7/17/2019</td>
<td>4:00:00 AM</td>
<td>0</td>
<td>34.66</td>
</tr>
<tr>
<td>7/17/2019</td>
<td>5:00:00 AM</td>
<td>0</td>
<td>34.5</td>
</tr>
<tr>
<td>7/17/2019</td>
<td>6:00:00 AM</td>
<td>30.22</td>
<td>34.42</td>
</tr>
<tr>
<td>7/17/2019</td>
<td>7:00:00 AM</td>
<td>140.6</td>
<td>37.69</td>
</tr>
<tr>
<td>7/17/2019</td>
<td>8:00:00 AM</td>
<td>209.7</td>
<td>39.02</td>
</tr>
<tr>
<td>7/17/2019</td>
<td>9:00:00 AM</td>
<td>503.2</td>
<td>40.09</td>
</tr>
<tr>
<td>7/17/2019</td>
<td>10:00:00 AM</td>
<td>726.8</td>
<td>40.37</td>
</tr>
<tr>
<td>7/17/2019</td>
<td>11:00:00 AM</td>
<td>820</td>
<td>39.3</td>
</tr>
<tr>
<td>7/17/2019</td>
<td>12:00:00 PM</td>
<td>868</td>
<td>40.82</td>
</tr>
<tr>
<td>7/17/2019</td>
<td>1:00:00 PM</td>
<td>865</td>
<td>39.07</td>
</tr>
<tr>
<td>7/17/2019</td>
<td>2:00:00 PM</td>
<td>772.3</td>
<td>38.87</td>
</tr>
<tr>
<td>7/17/2019</td>
<td>3:00:00 PM</td>
<td>670.1</td>
<td>39.09</td>
</tr>
<tr>
<td>7/17/2019</td>
<td>4:00:00 PM</td>
<td>509.1</td>
<td>38.51</td>
</tr>
<tr>
<td>7/17/2019</td>
<td>5:00:00 PM</td>
<td>323.8</td>
<td>37.88</td>
</tr>
<tr>
<td>7/17/2019</td>
<td>6:00:00 PM</td>
<td>138.4</td>
<td>35.2</td>
</tr>
<tr>
<td>7/17/2019</td>
<td>7:00:00 PM</td>
<td>25.21</td>
<td>32.84</td>
</tr>
<tr>
<td>7/17/2019</td>
<td>8:00:00 PM</td>
<td>0</td>
<td>31.56</td>
</tr>
<tr>
<td>7/17/2019</td>
<td>9:00:00 PM</td>
<td>0</td>
<td>30.09</td>
</tr>
<tr>
<td>7/17/2019</td>
<td>10:00:00 PM</td>
<td>0</td>
<td>29.08</td>
</tr>
<tr>
<td>7/17/2019</td>
<td>11:00:00 PM</td>
<td>0</td>
<td>31.34</td>
</tr>
</tbody>
</table>

### 4.4 Photovoltaic (PV) output

The PV electrical output depends on both the incident solar radiation on the PV surface
and the efficiency of the PV module in converting it to electricity. Each item is discussed separately below.

4.4.1 The Incident Solar Radiation on the PV Panel

PV modules make use of all the incident radiation on the panel surface. This compromises the beam component $I_b$, the ground reflected, and both the isotropic and anisotropic diffused. The solar radiation models and relation are employed to extrapolate all the incident radiation at any instant of time based on global radiation measurements on a horizontal surface, as discussed in section 0. The results are strongly affected by the solar incidence angle ($\theta$), which is the angle between the normal to the collector surface and the sun’s direct beam.

The angle ($\theta$), on the other hand, is a geometric quantity and depends on the time of the day, the collector inclination $\beta$, and the local angle of latitude $\phi$, as shown in Figure 21 Different solar angles for an inclined surface [243]. The smaller the angle, the larger the intensity of solar radiation. However, to minimize $\theta$, continuous tracking of the sun is required, which is not practical. Hence, in this work, we are considering only a fixed angle of inclination $\beta$ for rooftop PV, while maintaining a constant zero azimuth angle (PV always facing south). The selected angle $\beta$ is optimized to yield maximum solar radiation energy over the entire year as our PV installation is grid connected.

4.4.1.1 Optimum Tilt Angle ($\beta$)

The PV electric output depends on the quantity of solar radiation obtained by the Photovoltaic. The tilt of a panel clearly affects the collected yield amount. Therefore, PVs must be tilted at the best angles to capture the most intense solar energy accessible in a specific site. Assessing the solar radiation on tilted PV is an obligatory aspect in selecting the tilt angle that affects the amount of solar radiation collected by the PV module surfaces. Every site has a particular tilt angle which varies from other sites because one of the causes that significantly impacts tilt angle values is the site’s latitude. Some scholars have determined the tilt angle value for various cities [244]. For rooftops of houses, the suggested design consists of 4 connected PVs forming one string and their slope or the angle between the collector-surface plane and the horizontal $\beta = 30^\circ$ facing south as shown in Figure 22a. Moreover, the parking will be covered with horizontal PVs to avoid their shades impacting each other, as shown in Figure 22b.
4.4.1.2 Shading Effect

The presence of an object in the path of the sun’s rays can cause shading, which has a detrimental effect on PV performance. Indeed, the shading of only one cell in a string causes it to block the passage of current in all cells of the PV string. Since shading is highly site-specific and affected by neighboring buildings, trees, and solar radiation angles, it is impossible to generate it with any degree of precision. Indeed, it would require solar sun path diagrams, Figure 23, on which all neighboring obstacles must be plotted. Thus, in this work, we decided to consider only available areas free of shading as potential sites for PVs.
4.4.1.3 PV module Efficiency

The PV module efficiency is defined as the net electrical energy generated by the PV module divided by the total incident solar radiation incident on the PV surface. This can be derived from the manufactures I-V characteristic for different values of $G$; alternatively, a mean efficiency can be used for all $G$ values. This work selects a monocrystalline PV module [273] due to its advantages over other types, as depicted in Table 14. The characteristics of the PV are presented in Appendix 14 PV Characteristics.

Table 14. PVs classification based on their basic physical configuration [5], [249], [250]

<table>
<thead>
<tr>
<th>Category</th>
<th>PV panel</th>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>Monocrystalline silicon PV panel</td>
<td>High efficiency</td>
<td>Prime cost</td>
</tr>
<tr>
<td></td>
<td>Polycrystalline silicon PV panel</td>
<td>Stable performance</td>
<td>A high amount of semiconductor material is required per cell</td>
</tr>
<tr>
<td></td>
<td>Amorphous silicon PV panel</td>
<td>Aesthetics</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Easy to test, more accurate under sunlight</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Cadmium telluride PV panel</td>
<td>Stable performance</td>
<td>Low efficiency</td>
</tr>
<tr>
<td></td>
<td>Cadmium sulphide PV panel</td>
<td>Low cost</td>
<td>Low aesthetic value</td>
</tr>
<tr>
<td>Hybrid</td>
<td>Hybrid PV panel</td>
<td>Good performance,</td>
<td>High prime cost</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Good efficiency</td>
<td>Short lifetime</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Limited for appliances</td>
</tr>
<tr>
<td></td>
<td>Organic PV panel</td>
<td>Low cost</td>
<td>Performance and efficiency are so limited</td>
</tr>
</tbody>
</table>

Figure 23 Solar path diagram adopted from [248]
<table>
<thead>
<tr>
<th>Category</th>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic and polymer</td>
<td></td>
<td>Stable in the dark, degrade in light conditions</td>
</tr>
<tr>
<td>Thin film PV panel</td>
<td>High efficiency</td>
<td>Prime cost</td>
</tr>
<tr>
<td></td>
<td>Aesthetics</td>
<td>Less stable</td>
</tr>
<tr>
<td></td>
<td>Light-weight</td>
<td>Short lifetime</td>
</tr>
<tr>
<td></td>
<td>A small amount of semiconductor material is required per cell</td>
<td></td>
</tr>
</tbody>
</table>

The selected PV module is commercially available, and it was found that the PV nominal efficiency is practically unaffected by the variations in $G$ value, so an average value of the nominal PV efficiency was used. However, the nominal efficiency value is for standard laboratory conditions (cell temp 25°C); hence, a temperature convention factor is introduced based on the manufacturer’s quoted temperature efficiency.

### 4.4.2 Estimated PV Output for Differently Inclined Angle $\beta$

After developing the HDKR model, the output for a single PV output per month is estimated for $\beta =0^\circ, \beta =10^\circ, \beta =20^\circ, \beta =30^\circ, \beta =45^\circ$. The reported results are for the 21st of March, June, and December.

#### 4.4.2.1 Results for Tilted Angle $\beta =0^\circ$

The results for one PV within the same inclined angle $\beta =0^\circ$ differs from month to month. For example, the resulting output for one PV when $\beta =0^\circ$ on the 21st of March = 0.93 kWh/m²/d and the peak of the generated energy is in the noon, and it equals 0.14 kWh/m² as shown in Figure 24. In addition, the resulting output on the 21st of June = 1.33 kWh/m²/d, and the peak of the generated energy is in the noon, which equals 0.16 kWh/m², as shown in Figure 25. Finally, the resulting output on the 21st of December = 0.56 kWh/m²/d, and the peak of the generated energy is in the noon, which equals 0.1 kWh/m², as shown in Figure 26.
Figure 24. Single PV output on March day, $\beta=0$, $E=0.93 \text{ kWh/m}^2/\text{d}$

Figure 25. Single PV output on June day, $\beta=0$, $E=1.33 \text{ kWh/m}^2/\text{d}$
Figure 26. Single PV output on December day, \( \beta=0, \ E=0.56 \text{ kWh/m}^2/\text{d} \)

4.4.2.2 Results for Tilted Angle \( \beta=10^\circ \)

The results for one PV within the same inclined angle \( \beta=10^\circ \) differs from month to month. For example, the resulting output for one PV when \( \beta=10^\circ \) on the 21st of March = 1 kWh/m\(^2\)/d and the peak of the generated energy is in the noon, and it equals 0.15 kWh/m\(^2\) as shown in Figure 27. In addition, the resulting output for one PV on the 21st of June = 1.3 kWh/m\(^2\)/d, and the peak of the generated energy is in the noon, which equals 0.17 kWh/m\(^2\), as shown in Figure 28. Finally, the resulting output for one PV on the 21st of December = 0.66 kWh/m\(^2\)/d, and the peak of the generated energy is in the noon, which equals 0.12 kWh/m\(^2\), as shown in Figure 29.
4.4.2.3 Results for Tilted Angle $\beta = 20^\circ$

The results for one PV within the same inclined angle $\beta = 20^\circ$ differs from month to month.
For example, the resulting output for one PV when $\beta = 20^\circ$ on the 21st of March = 1.04 kWh/m$^2$/d and the peak of the generated energy is in the noon, and it equals 0.158 kWh/m$^2$ as shown in Figure 30. In addition, the resulting output for one PV on the 21st of June = 1.25 kWh/m$^2$/d, and the peak of the generated energy is in the noon, which equals 0.16 kWh/m$^2$, as shown in Figure 31. Finally, the resulting output for one PV on the 21st of December = 0.74 kWh/m$^2$/d, and the peak of the generated energy is in the noon, which equals 0.138 kWh/m$^2$, as shown in Figure 32.

Figure 30 Single PV output on March day, $\beta=20$, $E=1.04$ kWh/m$^2$/d

Figure 31 Single PV output on June day, $\beta=20$, $E=1.25$ kWh/m$^2$/d
4.4.2.4 Results for Tilted Angle $\beta = 30^\circ$

The results for one PV within the same inclined angle $\beta = 30^\circ$ differs from month to month. For example, the resulting output for one PV when $\beta = 30^\circ$ on the 21st of March = 1.05 kWh/m$^2$/d and the peak of the generated energy is in the noon, and it equals to 0.16 kWh/m$^2$ as shown in Figure 33. In addition, the resulting output for one PV on the 21st of June = 1.16 kWh/m$^2$/d, and the peak of the generated energy is in the noon, which equals 0.16 kWh/m$^2$, as shown in Figure 43. Finally, the resulting output for one PV on the 21st of December = 0.8 kWh/m$^2$/d, and the peak of the generated energy is in the noon, which equals 0.14 kWh/m$^2$ as shown in Figure 35.
Figure 33. Single PV output on March day, $\beta=30$, $E=1.05$ kWh/m$^2$/d

Figure 34. Single PV output on June day, $\beta=30$, $E=1.16$ kWh/m$^2$/d
4.4.2.5 Results for Tilted Angle $\beta = 45^\circ$

The results for one PV within the same inclined angle $\beta = 45^\circ$ differs from month to month. For example, the resulting output for one PV when $\beta = 45^\circ$ on the 21st of March = 1.04 kWh/m²/d and the peak of the generated energy is in the noon, and it equals 0.158 kWh/m². In addition, the resulting output for one PV on the 21st of June = 0.99 kWh/m²/d, and the peak of the generated energy is in the noon, which equals 0.14 kWh/m², as shown in Figure 36 and Figure 37. Finally, the resulting output for one PV on the 21st of December = 0.86 kWh/m²/d, and the peak of the generated energy is in the noon, which equals 0.158 kWh/m² as shown in Figure 38.
Figure 36 Single PV output on March day, $\beta=45$, $E=1.04$ kWh/m$^2$/d

Figure 37 Single PV output on June day, $\beta=45$, $E=0.99$ kWh/m$^2$/d
Figure 38. Single PV output on December day, $\beta=45$, $E=0.86 \text{kWh/m}^2\text{d}$
Chapter 5 Methods and Results

Chapter 5 presents the methodology employed for estimating the electrical energy derived from the rooftop PVs after deducing the available net suitable areas and the PV output per unit area.

The solar radiation data on horizontal surfaces and the models used to extrapolate the PV electrical energy output per m² of PV surface area were presented in Chapter 4. Whereas, the techniques used to produce the geometry and orientation of the house roofs based on GIS and remote sensing were presented in Chapter 3. In this chapter the net results of integration of all those models are presented.

An estimate is made for the upper and lower utilizable area ratios, as well as the upper lower limits of electrical energy produced per house. From these an estimate is made of the upper and lower total daily sustainable mileage covered by electrical vehicles per house.

5.1 Study Area

According to the website of the new urban communities authority [251], New Cairo was built by presidential decree (191/2000), and it is located fifteen km from Almaadi and ten km from Nasr City-New Cairo has three housing sectors: villas, buildings, and families, with around 46346 land plots. Housing units are 69764, built by the governmental (35730 units) and private sector (35730 units). There are 1500 thousand inhabitants, and the target population should reach 4 million. The land use is shown in Map 44.

Map 44. Land-use of the New Cairo City.[252]
5.2 Methodology

The research aims to identify “net suitable roof areas” for PV installation and to estimate the energy production of PVs installed in the compound area on the compound scale. The digitized buildings images from Pleades-1B are used to estimate the total roof area as well as the “net suitable area” which is deduced from the total roof area by subtracting the areas where the PV cannot be installed and subsequently removing shaded portions of these areas; the former removes the areas occupied by other built objects and areas which cannot be covered by the selected PVs' rectangular configuration with the restriction imposed in this study that no part of the PV should be shaded or extend outside the roof. The shaded area is calculated for the four key days of the year, namely “December 21st”, “March 21st” and “June 21st”, September 21st; shading being identical to that of March 21st, and the common unshaded area is the one considered within the net suitable area. Again, this is due to the restriction imposed in this study, and that is shading is not allowed at any time. The shaded area is estimated with the aid of the software built into the “Revit Architectural program” [254]

After this, the hourly solar incidence data are used in the model that estimates electrical energy produced from the PVs. Detailed calculations, with all considered aspects, are made for a sample compound, namely compound 6. The results are then employed to derive a “utilizability ratio” which is defined as the ratio of the net suitable occupied floor area divided by the total roof area, Table 19. For lack of time, it is assumed here that this ratio is typical for all the remaining compounds (1-5), which all feature horizontal roofs. However, the total roof area for each house in all of the 6 compounds is still derived making use of Pleades-1B, Table 12.

5.2.1 Shadow Analysis Estimation

The shadow analysis estimation requires knowledge of both the solar radiation rays’ angles and the geometric features of the PVs and their surroundings. It is noted that to eliminate the shading of PVs on each other, yet maximize their numbers, they are all arranged side by side on a common plane, i.e. their surfaces are coplanar.

The workflow diagram is demonstrated in Figure 39. The shadow analysis requires the height of buildings and level of the tops of any roof-rooms, as shown in the next section, in addition, to the latitude and longitude of the compound, which may be obtained from google maps. After estimating the heights, AutoCAD is used to develop a 3d model, which is exported to REVIT software. Using the illumination tool in REVIT software, the shadow analysis is completed for two building types on the 21st of March, June, and December, as shown in Figure 40 to Figure 45. The complete analysis is presented in Appendix 5: Shadows analysis for building type 1 through December 2022 to Appendix 10: Shadows analysis for building type 2 through June and March 2022

5.2.1.1 Calculating Heights of Buildings and Tops of Roof-rooms

Using the image analysis tool[253], which is part of ArcGIS, the height of the buildings
was estimated. This is because the image analysis tool uses the length of buildings’ shadows to estimate their heights. In compound 6, the height of the tops of roof-rooms is estimated to be 3 meters.

![Diagram of shadow analysis workflow]

**Figure 39. Shadow analysis workflow**

### 5.2.2 Criteria for Arranging PVs

#### 5.2.2.1 Shadow Limits

There are three observations that we can notice from the shadow analysis. The first observation is that shades do not extend much in the south direction except for a few hours, as shown in Figure 44. The second observation is that the shades extend to their maximum level in the east and west direction during the 21st of December, as shown in Figure 40 to Figure 44. More analyses are shown in Appendix 5: Shadows analysis for building type 1 through December 2022 to Appendix 10: Shadows analysis for building type 2 through June and March 2022. The third observation is that the length of the shade is approximately twice the height of the roof-room. Therefore, it is suggested to place the PVs away from the roof-room by a distance of at least 6 m, assuming that the room height is 3 m.

The following figures demonstrate the layout of two building types in compound 6. The figures demonstrate the shadow projection on the x-y horizontal plane, sun path, and the sun position in orange color and their position in relation to the building’s layout, day of the month, and hour.
Figure 40. Shades of building type 1 at 5 pm, March 21, 2022

Figure 41. Shades of building type 1 at 5 pm, June 21, 2022
Figure 42 Shades of building type 1 at 5 pm, Dec 21, 2022

Figure 43 Shades of building type 2 at 5 pm, Dec 21, 2022
5.2.2.2 Arrangement of PVs on The Roof

Design criteria are used to design the required arrangement of PVs on the roof. The first criterion is displacing PVs from any roof-rooms with a distance of 6 m in the direction of north, west, and east. The second criterion is that PVs should be placed on the south of any tall roof structure. The first and second criteria are based on dynamic shadow analysis. This is revealed in appendices from Appendix 5: Shadows analysis for building type 1 through December 2022 to Appendix 10: Shadows analysis for building type 2.
through June and March 2022. In addition, the third criterion is leaving a 1 m space on the inside of the parapet, to allow a person to clean the PVs. Moreover, the fourth planning criterion is raising the PV plane with a height of 1 m to avoid the shadow of the parapet. The fifth criterion is that the height of PVs installed on top of the roof-rooms must be less than 3 m. The final criteria are restricting the max height of PVs on the roof floor to be within 6 meters from roof surface, for artistic values and to manage the wind forces effectively; the latter often poses a restriction on the maximum angle of inclination of the PV surface, Table 15.

An upper limit, presented in Table 16, for the PV modules is defined here as the maximum possible number of PVs that can be installed on the roof top plus the top of any existing rooftop rooms within the restrictions imposed in this study, e.g. zero shading, no PV protruding, etc.; whereas a lower limit, presented in Table 17, is defined here as the number of PV modules that can be installed on the top of the roof rooms only, of course within the restrictions defined. Since the top of the roof rooms is higher than all surroundings, it guarantees no shading from surroundings and also does not occupy any area of the roof leaving free space for other applications.

Table 15 and Table 16 shows that the maximum number of PVs per compound decreases strongly and monotonically as the angle $\beta$ increases. This is due to the PV array height restriction imposed in this study. The difference varies between 2600 PVs for $\beta=0$ down to 1101 PVs for $\beta=45^\circ$, approximately a ratio of 2.5:1.

Table 17 shows similar trend as for the upper limit, and the ratio is approximately 2:1.

Table 18 shows the maximum utilizability for the upper limit is for PV inclination $\beta=0$ and it decreases monotonically with the increase of the angle of inclination. This is due to the restriction imposed regarding the maximum height of PVs above the roof floor (5m above bottom edge of the lower PV). Obviously as $\beta$ increases the upper edge of the highest PV will also increase in the vertical direction. In addition, there is also the effect of the PV shading on the floor, however since the PVs are all facing south, they will only shade the area south of them during early hours of the morning and late hours in the afternoon, and only during the summer months, hence this effect is expected to be secondary, yet it was taken into account.

Similarly, the lower limit which is based on the area of the ceiling of the roof rooms also suffer from similar height restrictions (3m above room ceiling height).
### Table 15. Height of the PV array within maximum height restrictions

<table>
<thead>
<tr>
<th>PV inclination angle $\beta$ [degrees]</th>
<th>PVs height above roof floor (elevation) [m]</th>
<th>PVs height above roof-rooms [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>10.0</td>
<td>4.9</td>
<td>2.6</td>
</tr>
<tr>
<td>20.0</td>
<td>4.8</td>
<td>2.7</td>
</tr>
<tr>
<td>30.0</td>
<td>5.0</td>
<td>3.0</td>
</tr>
<tr>
<td>45.0</td>
<td>4.9</td>
<td>2.8</td>
</tr>
</tbody>
</table>

### Table 16. The maximum number of PVS for compound 6 at different PV inclination angles ($\beta$)

<table>
<thead>
<tr>
<th>PV inclination angle $\beta$ [degrees]</th>
<th>Number of PVS/compound</th>
<th>The total area of PVS [m$^2$/compound]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2600</td>
<td>6692.868</td>
</tr>
<tr>
<td>10</td>
<td>2000</td>
<td>5148.36</td>
</tr>
<tr>
<td>20</td>
<td>1733</td>
<td>4461.05394</td>
</tr>
<tr>
<td>30</td>
<td>1341</td>
<td>3451.97538</td>
</tr>
<tr>
<td>45</td>
<td>1101</td>
<td>2834.17218</td>
</tr>
</tbody>
</table>

### Table 17. The lower limits for roofs of compound 6 at different PV inclination angles ($\beta$)

<table>
<thead>
<tr>
<th>PV inclination angle $\beta$ [degrees]</th>
<th>Number of PVS/compound</th>
<th>The total area of PVS/compound [m$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>353</td>
<td>908.68554</td>
</tr>
<tr>
<td>10</td>
<td>307</td>
<td>790.27326</td>
</tr>
<tr>
<td>20</td>
<td>245</td>
<td>630.6741</td>
</tr>
<tr>
<td>30</td>
<td>232</td>
<td>597.20976</td>
</tr>
<tr>
<td>45</td>
<td>180</td>
<td>463.3524</td>
</tr>
</tbody>
</table>

### Table 18. The utilizable ratio for compound 6

<table>
<thead>
<tr>
<th>Limit</th>
<th>PV inclination angle $\beta$ [degrees]</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper</td>
<td></td>
<td>0.2446</td>
<td>0.1881</td>
<td>0.1630</td>
<td>0.1261</td>
<td>0.1036</td>
</tr>
<tr>
<td>Lower</td>
<td></td>
<td>0.0332</td>
<td>0.0289</td>
<td>0.0230</td>
<td>0.0218</td>
<td>0.0169</td>
</tr>
</tbody>
</table>
The number of PVs for compound 6 could be estimated for other inclined angles from Figure 46 and Figure 47. For example, the upper limits for number of PVs at inclined angle $= 5^\circ$ is 2250 PVs, and the lower limit for number of PVs is 325 PVs as shown in Figure 47.
Map 45 layout of compound six, the map represents the lower limits at $\beta=0^\circ$, green shaded areas represent installed PVs.
Map 46 layout of compound six, the map represents the upper limits at $\beta=0^\circ$, green shaded areas represent installed PVs.
Map 47 layout of compound six, the map represents the lower limits at $\beta = 10^\circ$, green shaded areas represent installed PVs.
Map 49 layout of compound six, the map represents the upper limits at $\beta = 10^\circ$, green shaded areas represent installed PVs.
Map 50 layout of compound six, the map represents the lower limits at $\beta = 20^\circ$, green shaded areas represent installed PVs.
Map 51 Layout of compound six, the map represents the upper limits at $\beta = 20^\circ$, green shaded areas represent installed PVs.
Map 52 Layout of compound six, the map represents the lower limits at $\beta = 30^\circ$, green shaded areas represent installed PVs.
Map 53 layout of compound six, the map represents the upper limits at $\beta = 30^\circ$, green shaded areas represent installed PVs
Map 54 layout of compound six, the map represents the lower limits at $\beta = 45^\circ$, green shaded areas represent installed PVs.
Map 55 layout of compound six, the map represents the upper limit at $\beta = 45^\circ$, green shaded areas represent installed PVs
5.3 Results

This section presents the upper & lower areas available for PV installation at different PV inclination angles, for each compound. This is in addition to the upper & lower electric energy produced by the PV, from which the total available daily sustainable mobility per household is calculated.

5.3.1 Estimated Upper & Lower Areas Available for PV Installation

As mentioned in section 5.2, the utilizability ratio for compound 6 is used to estimate the upper & lower areas available for PV installation at different PV inclination angles, for each compound. The results are summarized in Table 19.

Table 19. The upper & lower utilizable areas for different PV inclination in m²

<table>
<thead>
<tr>
<th>Compound</th>
<th>No of houses</th>
<th>Total Roof Area [m²]</th>
<th>Limit</th>
<th>PV inclination angle β [degrees]</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>48</td>
<td>10090</td>
<td>Upper</td>
<td>2467.61</td>
<td>1898.16</td>
<td>1644.76</td>
<td>1272.72</td>
<td>1044.94</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lower</td>
<td>335.03</td>
<td>291.37</td>
<td>232.52</td>
<td>220.19</td>
<td>170.83</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>25331</td>
<td>Upper</td>
<td>6194.94</td>
<td>4765.34</td>
<td>4129.17</td>
<td>3195.16</td>
<td>2623.32</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lower</td>
<td>841.08</td>
<td>731.48</td>
<td>583.75</td>
<td>552.78</td>
<td>428.88</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>90</td>
<td>56832</td>
<td>Upper</td>
<td>13898.82</td>
<td>10691.40</td>
<td>9264.10</td>
<td>7168.58</td>
<td>5885.62</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lower</td>
<td>1887.03</td>
<td>1641.13</td>
<td>1309.70</td>
<td>1240.20</td>
<td>962.23</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>36</td>
<td>19042</td>
<td>Upper</td>
<td>4656.81</td>
<td>3582.16</td>
<td>3103.94</td>
<td>2401.84</td>
<td>1971.98</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lower</td>
<td>632.25</td>
<td>549.86</td>
<td>438.81</td>
<td>415.53</td>
<td>322.39</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>16</td>
<td>4191</td>
<td>Upper</td>
<td>1025.00</td>
<td>788.46</td>
<td>683.20</td>
<td>528.66</td>
<td>434.05</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lower</td>
<td>139.16</td>
<td>121.03</td>
<td>96.59</td>
<td>91.46</td>
<td>70.96</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>61</td>
<td>27367</td>
<td>Upper</td>
<td>6692.87</td>
<td>5148.36</td>
<td>4461.05</td>
<td>3451.98</td>
<td>2834.17</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lower</td>
<td>908.69</td>
<td>790.27</td>
<td>630.67</td>
<td>597.21</td>
<td>463.35</td>
<td></td>
</tr>
</tbody>
</table>

5.3.2 Estimated Upper & Lower Electric Energy Produced

After developing the HDKR model, in Chapter 4, the available daily electric energy produced by the PV is calculated for each month and at different PV inclinations $\beta =0^\circ$, $\beta =10^\circ$, $\beta =20^\circ$, $\beta =30^\circ$, and $\beta =45^\circ$. Table 20 depicts the available daily electric energy produced by the PV during the months of July and December.

Table 20. Available daily electric energy produced by the PV in kWh/m2/d

<table>
<thead>
<tr>
<th>PV inclination angle β [degrees]</th>
<th>July</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.301</td>
<td>1.278</td>
<td>1.235</td>
<td>1.163</td>
<td>1.003</td>
</tr>
<tr>
<td>10</td>
<td>0.560</td>
<td>0.657</td>
<td>0.739</td>
<td>0.803</td>
<td>0.865</td>
</tr>
</tbody>
</table>
Figure 47. Available daily electric energy produced by the PVs in kWh/m²/d in July

Figure 48. Available daily electric energy produced by the PV in kWh/m²/d in December

In order to know how much available daily electric energy produced by the PVs for different tilted angles that were not considered in this study, Figure 48 and Figure 49 could be used to estimate how much available daily electric energy at certain inclined
angle. For example, when the inclined angle = 5°, the available daily electric energy produced by the PVs = 1.3 in July 6 kWh/m²/d as shown in Figure 48. In addition, the available daily electric energy produced by the PVs is 0.6 kWh/m²/d in December as shown in Figure 49.

The data available from Table 19 and Table 20 is used to calculate the upper and lower limits for the available daily electric energy produced by the PV, for each compound, during the month of July and December, as depicted in Table 21 to Table 32.

For the month of July, Table 21 shows that for the upper limit, the maximum energy available from the PVs is for β=0, and that it is more than 3 times as much for β=0 than for β=45°, and even almost double as much as for β=30° which corresponds to the angle of latitude for Cairo and hence it is the most common angle employed by default. For the lower limit, the table also shows the superiority of β=0 angle; this can attributed to two effects, the first of these is that the sun is high in the sky during the month of July, so the sun is almost perpendicular to the PV surface, and the second reason is that due to the height restriction which results in a lower utilizability as displayed in Table 18.

For the month of December, Table 22 shows that again for the upper limit, the maximum energy available from the PVs is for β=0, however it is quite close to the other angles and this is because of the two conflicting effects; the sun is lowest in the sky which favors the larger angles of β whereas the height restriction reduces the utilizability factor, as displayed in Table 18. For the lower limit, Table 22 reveals the highest output is for β=30°, but all the values are quite close again because of the conflicting effects.

It is true that the overhead cost of the PVs will be determined by their number which is affected directly by their total surface area and this varies with the angle β, however the results indicate that this is not a decisive factor because the maximum summer performance is for β=0 and to make use of the higher solar energy available in summer, the number PVs acquired will have to be based on summer requirement in order to get the best performance of the year.

Table 21. The available daily electric energy produced by the PV for compound-1, during the month of July (kWh/d/house)

<table>
<thead>
<tr>
<th>PV inclination angle β [degrees]</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limit (kWh/d/house)</td>
<td>66.9</td>
<td>51.3</td>
<td>45.0</td>
<td>35.6</td>
<td>28.5</td>
</tr>
<tr>
<td>Lower limit (kWh/d/house)</td>
<td>9.1</td>
<td>7.9</td>
<td>6.4</td>
<td>6.2</td>
<td>4.7</td>
</tr>
</tbody>
</table>
Table 22. The available daily electric energy produced by the PV for compound-1, during the month of December (kWh/d/house)

<table>
<thead>
<tr>
<th>PV inclination angle β [degrees]</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limit (kWh/d/house)</td>
<td>28.8</td>
<td>26.4</td>
<td>26.9</td>
<td>24.6</td>
<td>24.6</td>
</tr>
<tr>
<td>Lower limit (kWh/d/house)</td>
<td>3.9</td>
<td>4.0</td>
<td>3.8</td>
<td>4.3</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Table 23. The available daily electric energy produced by the PV for compound-2, during the month of July (kWh/d/house)

<table>
<thead>
<tr>
<th>PV inclination angle β [degrees]</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limit (kWh/d/house)</td>
<td>201.5</td>
<td>154.6</td>
<td>135.7</td>
<td>107.2</td>
<td>85.9</td>
</tr>
<tr>
<td>Lower limit (kWh/d/house)</td>
<td>27.4</td>
<td>23.7</td>
<td>19.2</td>
<td>18.6</td>
<td>14.0</td>
</tr>
</tbody>
</table>

Table 24. The available daily electric energy produced by the PV for compound-2, during the month of December (kWh/d/house)

<table>
<thead>
<tr>
<th>PV inclination angle β [degrees]</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limit (kWh/d/house)</td>
<td>86.7</td>
<td>79.5</td>
<td>81.1</td>
<td>74.1</td>
<td>74.0</td>
</tr>
<tr>
<td>Lower limit (kWh/d/house)</td>
<td>11.8</td>
<td>12.2</td>
<td>11.5</td>
<td>12.8</td>
<td>12.1</td>
</tr>
</tbody>
</table>

Table 25. The available daily electric energy produced by the PV for compound-3, during the month of July (kWh/d/house)

<table>
<thead>
<tr>
<th>PV inclination angle β [degrees]</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limit (kWh/d/house)</td>
<td>200.9</td>
<td>154.1</td>
<td>135.3</td>
<td>106.9</td>
<td>85.7</td>
</tr>
<tr>
<td>Lower limit (kWh/d/house)</td>
<td>27.3</td>
<td>23.7</td>
<td>19.1</td>
<td>18.5</td>
<td>14.0</td>
</tr>
</tbody>
</table>
Table 26. The available daily electric energy produced by the PV for compound-3, during the month of December (kWh/d/house)

<table>
<thead>
<tr>
<th>PV inclination angle $\beta$ [degrees]</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limit (kWh/d/house)</td>
<td>86.5</td>
<td>79.2</td>
<td>80.9</td>
<td>73.9</td>
<td>73.8</td>
</tr>
<tr>
<td>Lower limit (kWh/d/house)</td>
<td>11.7</td>
<td>12.2</td>
<td>11.4</td>
<td>12.8</td>
<td>12.1</td>
</tr>
</tbody>
</table>

Table 27. The available daily electric energy produced by the PV for compound-4, during the month of July (kWh/d/house)

<table>
<thead>
<tr>
<th>PV inclination angle $\beta$ [degrees]</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limit (kWh/d/house)</td>
<td>168.3</td>
<td>129.1</td>
<td>113.3</td>
<td>89.6</td>
<td>71.7</td>
</tr>
<tr>
<td>Lower limit (kWh/d/house)</td>
<td>22.8</td>
<td>19.8</td>
<td>16.0</td>
<td>15.5</td>
<td>11.7</td>
</tr>
</tbody>
</table>

Table 28. The available daily electric energy produced by the PV for compound-4, during the month of December (kWh/d/house)

<table>
<thead>
<tr>
<th>PV inclination angle $\beta$ [degrees]</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limit (kWh/d/house)</td>
<td>72.4</td>
<td>66.4</td>
<td>67.8</td>
<td>61.9</td>
<td>61.8</td>
</tr>
<tr>
<td>Lower limit (kWh/d/house)</td>
<td>9.8</td>
<td>10.2</td>
<td>9.6</td>
<td>10.7</td>
<td>10.1</td>
</tr>
</tbody>
</table>

Table 29. The available daily electric energy produced by the PV for compound-5, during the month of July (kWh/d/house)

<table>
<thead>
<tr>
<th>PV inclination angle $\beta$ [degrees]</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limit (kWh/d/house)</td>
<td>83.3</td>
<td>63.9</td>
<td>56.1</td>
<td>44.4</td>
<td>35.5</td>
</tr>
<tr>
<td>Lower limit (kWh/d/house)</td>
<td>11.3</td>
<td>9.8</td>
<td>7.9</td>
<td>7.7</td>
<td>5.8</td>
</tr>
</tbody>
</table>
Table 30. The available daily electric energy produced by the PV for compound-5, during the month of December (kWh/d/house)

<table>
<thead>
<tr>
<th>PV inclination angle $\beta$ [degrees]</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limit (kWh/d/house)</td>
<td>35.9</td>
<td>32.9</td>
<td>33.6</td>
<td>30.7</td>
<td>30.6</td>
</tr>
<tr>
<td>Lower limit (kWh/d/house)</td>
<td>4.9</td>
<td>5.0</td>
<td>4.7</td>
<td>5.3</td>
<td>5.0</td>
</tr>
</tbody>
</table>

Table 31. The available daily electric energy produced by the PV for compound-6, during the month of July (kWh/d/house)

<table>
<thead>
<tr>
<th>PV inclination angle $\beta$ [degrees]</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limit (kWh/d/house)</td>
<td>142.7</td>
<td>109.5</td>
<td>96.1</td>
<td>76.0</td>
<td>60.9</td>
</tr>
<tr>
<td>Lower limit (kWh/d/house)</td>
<td>19.4</td>
<td>16.8</td>
<td>13.6</td>
<td>13.1</td>
<td>9.9</td>
</tr>
</tbody>
</table>

Table 32. The available daily electric energy produced by the PV for compound-6, during the month of December (kWh/d/house)

<table>
<thead>
<tr>
<th>PV inclination angle $\beta$ [degrees]</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limit (kWh/d/house)</td>
<td>61.4</td>
<td>56.3</td>
<td>57.5</td>
<td>52.5</td>
<td>52.4</td>
</tr>
<tr>
<td>Lower limit (kWh/d/house)</td>
<td>8.3</td>
<td>8.6</td>
<td>8.1</td>
<td>9.1</td>
<td>8.6</td>
</tr>
</tbody>
</table>

5.3.3 Estimated upper & lower available sustainable mileage

This subsection presents the results for the upper and lower limits for the sustainable mileage for an EV per household for the 6 compounds, as depicted in Table 33 to Table 50. Data is presented for the months of July and December to bracket all possible scenarios.

Considering the average electric energy required by an electric vehicle 0.15 kWh/km, then the data previously depicted in Table 21 to Table 32 is used to predict the upper & lower available sustainable mileage per house. This is calculated by dividing all values in Table 21 to Table 32 by 0.15 kWh/km.

Table 33 reveals the estimated distances that can be covered by the PV produced electricity during the month of July for both the upper and lower limits per house. Since
those numbers are based on the total electrical energy produced by the PVs and were presented and discussed in Table 21 and Table 22, together with an estimated 0.15 kWh/km typical of today's electric vehicles, the same performance profiles are shown. The same applies to Table 33 and Table 34. For the upper limit and $\beta=0$, Table 33 shows that a total of 446 sustainable km/day/house can be traveled (which is substantial), whereas even with the lower limit of 61 km/day/house most households will be well suited.

Table 34 shows that even in the month with the lowest solar energy the upper limit caters for up to 192 sustainable km/day/house which is more than the typical household usage. The lower limit however maybe more critical, at 28 km/day/house.

Table 35 gives an indication of the annual average performance which is the average of the months of July and December.

Table 33. Daily distance that can be traveled for compound-1 per house, during the month of July $\tilde{I}$ (km/day/house)

<table>
<thead>
<tr>
<th>PV inclination angle $\beta$ [degrees]</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limit (km/day/house)</td>
<td>446</td>
<td>342</td>
<td>300</td>
<td>237</td>
<td>190</td>
</tr>
<tr>
<td>Lower limit (km/day/house)</td>
<td>61</td>
<td>52</td>
<td>42</td>
<td>41</td>
<td>31</td>
</tr>
</tbody>
</table>

Table 34. Daily distance that can be traveled for compound-1 per house, during the month of December $\tilde{I}$ (km/day/house)

<table>
<thead>
<tr>
<th>PV inclination angle $\beta$ [degrees]</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limit (km/day/house)</td>
<td>192</td>
<td>176</td>
<td>180</td>
<td>164</td>
<td>164</td>
</tr>
<tr>
<td>Lower limit (km/day/house)</td>
<td>26</td>
<td>27</td>
<td>25</td>
<td>28</td>
<td>27</td>
</tr>
</tbody>
</table>

Table 35. Daily average annual distance that can be traveled for compound-1, per house $\bar{I}$ (km/day/house)

<table>
<thead>
<tr>
<th>PV inclination angle $\beta$ [degrees]</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limit (km/day/house)</td>
<td>319</td>
<td>259</td>
<td>240</td>
<td>201</td>
<td>177</td>
</tr>
<tr>
<td>Lower limit (km/day/house)</td>
<td>43</td>
<td>40</td>
<td>34</td>
<td>35</td>
<td>29</td>
</tr>
</tbody>
</table>
Table 36. Daily distance that can be traveled for compound-2, per house during the month of July $\tilde{I}$ (km/day/house)

<table>
<thead>
<tr>
<th>PV inclination angle $\beta$ [degrees]</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limit (km/day/house)</td>
<td>1343</td>
<td>1030</td>
<td>905</td>
<td>715</td>
<td>573</td>
</tr>
<tr>
<td>Lower limit (km/day/house)</td>
<td>182</td>
<td>158</td>
<td>128</td>
<td>124</td>
<td>94</td>
</tr>
</tbody>
</table>

Table 37. Daily distance that can be traveled for compound-2, per house during the month of December $\tilde{I}$ (km/day/house)

<table>
<thead>
<tr>
<th>PV inclination angle $\beta$ [degrees]</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limit (km/day/house)</td>
<td>578</td>
<td>530</td>
<td>541</td>
<td>494</td>
<td>494</td>
</tr>
<tr>
<td>Lower limit (km/day/house)</td>
<td>78</td>
<td>81</td>
<td>76</td>
<td>85</td>
<td>81</td>
</tr>
</tbody>
</table>

Table 38. Daily average annual distance that can be traveled for compound-2, per house $\tilde{I}$ (km/day/house)

<table>
<thead>
<tr>
<th>PV inclination angle $\beta$ [degrees]</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limit (km/day/house)</td>
<td>961</td>
<td>780</td>
<td>723</td>
<td>604</td>
<td>533</td>
</tr>
<tr>
<td>Lower limit (km/day/house)</td>
<td>130</td>
<td>120</td>
<td>102</td>
<td>105</td>
<td>87</td>
</tr>
</tbody>
</table>

Table 39. Daily distance that can be traveled for compound-3, per house during the month of July $\tilde{I}$ (km/day/house)

<table>
<thead>
<tr>
<th>PV inclination angle $\beta$ [degrees]</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limit (km/day/house)</td>
<td>1339</td>
<td>1027</td>
<td>902</td>
<td>713</td>
<td>571</td>
</tr>
<tr>
<td>Lower limit (km/day/house)</td>
<td>182</td>
<td>158</td>
<td>128</td>
<td>123</td>
<td>93</td>
</tr>
</tbody>
</table>
Table 40. Daily distance that can be traveled for compound-3, per house during the month of December $\bar{t}$ (km/day/house)

<table>
<thead>
<tr>
<th>PV inclination angle $\beta$ [degrees]</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limit (km/day/house)</td>
<td>577</td>
<td>528</td>
<td>539</td>
<td>493</td>
<td>492</td>
</tr>
<tr>
<td>Lower limit (km/day/house)</td>
<td>78</td>
<td>81</td>
<td>76</td>
<td>85</td>
<td>80</td>
</tr>
</tbody>
</table>

Table 41. Daily average annual distance that can be traveled for compound-3, per house $\bar{t}$ (km/day/house)

<table>
<thead>
<tr>
<th>PV inclination angle $\beta$ [degrees]</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limit (km/day/house)</td>
<td>958</td>
<td>778</td>
<td>721</td>
<td>603</td>
<td>532</td>
</tr>
<tr>
<td>Lower limit (km/day/house)</td>
<td>130</td>
<td>119</td>
<td>102</td>
<td>104</td>
<td>87</td>
</tr>
</tbody>
</table>

Table 42. Daily distance that can be traveled for compound-4, per house during the month of July $\bar{t}$ (km/day/house)

<table>
<thead>
<tr>
<th>PV inclination angle $\beta$ [degrees]</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limit (km/day/house)</td>
<td>1122</td>
<td>861</td>
<td>755</td>
<td>597</td>
<td>478</td>
</tr>
<tr>
<td>Lower limit (km/day/house)</td>
<td>152</td>
<td>132</td>
<td>107</td>
<td>103</td>
<td>78</td>
</tr>
</tbody>
</table>

Table 43. Daily distance that can be traveled for compound-4, per house during the month of December $\bar{t}$ (km/day/house)

<table>
<thead>
<tr>
<th>PV inclination angle $\beta$ [degrees]</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limit (km/day/house)</td>
<td>483</td>
<td>442</td>
<td>452</td>
<td>413</td>
<td>412</td>
</tr>
<tr>
<td>Lower limit (km/day/house)</td>
<td>66</td>
<td>68</td>
<td>64</td>
<td>71</td>
<td>67</td>
</tr>
</tbody>
</table>
Table 44. Daily average annual distance that can be traveled for compound-4, per house $\bar{l}$ (km/day/house)

<table>
<thead>
<tr>
<th>PV inclination angle $\beta$ [degrees]</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limit (km/day/house)</td>
<td>802</td>
<td>651</td>
<td>604</td>
<td>505</td>
<td>445</td>
</tr>
<tr>
<td>Lower limit (km/day/house)</td>
<td>109</td>
<td>100</td>
<td>85</td>
<td>87</td>
<td>73</td>
</tr>
</tbody>
</table>

Table 45. Daily distance that can be traveled for compound-5, per house during the month of July $\bar{l}$ (km/day/house)

<table>
<thead>
<tr>
<th>PV inclination angle $\beta$ [degrees]</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limit (km/day/house)</td>
<td>556</td>
<td>426</td>
<td>374</td>
<td>296</td>
<td>237</td>
</tr>
<tr>
<td>Lower limit (km/day/house)</td>
<td>75</td>
<td>65</td>
<td>53</td>
<td>51</td>
<td>39</td>
</tr>
</tbody>
</table>

Table 46. Daily distance that can be traveled for compound-5, per house during the month of December $\bar{l}$ (km/day/house)

<table>
<thead>
<tr>
<th>PV inclination angle $\beta$ [degrees]</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limit (km/day/house)</td>
<td>239</td>
<td>219</td>
<td>224</td>
<td>204</td>
<td>204</td>
</tr>
<tr>
<td>Lower limit (km/day/house)</td>
<td>32</td>
<td>34</td>
<td>32</td>
<td>35</td>
<td>33</td>
</tr>
</tbody>
</table>

Table 47. Daily average annual distance that can be traveled for compound-5, per house $\bar{l}$ (km/day/house)

<table>
<thead>
<tr>
<th>PV inclination angle $\beta$ [degrees]</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limit (km/day/house)</td>
<td>397</td>
<td>323</td>
<td>299</td>
<td>250</td>
<td>221</td>
</tr>
<tr>
<td>Lower limit (km/day/house)</td>
<td>54</td>
<td>50</td>
<td>42</td>
<td>43</td>
<td>36</td>
</tr>
</tbody>
</table>
Table 48. Daily distance that can be traveled for compound-6, per house during the month of July $\bar{I}$ (km/day/house)

<table>
<thead>
<tr>
<th>PV inclination angle $\beta$ [degrees]</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limit (km/day/house)</td>
<td>952</td>
<td>730</td>
<td>641</td>
<td>506</td>
<td>406</td>
</tr>
<tr>
<td>Lower limit (km/day/house)</td>
<td>129</td>
<td>112</td>
<td>91</td>
<td>88</td>
<td>66</td>
</tr>
</tbody>
</table>

Table 49. Daily distance that can be traveled for compound-6, per house during the month of December $\bar{I}$ (km/day/house)

<table>
<thead>
<tr>
<th>PV inclination angle $\beta$ [degrees]</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limit (km/day/house)</td>
<td>410</td>
<td>375</td>
<td>383</td>
<td>350</td>
<td>350</td>
</tr>
<tr>
<td>Lower limit (km/day/house)</td>
<td>56</td>
<td>58</td>
<td>54</td>
<td>61</td>
<td>57</td>
</tr>
</tbody>
</table>

Table 50. Daily average annual distance that can be traveled for compound-6, per house $\bar{I}$ (km/day/house)

<table>
<thead>
<tr>
<th>PV inclination angle $\beta$ [degrees]</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limit (km/day/house)</td>
<td>681</td>
<td>553</td>
<td>512</td>
<td>428</td>
<td>378</td>
</tr>
<tr>
<td>Lower limit (km/day/house)</td>
<td>92</td>
<td>85</td>
<td>72</td>
<td>74</td>
<td>62</td>
</tr>
</tbody>
</table>
Figure 49. Daily average annual distance that can be traveled at different PV inclinations for the 6 compounds (km/day/house)
A comparison between the daily average annual distance that can be traveled for different PV inclinations of the six compounds is demonstrated in Figure 50. It is obvious that compound 2 and compound 3 have the highest upper limit for the daily average annual distance, while compound 1 has the lowest value. This could be because the available area of compound 2 and compound 3 is bigger than the available area of compound 1 as shown in Table 12. Table illustrates available areas for PVs installation for each compound. The lower limits for the daily average annual distance in compounds 2, 3, 4, and 6 are almost the same and they are relatively higher than the lower limits for the daily average annual distance in compounds 1 and 5. This could be due to the small available area for compounds 1 and 5.
Chapter 6 Conclusion and Recommendation Work

6.1 Conclusion

This study aims to estimate the available solar-PV electricity produced from rooftops of New Cairo houses, and the potential for employing it to charge electric vehicles; the study differs from previous work in that it strives to achieve the highest accuracy while maintaining practical generality so that it can be applied in practice to predict future performance without the need to repeat the detailed analysis for each scenario.

As a compromise between generality and accuracy the present work is confined to compounds of New Cairo. Moreover, this region is characterized by a high potential for rooftop PV installations.

To achieve the above objectives, resort was made to local metrological measurements for ground solar energy radiation and ambient temperatures. These were extrapolated to inclined surfaces of the rooftop PVs using HDKR model and the electricity produced from PVs employed an actual commercial PV characteristic. A major feature of this study is the effort exerted to determine the available rooftop space for PVs, under real life conditions, e.g. restrictions on the height of the PV above the roof, restricting PVs to lie within the boundaries of the roof within the actual dimensions and shape of the selected PV (2.27m×1.35 m, which is typical of rooftop PVs), as well as allowing corridor space between the PVs for maintenance and cleaning. In order to avoid inter-shading between PVs, they were arranged to lie side-by-side on a single inclined plane, and were permanently fixed throughout the entire year. Moreover, shading of external objects was avoided by determining their shaded area throughout the entire year. To determine the latter, resort was made to GIS and RS data for the compounds considered in order to determine the areas and shapes of the house rooftops and then the processed data was introduced in the REVIT software and its built in shading analysis tool was used. By combining all those models an estimate is made of the total daily electric energy produced from the roof PVs.

For each case, both an upper and lower PV area limit was set; the former is based determining the largest area for PV installation within the restrictions imposed in this study, whereas the latter is based on the area of the rooftop rooms only, again within the restriction of the maximum allowable PV height above the room ceiling. It is noted that the lower limit allows full use of the rooftop floor for other applications.

The results of the study reveal that the maximum utilizable floor area is strongly dependent on the adopted angle of inclination of the PVs, increasing with the decrease of the angle of PV inclination. This is found to be due mainly to the maximum height restriction of the PV array, which reduces the allowable number of PVs as the angle of inclination increases, to the extent that the maximum number of allowable PVs per compound drops from 2600 PVs for $\beta=0$ down to 1101 PVs for $\beta=45^\circ$. Thus, had PVs of smaller size been selected it is expected that the total number of PVs would have
increased, resulting in a larger total area of PV surface.

The study reveals that the PV output within the restrictions imposed is maximum for $\beta=0$ and minimum for $\beta=45^\circ$ in summer, regardless of whether the upper or lower limit area is adopted. The cause is the larger allowable number of PVs with $\beta=0$. For winter, the study shows that the variation between the PV output $\beta=0$ and $\beta=45^\circ$ is much less than before and this is due to the two conflicting effects; the sun is lowest in the sky which favors the larger angles of $\beta$ whereas the height restriction reduces the utilizability factor; whereas in summer the sun is highest in the sky therefore both effects act in the same direction.

The total sustainable km/house/day powered by the PV generated electricity is maximum in summer for $\beta=0$ and minimum for $\beta=45^\circ$ as expected from the previous arguments for the electricity generated from the PV. The total sustainable km/house/day in winter also follows the same trend like the electricity generated per day by the PVs since the difference is only a scaling factor of 0.15 kWh/km. It is revealed that under summer conditions the maximum number of kms covered per day per house from PV produced electricity reaches 952 km/day. This is equivalent to 19 cars running an average of 18,250 km/year, which is far above the needs of any household. Whereas the lowest number of km per day, which corresponds to winter condition with only the “lower limit area” is 61 km/day for $\beta=30^\circ$, however since the recommendation will be that the PV will be fixed at $\beta=0$ since it far outperforms other angles in summer then we are bound by lower limit of $\beta=0$ which produces 56 km/day. This corresponds to two cars running each slightly more than 10,000 km/year. The latter may satisfy some households, but not all. Thus, it is expected that some households will need a PV area lying some where between the upper and lower area limit. It maybe worth mentioning with the upper area limit in winter and $\beta=0$ the corresponding number of km per day per house is 410 km/day, corresponding to 8 cars each running at 18,250 km/year. Thus, it is established that sustainable mobility can be always achieved for all compound houses employing roof mounted PVs.

**6.2 Recommendation Work**

The investigation in this study reveal that it is viable to achieve sustainable mobility employing roof mounted PVs. However, further investigations are recommended to optimize the findings. They are listed as follows

1. Investigate the effect of using PVs of smaller dimensions on the maximum number of PVs installed and therefor the maximum possible electric output, and on the optimum angle of $\beta$.

2. Since the price of PVs installation is directly proportional to the number of PVs of particular size and that the angle $\beta=0$ that produces the maximum output is also the one that uses the maximum number of PVs, then it is also the most expensive choice. Hence, in interset of cost optimization it is recommended to compare the price of kWh produced for the different $\beta$ angles and to select the one delivering
minimum cost while satisfying the sustainable mobility requirements.

3. The results of the present study were penalized by two factors which are the fixed PV angle inclination for all seasons and the maximum allowable height of the PV arrays. An optimum angle and better results can be obtained if this study allows seasonal readjustment of the PV inclination angle and/or slightly higher allowable PV array heights. The heights were selected so that the maximum height of the house does not exceed at any point the equivalent of four floors which is the most severe restriction in some compounds. However, other compounds allow for one or more floor heights. Hence it is recommended to extend this study to higher maximum heights to investigate the resulting gain.
References


scripts/data-fusion/sand-oriented_land_cover_classification_s1_s2/ (accessed May 06, 2022).


[74] “Tool Morphological Filter / SAGA-GIS Tool Library Documentation (v6.1.0).”


[76] “Area Solar Radiation—Help | ArcGIS for Desktop.”


J. Khan, “Estimation of rooftop solar photovoltaic potential using geo-spatial techniques: A perspective from planned neighborhood of Karachi – Pakistan -


https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/ers/instruments/sar/applications/radar-courses/content-3/-/asset_publisher/mQ9R7ZVkJg5P/content/radar-course-3-synthetic-aperture-radar#thirteen (accessed Aug. 03, 2021).


[237] “Setting up and running Attribute Calculation.”


Somerset, UNITED STATES: John Wiley & Sons, Incorporated, 2013. Accessed:


“UO SRML: Sun chart program.”


“New Cairo,” 2022.


“Getting height measurements from imagery – ArcMap | Documentation.”

“REVIT software” 2022.
Appendix 1 Sentinel 2 after processing

Map 1. Band 2 (B2)

Map 2. Band 3 (B3)

Map 3. Band 4 (B4)

Map 4. Band 5 (B5)
Map 1-5. Band 6 (B6)  
Map 57 (B7)
Map 1-7. Band 8A (B8A)

Map 1-8. Built-Up Area (BRBA)

Map 1-9. normalized built-up area index (NBAI)

Map 1-10. biophysical composition index (BCI)
Map 1-11. Sigma 0 IW 2 VH Contrast

Map 1-12. Sigma 0 VV contrast

Map 1-13. Sigma0 IW2 VV GLCM variance
Appendix 2 Input layers for classifications

Map 2-1 A region of the Buildings layer

Map 2-2. Green areas layer

Map 2-3. Streets layer

Map 2-4. Desert/ bare ground layer
Appendix 3 Overall accuracy for different parameters in the RT model

Table 3-1. Classification for Sentinel-1 and Sentinel-2 without BCI

<table>
<thead>
<tr>
<th>Cross Validation</th>
<th>Number of classes = 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>class 0.0: Buildings</td>
<td>accuracy = 0.7343 precision = 0.5381 correlation = 0.5765 errorRate = 0.1270 TruePositives = 1698.0000 FalsePositives = 1361.0000 TrueNegatives = 6132.0000 FalseNegatives = 802.0000</td>
</tr>
<tr>
<td>class 1.0: soil</td>
<td>accuracy = 0.7994 precision = 0.5862 correlation = 0.5913 errorRate = 0.2006 TruePositives = 1679.0000 FalsePositives = 1185.0000 TrueNegatives = 6315.0000 FalseNegatives = 821.0000</td>
</tr>
<tr>
<td>class 2.0: streets</td>
<td>accuracy = 0.7583 precision = 0.5807 correlation = 0.4675 errorRate = 0.2497 TruePositives = 1032.0000 FalsePositives = 1029.0000 TrueNegatives = 6471.0000 FalseNegatives = 1468.0000</td>
</tr>
<tr>
<td>class 3.0: green</td>
<td>accuracy = 0.9819 precision = 0.9529 correlation = 0.9457 errorRate = 0.1891 TruePositives = 1264.0000 FalsePositives = 745.0000 TrueNegatives = 6755.0000 FalseNegatives = 1236.0000</td>
</tr>
</tbody>
</table>

Using Testing dataset, % correct predictions = 56.7300

| Total samples = 20000 |
| MSE = 1.20545975625717 |
| Bias = -0.1957080000000001 |

**Distribution:**
- class 0.0: ClassificationBuildings 5000 (25.00000%)
- class 1.0: Classificationsoil 5000 (25.00000%)
- class 2.0: Classificationstreets 5000 (25.00000%)
- class 3.0: Classificationgreen 5000 (25.00000%)

**Testing feature importance score:**
Each feature is perturbed 3 times and the % correct predictions are averaged

<table>
<thead>
<tr>
<th>rank</th>
<th>feature</th>
<th>score</th>
<th>accuracy</th>
<th>precision</th>
<th>recall</th>
<th>correlation</th>
<th>errorRate</th>
<th>cost</th>
<th>GainRatio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BRSA_mst_2Mar2020</td>
<td>0.4649</td>
<td>0.4225</td>
<td>0.4297</td>
<td>0.4239</td>
<td>-0.4225</td>
<td>0.2325</td>
<td>-1.8956</td>
<td>0.1156</td>
</tr>
<tr>
<td>2</td>
<td>IB41_mst_2Mar2020</td>
<td>0.3858</td>
<td>0.3783</td>
<td>0.3791</td>
<td>0.3618</td>
<td>-0.3636</td>
<td>0.1919</td>
<td>-0.8361</td>
<td>0.0547</td>
</tr>
<tr>
<td>3</td>
<td>Sigma0_12_VV_GLCMvariance_s1_s1_c0_3Nov2020</td>
<td>0.3785</td>
<td>0.3785</td>
<td>0.3785</td>
<td>0.3643</td>
<td>-0.3785</td>
<td>0.1892</td>
<td>-0.7917</td>
<td>0.0167</td>
</tr>
<tr>
<td>4</td>
<td>Sigma0_12_VH_GLCMvariance_s1_s1_c0_3Nov2020</td>
<td>0.3523</td>
<td>0.3523</td>
<td>0.3523</td>
<td>0.3324</td>
<td>-0.3523</td>
<td>0.1762</td>
<td>-0.6762</td>
<td>0.0165</td>
</tr>
<tr>
<td>5</td>
<td>Sigma0_12_VH_GLCMvariance_s2_s2_c0_3Nov2020</td>
<td>0.3238</td>
<td>0.3238</td>
<td>0.3238</td>
<td>0.3055</td>
<td>-0.3238</td>
<td>0.1554</td>
<td>-0.5595</td>
<td>0.0007</td>
</tr>
<tr>
<td>6</td>
<td>Sigma0_12_VH_GLCMvariance_s2_s2_c0_3Nov2020</td>
<td>0.1750</td>
<td>0.1750</td>
<td>0.1750</td>
<td>0.1695</td>
<td>-0.1750</td>
<td>0.1002</td>
<td>-0.4075</td>
<td>0.0076</td>
</tr>
<tr>
<td>7</td>
<td>812_mst_20Mar2020</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>-0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
</tbody>
</table>
### Table 3-2. Classification for Sentinel-1 and Sentinel-2 without BCI

**Cross Validation**

Number of classes = 4

class 0.0: Buildings  
accuracy = 0.6250 precision = 0.3333 correlation = 0.4472 errorRate = 0.3750  
TruePositives = 1.0000 FalsePositives = 2.0000 TrueNegatives = 4.0000 FalseNegatives = 1.0000
class 1.0: Soil  
accuracy = 0.6250 precision = 0.0000 correlation = 0.2182 errorRate = 0.3750  
TruePositives = 0.0000 FalsePositives = 1.0000 TrueNegatives = 5.0000 FalseNegatives = 2.0000
class 2.0: Streets  
accuracy = 0.8750 precision = 0.8667 correlation = 0.7054 errorRate = 0.1250  
TruePositives = 2.0000 FalsePositives = 1.0000 TrueNegatives = 5.0000 FalseNegatives = 0.0000
class 3.0: Green  
accuracy = 0.8750 precision = 1.0000 correlation = 0.6547 errorRate = 0.1250  
TruePositives = 1.0000 FalsePositives = 0.0000 TrueNegatives = 6.0000 FalseNegatives = 1.0000

Using Testing dataset, % correct predictions = 50.0000

Total samples = 20  
RMSE = 0.7071067811865476  
Bias = -0.25

**Distribution:**

class 0.0: ClassificationBuildings 5 (25.00000%)
class 1.0: Classificationsoil 5 (25.00000%)
class 2.0: Classificationstreets 5 (25.00000%)
class 3.0: Classificationgreen 5 (25.00000%)

Testing feature importance score:  
Each feature is perturbed 3 times and the % correct predictions are averaged  
The importance score is the original % correct prediction - average

rank 1 feature 1: BRSA_mst_20Mar2020 score: tp=0.2500 accuracy=0.1250 precision=0.2708 correlation=0.2507 errorRate=0.1250 cost=-Inf GainRatio = 0.6882  
rank 2 feature 3: BCI_mst_20Mar2020 score: tp=0.1667 accuracy=0.0833 precision=0.0972 correlation=0.1521 errorRate=0.0833 cost=-0.2917 GainRatio = 0.6882  
rank 3 feature 7: Sigma0_INV_VH_GLC/Mariance_slv1_30Nov2020 score: tp=0.1250 accuracy=0.0625 precision=0.0833 correlation=0.1500 errorRate=0.0625 cost=-0.1250 GainRatio = 0.6882

**Warning:** rank <= feature&endlist.length
Table 3-3. Classification for Sentinel-2 only

<table>
<thead>
<tr>
<th>Cross Validation</th>
<th>Number of classes = 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>class 0.0: Buildings</td>
<td>accuracy = 0.2502 precision = 0.2500 correlation = 0.0173 errorRate = 0.7498</td>
</tr>
<tr>
<td></td>
<td>TruePositives = 2499.0000 FalsePositives = 7497.0000 TrueNegatives = 3.0000 FalseNegatives = 1.0000</td>
</tr>
<tr>
<td>class 1.0: Soil</td>
<td>accuracy = 0.7500 precision = NaN correlation = NaN errorRate = 0.2500</td>
</tr>
<tr>
<td></td>
<td>TruePositives = 0.0000 FalsePositives = 0.0000 TrueNegatives = 7500.0000 FalseNegatives = 2500.0000</td>
</tr>
<tr>
<td>class 2.0: Classificationstreets</td>
<td>accuracy = 0.7500 precision = NaN correlation = NaN errorRate = 0.2500</td>
</tr>
<tr>
<td></td>
<td>TruePositives = 0.0000 FalsePositives = 0.0000 TrueNegatives = 7500.0000 FalseNegatives = 2500.0000</td>
</tr>
<tr>
<td>class 3.0: Green</td>
<td>accuracy = 0.7502 precision = 0.7500 correlation = 0.0289 errorRate = 0.2498</td>
</tr>
<tr>
<td></td>
<td>TruePositives = 3.0000 FalsePositives = 1.0000 TrueNegatives = 7499.0000 FalseNegatives = 2497.0000</td>
</tr>
</tbody>
</table>

Using Testing dataset, % correct predictions = 25.0200

Total samples = 200000
RMSE = 1.870347561253731
Bias = -1.4988

Distribution:
| class 0.0: ClassificationBuildings | 5000 (25.0000%) |
| class 1.0: Classificationsoil | 5000 (25.0000%) |
| class 2.0: Classificationstreets | 5000 (25.0000%) |
| class 3.0: ClassssificationGreen | 5000 (25.0000%) |

Testing feature importance score:
Each feature is perturbed 3 times and the % correct predictions are averaged
The importance score is the original % correct prediction - average

<table>
<thead>
<tr>
<th>rank</th>
<th>feature</th>
<th>description</th>
<th>score</th>
<th>tp</th>
<th>accuracy</th>
<th>precision</th>
<th>recall</th>
<th>correlation</th>
<th>errorRate</th>
<th>cost</th>
<th>Infinity Gain</th>
<th>GainRatio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>feature 11</td>
<td>ORBAN_mst_20Mar2020</td>
<td>tp = 0.0000</td>
<td>accuracy = 0.0001</td>
<td>precision = 0.1072</td>
<td>correlation = 0.0110</td>
<td>errorRate = 0.0001</td>
<td>cost = 0.1197</td>
<td>Infinity Gain Ratio = 0.1197</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>feature 12</td>
<td>NBI_mst_20Mar2020</td>
<td>score = tp = 0.0000</td>
<td>accuracy = 0.0001</td>
<td>precision = 0.0238</td>
<td>correlation = 0.0101</td>
<td>errorRate = 0.0001</td>
<td>cost = 0.3331</td>
<td>GainRatio = 0.0645</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>feature 13</td>
<td>SCI_mst_20Mar2020</td>
<td>score = tp = 0.0001</td>
<td>accuracy = 0.0001</td>
<td>precision = 0.0238</td>
<td>correlation = 0.0083</td>
<td>errorRate = 0.0001</td>
<td>cost = Infinity Gain Ratio = 0.1193</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>feature 14</td>
<td>S12_mst_20Mar2020</td>
<td>score = tp = 0.0000</td>
<td>accuracy = 0.0000</td>
<td>precision = 0.0000</td>
<td>correlation = 0.0000</td>
<td>errorRate = 0.0000</td>
<td>cost = 0.0000</td>
<td>GainRatio = 0.0000</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Warning: rank <= featureBandList.length
Table 3-4. A classification that produced 67.95 %

Cross Validation
Number of classes = 4
class 0.0: Buildings
  accuracy = 0.6350 precision = 0.6550 correlation = 0.6550 errorRate = 0.1650
  TruePositives = 1881.0000 FalsePositives = 1831.0000 TrueNegatives = 669.0000 FalseNegatives = 619.0000
class 1.0: Soil
  accuracy = 0.8872 precision = 0.7400 correlation = 0.7410 errorRate = 0.1129
  TruePositives = 2064.0000 FalsePositives = 692.0000 TrueNegatives = 6888.0000 FalseNegatives = 436.0000
class 2.0: Streets
  accuracy = 0.7935 precision = 0.5956 correlation = 0.5493 errorRate = 0.2065
  TruePositives = 1355.0000 FalsePositives = 920.0000 TrueNegatives = 6588.0000 FalseNegatives = 1145.0000
class 3.0: Green
  accuracy = 0.8433 precision = 0.7268 correlation = 0.6349 errorRate = 0.1567
  TruePositives = 1495.0000 FalsePositives = 562.0000 TrueNegatives = 6938.0000 FalseNegatives = 1005.0000

Using Testing dataset, % correct predictions = 67.9500
Total samples = 20000
RMSE = 1.85856725852641
Bias = -0.15239999999999

Distribution:
class 0.0: ClassificatioBuildings 5000 (25.0000%)
class 1.0: ClassificatioSoil 5000 (25.0000%)
class 2.0: ClassificatioStreets 5000 (25.0000%)
class 3.0: ClassificatioGreen 5000 (25.0000%)

Testing feature importance score:
Each feature is perturbed 3 times and the % correct predictions are averaged

The importance score is the original % correct prediction - average
rank 1 feature 2 : B3BA_mst_29Mar2020 score: tp=0.4560 accuracy=0.2284 precision=0.2284 correlation=0.4356 errorRate=0.2284 cost=0.9262 GainRatio = 0.1425rank 2 feature 4 : B2CI_mst_29Mar2020 score: tp=0.3728 accuracy=0.1864 precision=0.3551 correlation=0.3617 errorRate=0.1864 cost=0.7759 GainRatio = 0.1304rank 3 feature 3 : B3BA_mst_29Mar2020 score: tp=0.2290 accuracy=0.1145 precision=0.2226 correlation=0.2930 errorRate=0.2145 cost=0.3516 GainRatio = -0.5364
rank 4 feature 7 : Sigma0_D1z_DV_Contrast_s1v3_30Nov2020 score: tp=0.4115 accuracy=0.1051 precision=0.2027 correlation=0.2365 errorRate=0.1855 cost=0.3050 GainRatio = 0.2077
rank 5 feature 6 : Sigma0_D1z_DV_GlonVariance_s1v2_30Nov2020 score: tp=0.1965 accuracy=0.0983 precision=0.1539 correlation=0.2189 errorRate=0.0983 cost=0.2458 GainRatio = 0.1940
rank 6 feature 7 : Sigma0_D1z_DV_Contrast_s1v3_30Nov2020 score: tp=0.1811 accuracy=0.0906 precision=0.1759 correlation=0.2021 errorRate=0.0986 cost=0.2690 GainRatio = 0.0894
rank 7 feature 5 : Sigma0_D1z_DV_Contrast_s1v1_30Nov2020 score: tp=0.1873 accuracy=0.0951 precision=0.1551 errorRate=0.1827 cost=0.2544 GainRatio = 0.1133
rank 8 feature 1 : B3J_mst_29Mar2020 score: tp=0.0000 accuracy=0.0000 precision=0.0000 correlation=0.0000 errorRate=0.0000 cost=0.0000 GainRatio = 0.0000

160
Table 3.5. Selected bands by RT algorithm

Cross Validation
Number of classes = 4
Class 0.0: Buildings
  Accuracy = 0.7718, precision = 0.5246, correlation = 0.5993, error rate = 0.2284
  True Positives = 2394.0000, False Positives = 2888.0000, True Negatives = 5422.0000, False Negatives = 196.0000
Class 1.0: Soil
  Accuracy = 0.8501, precision = 0.7474, correlation = 0.6668, error rate = 0.1399
  True Positives = 1663.0000, False Positives = 562.0000, True Negatives = 6938.0000, False Negatives = 837.0000
Class 2.0: Streets
  Accuracy = 0.7611, precision = 0.5335, correlation = 0.4473, error rate = 0.2389
  True Positives = 885.0000, False Positives = 774.0000, True Negatives = 6726.0000, False Negatives = 1615.0000
Class 3.0: Green
  Accuracy = 0.8748, precision = 0.8596, correlation = 0.6727, error rate = 0.1260
  True Positives = 1482.0000, False Positives = 242.0000, True Negatives = 7258.0000, False Negatives = 1018.0000

Using Testing dataset, % correct predictions = 61.3400
Total samples = 20000
RMS = 1.0595854811196597
Bias = -0.42850000000000001

Distribution:
class 0.0: ClassificationBuildings = 5000 (25.00000)
class 1.0: ClassificationSoil = 5000 (25.00000)
class 2.0: ClassificationStreets = 5000 (25.00000)
class 3.0: ClassificationGreen = 5000 (25.00000)

Testing feature importance score:
Each feature is perturbed three times and the % correct predictions are averaged
The importance score is the original % correct prediction - average

rank 1: feature 11: B11A/mst_29Mar2000 score = 0.3784 accuracy = 0.1852 precision = 0.2994 correlation = 0.3479 error rate = 0.1852 cost = 0.7918 Gain Ratio = 0.1812
rank 2: feature 15: Sigma0_1W_2H_GLOM1/Lam_False_v3_3Nov2020 score = 0.2926 accuracy = 0.1463 precision = 0.1613 correlation = 0.3030 error rate = 0.1463 cost = 0.4175 Gain Ratio = 0.1652
rank 3: feature 13: B11A/mst_29Mar2000 score = 0.3333 accuracy = 0.1460 precision = 0.2639 correlation = 0.2316 error rate = 0.1460 cost = 0.6221 Gain Ratio = 0.1652
rank 4: feature 12: B11A/mst_29Mar2000 score = 0.2089 accuracy = 0.1464 precision = 0.2492 correlation = 0.2793 error rate = 0.2492 cost = 0.5353 Gain Ratio = 0.1575
rank 5: feature 17: Sigma0_1W_2H_GLOM1/Lam_v3_3Nov2020 score = 0.2123 accuracy = 0.1859 precision = 0.1859 correlation = 0.2265 error rate = 0.1859 cost = 0.3875 Gain Ratio = 0.1575
rank 6: feature 14: Sigma0_1W_2H_Contrast_v3_3Nov2020 score = 0.1493 accuracy = 0.0746 precision = 0.1193 correlation = 0.1554 error rate = 0.0746 cost = 0.2284 Gain Ratio = 0.
rank 7: feature 16: Sigma0_1W_2H_Contrast_v3_3Nov2020 score = 0.1300 accuracy = 0.0650 precision = 0.1353 correlation = 0.1388 error rate = 0.0650 cost = 0.2299 Gain Ratio = 0.
rank 8: feature 10: B12_mst_29Mar2020 score = 0.0000 accuracy = 0.0000 precision = 0.0000 correlation = 0.0000 error rate = 0.0000 cost = 0.0000 Gain Ratio = 0.0000

Warning: rank <= featureBandList.length
### Appendix 4 comparison between RT and SVM overall accuracy for different compounds

Table 4-1. SVM accuracy assessment for compound 4

<table>
<thead>
<tr>
<th>Class</th>
<th>Producer's 95% Confidence Interval</th>
<th>User's 95% Confidence Interval</th>
<th>Kappa Statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>room</td>
<td>65.71% (52.64% - 78.80%)</td>
<td>75.00% (30.74% - 100.00%)</td>
<td>0.718</td>
</tr>
<tr>
<td>vegetation</td>
<td>75.00% (64.33% - 85.99%)</td>
<td>69.25% (40.29% - 98.36%)</td>
<td>0.619</td>
</tr>
<tr>
<td>roof</td>
<td>92.23% (80.00% - 100.00%)</td>
<td>90.00% (69.37% - 100.00%)</td>
<td>0.000</td>
</tr>
<tr>
<td>streets</td>
<td>80.00% (31.93% - 100.00%)</td>
<td>60.00% (9.20% - 90.69%)</td>
<td>0.456</td>
</tr>
<tr>
<td>pedestrians</td>
<td>16.67% (0.00% - 54.82%)</td>
<td>100.00% (99.00% - 100.00%)</td>
<td>1.000</td>
</tr>
<tr>
<td>shades</td>
<td>88.89% (62.00% - 100.00%)</td>
<td>80.00% (50.28% - 100.00%)</td>
<td>0.767</td>
</tr>
<tr>
<td>trees</td>
<td>81.81% (54.48% - 100.00%)</td>
<td>75.00% (46.33% - 100.00%)</td>
<td>0.691</td>
</tr>
<tr>
<td>author</td>
<td>0.000% (0.00% - 0.00%)</td>
<td>0.000% (0.00% - 0.00%)</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Quantity Disagreement: 11.11% Allocation Disagreement: 14.28%

Table 4-2. RT accuracy assessment for compound 4

<table>
<thead>
<tr>
<th>Class</th>
<th>Producer's 95% Confidence Interval</th>
<th>User's 95% Confidence Interval</th>
<th>Kappa Statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>room</td>
<td>71.43% (39.81% - 99.00%)</td>
<td>83.33% (45.10% - 100.00%)</td>
<td>0.612</td>
</tr>
<tr>
<td>vegetation</td>
<td>66.67% (35.82% - 97.50%)</td>
<td>66.67% (35.82% - 97.50%)</td>
<td>0.682</td>
</tr>
<tr>
<td>roof</td>
<td>91.67% (71.86% - 100.00%)</td>
<td>84.61% (61.36% - 100.00%)</td>
<td>0.810</td>
</tr>
<tr>
<td>streets</td>
<td>60.00% (7.05% - 92.00%)</td>
<td>37.50% (0.00% - 77.29%)</td>
<td>0.321</td>
</tr>
<tr>
<td>pedestrians</td>
<td>16.67% (0.00% - 54.82%)</td>
<td>50.00% (0.00% - 100.00%)</td>
<td>0.447</td>
</tr>
<tr>
<td>shades</td>
<td>88.89% (62.00% - 100.00%)</td>
<td>61.50% (31.24% - 91.83%)</td>
<td>0.553</td>
</tr>
<tr>
<td>trees</td>
<td>72.72% (41.86% - 92.00%)</td>
<td>88.88% (62.00% - 100.00%)</td>
<td>0.854</td>
</tr>
<tr>
<td>author</td>
<td>0.000% (0.00% - 0.00%)</td>
<td>0.000% (0.00% - 0.00%)</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Quantity Disagreement: 12.69% Allocation Disagreement: 17.46%
Table 4-3 SVM accuracy assessment for compound 6

<table>
<thead>
<tr>
<th>Class</th>
<th>Overall Accuracy</th>
<th>95% Confidence Interval</th>
<th>Overall Kappa Statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Streets</td>
<td>97.59%</td>
<td>(74.47%, 100.00%)</td>
<td>0.9274</td>
</tr>
<tr>
<td>Ground</td>
<td>53.33%</td>
<td>(24.75%, 81.91%)</td>
<td>0.5583</td>
</tr>
<tr>
<td>Building type (white)</td>
<td>97.59%</td>
<td>(60.19%, 100.00%)</td>
<td>1.0000</td>
</tr>
<tr>
<td>Green</td>
<td>100.00%</td>
<td>(93.75%, 100.00%)</td>
<td>1.0000</td>
</tr>
<tr>
<td>Facades</td>
<td>50.00%</td>
<td>(1.65%, 98.34%)</td>
<td>0.4727</td>
</tr>
<tr>
<td>Additional room</td>
<td>90.47%</td>
<td>(75.54%, 100.00%)</td>
<td>0.6713</td>
</tr>
<tr>
<td>Building type 3</td>
<td>75.00%</td>
<td>(30.74%, 100.00%)</td>
<td>0.8466</td>
</tr>
<tr>
<td>Shingles</td>
<td>100.00%</td>
<td>(93.75%, 100.00%)</td>
<td>1.0000</td>
</tr>
<tr>
<td>Building type 2</td>
<td>100.00%</td>
<td>(75.00%, 100.00%)</td>
<td>1.0000</td>
</tr>
</tbody>
</table>

Quantity Disagreement: 4.31% Allocation Disagreement: 12.91%

Table 4-4 SVM accuracy assessment for compound 6

<table>
<thead>
<tr>
<th>Class</th>
<th>Overall Accuracy</th>
<th>95% Confidence Interval</th>
<th>Overall Kappa Statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Streets</td>
<td>90.62%</td>
<td>(78.93%, 100.00%)</td>
<td>0.8326</td>
</tr>
<tr>
<td>Ground</td>
<td>93.33%</td>
<td>(24.75%, 81.91%)</td>
<td>0.6688</td>
</tr>
<tr>
<td>Building type (white)</td>
<td>93.75%</td>
<td>(76.76%, 100.00%)</td>
<td>1.0000</td>
</tr>
<tr>
<td>Green</td>
<td>100.00%</td>
<td>(93.75%, 100.00%)</td>
<td>1.0000</td>
</tr>
<tr>
<td>Facades</td>
<td>50.00%</td>
<td>(1.65%, 98.34%)</td>
<td>0.4727</td>
</tr>
<tr>
<td>Additional room</td>
<td>90.47%</td>
<td>(75.54%, 100.00%)</td>
<td>0.6713</td>
</tr>
<tr>
<td>Building type 3</td>
<td>62.50%</td>
<td>(22.70%, 100.00%)</td>
<td>1.0000</td>
</tr>
<tr>
<td>Shingles</td>
<td>100.00%</td>
<td>(93.75%, 100.00%)</td>
<td>1.0000</td>
</tr>
<tr>
<td>Building type 2</td>
<td>50.00%</td>
<td>(0.00%, 100.00%)</td>
<td>1.0000</td>
</tr>
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</table>

Quantity Disagreement: 9.48% Allocation Disagreement: 9.62%
Appendix 5: Shadows analysis for building type 1 through December 2022

Figure 5-1. Shadow analysis from 6 am to 11 am in December (building type 1).
Figure 5-2. Shadow analysis from 12 pm to 5 pm in December (Building type1).
Appendix 6: Shadows analysis for building type 1 through June 2022

Figure 6-1. Shadow analysis from 6 am to 11 am in June (Building type 1).
Figure 6-2. Shadow analysis from 12 pm to 5 pm in June (Building type 1)
Appendix 7: Shadows analysis for building type 1 through March 2022

Figure 7-1. Shadow analysis from 6 am to 11 am in March (Building type 1).
Figure 7-2. Shadow analysis from 12 pm to 5 pm in March (Building type 1).
Appendix 8: Shadows analysis for building type 2 through December 2022

Figure 8-1. Shadow analysis from 6 am to 11 am in December (Building type 2)
Figure 8-2. Shadow analysis from 12 pm to 5 pm in December (Building type 2)
Appendix 9: Shadows analysis for building type 2 through March 2022

Figure 9-1. Shadow analysis from 6 am to 11 am in March (Building type 2)
Figure 9-2. Shadow analysis from 12 pm to 5 pm in March (Building type 2)
Appendix 10: Shadows analysis for building type 2 through June and March 2022

Figure 10-1. Shadow analysis from 6 am to 10 am in June (Building type 2)
Figure 10-2. Shadow analysis from 11 am to 4 pm in March (Building type 2)
Figure 10- Shadow analysis from 7 am to 11 pm in March (Building type 2)
Figure 10-4 Shadow analysis from 12 pm to 5 pm in March (Building type 2).
Appendix 11 Pyrometer Specifications

**Pyrometer**

For accurate measurement of solar irradiance

**IEC 61724 Class A**

- ISO 9060 Spectrally Flat Class A
- The solar energy industry standard
- Accurate and independent data for performance ratio calculations
- Analog and digital outputs
- 5 year warranty

**ISO 9060 & IEC 61724 Class A**

Models CMP10, CMP11, SMP10 and SMP11 are the high quality pyrometers that are most commonly used in meteorological networks and solar energy applications around the world and all comply with Class A of ISO 9060 and IEC 61724.

**Analog or digital outputs**

CMP10 and CMP11 do not require any power. Incoming solar radiation generates a continuous millivolts output, which is converted in a data logger to irradiance in W/m² using the calibrated sensitivity. For easy integration into SCADA systems SMP10 and SMP11 have Modbus® RTU RS-485 serial communication, plus an amplified analog output. The sensitivity is stored inside for standardized outputs and they feature improved response time and better temperature compensation.

**With or without drying cartridge**

To prevent internal condensation, pyrometers are fitted with a desiccant to keep the internal humidity low and the accuracy high. CMP11 and SMP11 have an external drying cartridge with a desiccant that needs regular inspection and replacement every 3 to 6 months, depending on the local climate conditions. To save maintenance time and cost, CMP10 and SMP10 have internal desiccant that lasts up to 10 years.

**5 Year Warranty**

All pyrometers from Kipp & Zonen come with a 5 year warranty and we have service and calibration centers around the world.
## Technical Specifications

<table>
<thead>
<tr>
<th>Classification to ISO WRR:2018</th>
<th>CMP10</th>
<th>CMP11</th>
<th>CMP10</th>
<th>CMP11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectrally flat Class A</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spectrally flat Class A</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensitivity</td>
<td>7 to 14 V (0 to 1 V)</td>
<td></td>
<td>7 to 14 V (0 to 1 V)</td>
<td></td>
</tr>
<tr>
<td>Impedance</td>
<td>1 kΩ to 120 kΩ</td>
<td></td>
<td>1 kΩ to 120 kΩ</td>
<td></td>
</tr>
<tr>
<td>Expected output range (0 to 1300 W/m²)</td>
<td>0 to 20 mA</td>
<td></td>
<td>0 to 20 mA</td>
<td></td>
</tr>
<tr>
<td>Maximum operational irradiance</td>
<td>4000 W/m²</td>
<td></td>
<td>4000 W/m²</td>
<td></td>
</tr>
<tr>
<td>Analog output - Voltage</td>
<td>-</td>
<td></td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Analog output range</td>
<td>-</td>
<td></td>
<td>-500 to 5000 W/m²</td>
<td></td>
</tr>
<tr>
<td>Analog output + Current</td>
<td>-</td>
<td></td>
<td>-500 to 5000 W/m²</td>
<td></td>
</tr>
<tr>
<td>Analog output + Deviation</td>
<td>-</td>
<td></td>
<td>-500 to 5000 W/m²</td>
<td></td>
</tr>
<tr>
<td>Serial output</td>
<td>-</td>
<td></td>
<td>-500 to 5000 W/m²</td>
<td></td>
</tr>
<tr>
<td>Serial output range</td>
<td>-</td>
<td></td>
<td>-500 to 5000 W/m²</td>
<td></td>
</tr>
<tr>
<td>Response time (±2%)</td>
<td>&lt; 0.1 s</td>
<td></td>
<td>&lt; 0.1 s</td>
<td></td>
</tr>
<tr>
<td>Response time (±5%)</td>
<td>&lt; 0.5 s</td>
<td></td>
<td>&lt; 0.5 s</td>
<td></td>
</tr>
<tr>
<td>Spectral range (25% points)</td>
<td>270 to 2030 nm</td>
<td></td>
<td>270 to 2030 nm</td>
<td></td>
</tr>
<tr>
<td>Spectral range (50% points)</td>
<td>255 to 2550 nm</td>
<td></td>
<td>255 to 2550 nm</td>
<td></td>
</tr>
<tr>
<td>Non-linearity (1000 to 1500 W/m²)</td>
<td>&lt; 0.2 %</td>
<td></td>
<td>&lt; 0.2 %</td>
<td></td>
</tr>
<tr>
<td>Directional response (0° to 80°) with 1000 W/m² beams</td>
<td>&lt; 10 W/m²</td>
<td></td>
<td>&lt; 10 W/m²</td>
<td></td>
</tr>
<tr>
<td>Spectral selectivity (300 to 1500 nm)</td>
<td>&lt; 3 %</td>
<td></td>
<td>&lt; 3 %</td>
<td></td>
</tr>
<tr>
<td>TIR: response (0° to 180°) at 1000 W/m²</td>
<td>&lt; 0.2 %</td>
<td></td>
<td>&lt; 0.2 %</td>
<td></td>
</tr>
<tr>
<td>Temperature response</td>
<td>&lt; 1 % (10°C to 40°C)</td>
<td></td>
<td>&lt; 1 % (20°C to 60°C)</td>
<td></td>
</tr>
<tr>
<td>Field of view</td>
<td>160°</td>
<td></td>
<td>160°</td>
<td></td>
</tr>
<tr>
<td>Accuracy of bubble level</td>
<td>&lt; 0.1 °</td>
<td></td>
<td>&lt; 0.1 °</td>
<td></td>
</tr>
<tr>
<td>Power consumption (at 12 VDC)</td>
<td>5.3 mmHg 55 mA</td>
<td></td>
<td>Average: 100 mA</td>
<td></td>
</tr>
<tr>
<td>Supply voltage</td>
<td>5 to 30 VDC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Software, Windows™</td>
<td>5Smart Explorer Software, for configuration, test and data logging</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Detector type:** Thermopile  | 5Smart Explorer Software, for configuration, test and data logging

**Field of view:** 160°  | 160°

**Temperature response:** < 1 % (10°C to 40°C)  | < 1 % (20°C to 60°C)

**Humidity range:** 10% to 100%  | 10% to 100%

**Storage temperature range:** -40°C to 80°C  | -40°C to 80°C

**Washdown time between failures:** > 10 years  | > 10 years

**IP rating:** 07  | 07

**Recommended applications:** Meteorological networks, PV panel and thermal collector testing, materials testing  | High performance for PV panel and thermal collector testing, solar energy research, solar panel testing, advanced materials testing, and climate research

---

**Note:** The performance specifications stated are worst-case and/or maximum values.


## Dimensions

![Dimensions Diagram](image)

179
Appendix 12 Weather Station Data Logger

CR1000 Specifications

Electric specifications are valid over a 25° to 60°C (77°F to 140°F), non-condensing environment, unless otherwise specified. Reconciliation recommended every three years. Critical specifications and system configuration should be confirmed with Campbell Scientific before purchase.

PROGRAM EXECUTION TIME
10 ms for each step of the application.

ANALOG INPUTS (12 at 618 or 12F-12FDR)
Analog inputs are filtered, high-impedance, current-source, 3.5 V, 0 to 5 V, 4 to 20 mA, 0 to 2.5 V, 10 V, or differential. Each channel contains a 1 kΩ resistor to ground. The maximum current draw is limited to 100 μA at 5 V,

DIN-RAIL INSTALLATION
A DIN-rail mounted enclosure is available for the CR1000 with integrated power supply. The enclosure is designed to accommodate two CR1000s. The DIN-rail mount is compatible with standard 35mm rail systems and requires M 3 screws for installation. The enclosure provides protection against dust, moisture, and other environmental factors.

COMMUNICATIONS
RS-232 PORTS
Two RS-232 ports are provided for communication with a computer or other instruments. These ports can be used for remote monitoring, data logging, or control applications. The RS-232 ports support standard 9-pin connectors and are compatible with standard RS-232 protocols. They can be configured for various baud rates, data bit lengths, and stop bits. Maximum data rate is 115,200 bps. The ports support both full-duplex and half-duplex communication modes.

RS-485 PORTS
Two RS-485 ports are provided for communication with other instruments that use a two-wire, half-duplex communication protocol. The RS-485 ports support standard 15-pin connectors and are compatible with standard RS-485 protocols. They can be configured for various baud rates, data bit lengths, and stop bits. Maximum data rate is 115,200 bps. The ports support both full-duplex and half-duplex communication modes.

USB PORT
A USB port is provided for communication with a computer or other instruments. The USB port supports standard mini-B connectors and is compatible with standard USB protocols. It can be used for data logging, control applications, or power supply. Maximum data rate is 115,200 bps. The port supports standard USB protocols, including USB 2.0 and USB 3.0.

Ethernet PORT
An Ethernet port is provided for communication with a computer or other instruments over a network. The Ethernet port supports standard RJ-45 connectors and is compatible with standard Ethernet protocols. It can be used for data logging, control applications, or power supply. Maximum data rate is 115,200 bps. The port supports standard Ethernet protocols, including Ethernet 802.3 and Ethernet 802.11.

COMPLIANCE INFORMATION
Various protocols and specifications are met, including: CE, DOC, ROHS, WEEE, IEC 61326, DIN EN 60950, and other regulatory requirements.
Appendix 13 Sample of Calculations

6.3 Calculating the solar angles

The hour angle \( \omega \) corresponding to a solar time of 5.5 a.m. (i.e average for period 5 a.m. to 6 a.m. Solar time is the angle the earth has rotated since solar noon), hence

\[
\omega = \left( \frac{360^\circ}{24 \, h} \right) \times (t_{sol}(h) - 12 \, h)
\]

\[
\omega = \left( \frac{360^\circ}{24 \, h} \right) \times (5.5 - 12) \, h = -37.5^\circ
\]

The corresponding value of \( n \) for the day of the month producing for the monthly average energy of July is \( n = 198 \) [242]. The declination \( \delta \) for this day is calculated according to Eq. (8, Solar Radiation Conversion)

\[
\delta = 23.45 \sin \left( 360 \frac{284 + n}{365} \right)
\]

\[
\delta = 23.45 \sin \left( 360 \frac{284 + 198}{365} \right) = 21.18^\circ
\]

To calculate the angle of incidence \( \theta \) at any hour angle, it is assumed that the collectors are facing south so \( \gamma = 0 \) and the latitude angle is \( \emptyset \approx 30^\circ \). The angle of incidence is calculated according to Eq. (7, Solar Radiation Conversion)

\[
\cos \theta = \sin \delta \sin \emptyset \cos \beta \cos \omega - \sin \delta \cos \emptyset \sin \beta \cos \gamma + \cos \delta \cos \emptyset \cos \beta \cos \omega \\
+ \cos \delta \sin \emptyset \sin \beta \cos \gamma \cos \omega + \cos \delta \sin \beta \sin \gamma \sin \omega
\]

\[
\theta = \cos^{-1} \left[ \sin(21.18) \sin(30) \cos(30) - \sin(21.183693) \cos(30) \sin(30) \cos(0) \right. \\
+ \cos(21.183693) \cos(30) \cos(0) \cos(-37.5) \\
+ \cos(21.183693) \sin(30) \sin(30) \cos(0) \cos(-37.5) \\
+ \cos(21.183693) \sin(30) \sin(0) \sin(-37.5) \] = 42.29°
\]

The solar zenith angle \( \theta_z \) is calculated according to Eq. (9, Solar Radiation Conversion)

\[
\cos \theta_z = \cos \emptyset \cos \delta \cos \omega + \sin \emptyset \sin \delta
\]

\[
\theta_z = \cos^{-1} \left[ \cos 30 \cos 21.18 \cos -37.5 + \sin 30 \sin 21.18 \right] = 34.78°
\]
6.4 Calculating the incident solar radiation on the PV panel

$R_b$ is calculated according to Eq. (5, Solar Radiation Conversion)

\[
R_b = \frac{\cos 42.29}{\cos 34.78} = 0.9
\]

The solar radiation incident on a horizontal plane outside of the atmosphere, $G_o$, is calculated according to Eq. (4, Solar Radiation Conversion)

\[
G_o = G_{sc} \left( 1 + 0.033 \cos \frac{360n}{365} \right) \cos \theta_z
\]

\[
G_o = 1.367 \left( 1 + 0.033 \cos \frac{360 \times 198}{365} \right) \cos 34.78 = 1.087 \text{ kW/m}^2
\]

Since $I_o$, is the integration of the solar radiation incident on a horizontal plane outside of the atmosphere, $G_o$, over an hour, as a result $I_o = 1.087 \text{ kWh/m}^2$. The trapezoidal law is utilized to integrate the total irradiance, $G$, over an hour, as shown

\[
I = \left( \frac{726.8 \text{ W/m}^2 + 503.2 \text{ W/m}^2}{2} \times 1 \text{ hr} \right) \times 0.001 \frac{\text{kWh/m}^2}{\text{Wh/m}^2} = 0.615 \text{ kWh/m}^2
\]

The hourly clearness index $k_T$ is calculated according to Eq. Error! Reference source not found., Solar Radiation Conversion

\[
k_T = \frac{I}{I_o}
\]

\[
k_T = \frac{0.615}{1.087} = 0.566
\]

The hourly diffuse irradiation $I_d$ in kWh/m$^2$, is calculated using Eq. Error! Reference source not found., chapter 4.

for $k_T \leq 0.22$
\[
\frac{I_d}{I} = \begin{cases} 
1 - 0.09k_T & \text{for } 0.22 < k_T \\
0.9511 - 0.1604k_T + 4.388k_T^2 - 16.638k_T^3 + 12.336k_T^4 & \leq 0.80 \\
0.165 & \text{for } k_T > 0.8
\end{cases}
\]

\[
\frac{I_d}{I} = 0.9511 - 0.1604(0.566) + 4.388(0.566)^2 - 16.638(0.566)^3 + 12.336(0.566)^4 = 0.516
\]

\[
l_d = 0.615 \times 0.516 = 0.317 \text{ kWh/m}^2
\]

The hourly beam irradiation \( I_b \) in kWh/m\(^2\), is the difference between the hourly global irradiation, \( I \) received on a horizontal surface and the hourly diffuse irradiation, \( I_d \).

\[
l_b = I - I_d
\]

\[
l_b = 0.615 - 0.317 = 0.298 \text{ kWh/m}^2
\]

The anisotropy index \( A_i \) is calculated using Eq. (6, Solar Radiation Conversion)

\[
A_i = \frac{0.298}{1.087} = 0.274
\]

The value for the modulation factor \( f \) is

\[
f = \sqrt{\frac{l_b}{l}}
\]

\[
f = \sqrt{\frac{0.298}{0.615}} = 0.696
\]

Finally, Eq. Error! Reference source not found. , chapter 4, is used to calculate the hourly irradiation on the PV.

\[
I_T = (l_b + I_dA_i)R_b + I_d(1 - A_i) \left(\frac{1 + \cos \beta}{2}\right) \left[1 + f \sin\left(\frac{\beta}{2}\right)\right] + I_d \rho g \left(1 - \cos \beta\right) \frac{1}{2}
\]
\[ I_T = (0.298 + 0.317 \times 0.274)^{0.9} \]
\[ + 0.317(1 - 0.274) \frac{(1 + \cos 30)}{2} \left[ 1 + 0.696 \sin^3 \left( \frac{30}{2} \right) \right] + 0.615 \]
\[ \times 0.2 \frac{(1 - \cos 30)}{2} = 0.572 \, \text{kWh/m}^2 \]
Appendix 14 PV Characteristics

Model: Tiger Pro Jinko Solar model JKM535M-72HL4 PVs
Engineering Drawings

Electrical Performance & Temperature Dependence

Mechanical Characteristics
- Cell Type: P type Mono-crystalline
- No. of cells: 144 (8x18)
- Dimensions: 2274x1154x35mm (89.53x44.65x1.38 inch)
- Weight: 29.9 kg (63.7 lbs)
- Front Glass: 3.2mm Anti-Reflection Coating, High Transmittance, Low Iron, Tempered Glass
- Frame: Anodized Aluminum Alloy
- Junction Box: IP67 Rated
- Output Cables: TUV 1x4.0mm² (+/-), 400mm or Customized Length

Packaging Configuration
- 21 pieces per stack

SPECIFICATIONS

<table>
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<tr>
<th>Module Type</th>
<th>JKM500M-72H4</th>
<th>JKM515M-72H4</th>
<th>JKM540M-72H4</th>
<th>JKM45M-72H4</th>
<th>JKM500M-72H4</th>
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<tr>
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<td>STC NOCT</td>
<td>STC NOCT</td>
<td>STC NOCT</td>
<td>STC NOCT</td>
<td></td>
</tr>
<tr>
<td>Maximum Power (Pmax)</td>
<td>535Wp</td>
<td>530Wp</td>
<td>540Wp</td>
<td>545Wp</td>
<td>550Wp</td>
</tr>
<tr>
<td>Maximum Power Voltage (Vmp)</td>
<td>40.5V</td>
<td>37.8V</td>
<td>40.6V</td>
<td>37.9V</td>
<td>40.7V</td>
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<tr>
<td>Maximum Power Current (Imp)</td>
<td>13.07A</td>
<td>10.42A</td>
<td>13.17A</td>
<td>10.50A</td>
<td>13.27A</td>
</tr>
<tr>
<td>Open-circuit Voltage (Voc)</td>
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<td>46.6V</td>
<td>49.3V</td>
<td>46.6V</td>
<td>49.2V</td>
</tr>
<tr>
<td>Short-circuit Current (Isc)</td>
<td>13.71A</td>
<td>11.07A</td>
<td>13.79A</td>
<td>11.14A</td>
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</tr>
<tr>
<td>Module Efficiency STC (%)</td>
<td>20.50%</td>
<td>20.70%</td>
<td>20.94%</td>
<td>21.13%</td>
<td>21.33%</td>
</tr>
<tr>
<td>Operating Temperature(°C)</td>
<td>-40°C~+60°C</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Maximum system voltage</td>
<td>1000~1500VDC (EC)</td>
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<tr>
<td>Maximum series fusing rating</td>
<td>25A</td>
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<tr>
<td>Power tolerance</td>
<td>0~±3%</td>
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<tr>
<td>Temperature coefficients of Pmax</td>
<td>-0.35%/°C</td>
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<tr>
<td>Temperature coefficients of Voc</td>
<td>-0.21%/°C</td>
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<tr>
<td>Temperature coefficients of Isc</td>
<td>0.04%/°C</td>
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<tr>
<td>Nominal operating cell temperature (NOCT)</td>
<td>45±2°C</td>
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</table>

STC: ☀️ Irradiance 1000W/m²  Cell Temperature 25°C  AM=1.5
NOCT: ☀️ Irradiance 800W/m²  Ambient temperature 20°C  AM=1.5  Wind Speed 1m/s

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