

DEDICATION

I dedicate this work to the pursuit of knowledge and the relentless curiosity that drives scientific discovery.

To the experiences we never expected and the paths that were redirected.

Bharat Terang

DECLARATION BY THE CANDIDATE

I hereby declare that the thesis entitled "**A COMPREHENSIVE GIS-BASED FRAMEWORK FOR PHOTOVOLTAIC ENERGY PLANNING AND MANAGEMENT IN RURAL ASSAM**" has been submitted to the Department of Energy, Tezpur University, Assam, India, under the School of Engineering for partial fulfilment for the award of the degree of Doctor of Philosophy in Energy. This is an original work carried out by me under the supervision of Prof. Debendra Chandra Baruah. The research was conducted at the Energy Conservation Laboratory, Department of Energy, Tezpur University.

Additionally, I declare that no part of this work has been reproduced elsewhere for the award of any other degree from another university or institute.

All the assistance and support received from various sources have been duly acknowledged.

Date: 24/06/2025

Place: Tezpur


(Bharat Terang)



TEZPUR UNIVERSITY

(A Central University Established by an Act of Parliament of India)

Napaam, Tezpur - 784028

Assam, India

Prof. Debendra Chandra Baruah

Professor

Department of Energy, Tezpur University

E-mail: baruahd@tezu.ernet.in

Ph. No. : +91 3712 27 5301 (O)

+91-6001007767 (M)

Fax: +91-3712 267005/6

CERTIFICATE BY THE SUPERVISOR

This is to certify that the thesis entitled "**A COMPREHENSIVE GIS-BASED FRAMEWORK FOR PHOTOVOLTAIC ENERGY PLANNING AND MANAGEMENT IN RURAL ASSAM**" submitted to Tezpur University in the Department of Energy under the School of Engineering, in partial fulfillment for the award of the degree of Doctor of Philosophy in Energy, including coursework, is a record of original work carried out by Mr. Bharat Terang under my supervision and guidance. He has complied with all the requirements stipulated in Tezpur University's regulations.

All assistance and support he received from various sources have been duly acknowledged.

No part of this thesis has been reproduced elsewhere for the award of any other degree.

(Prof. Debendra Chandra Baruah)

Date: 24.06.25

Place: Tezpur

DECLARATION BY THE CANDIDATE

I hereby declare that the thesis entitled "**A COMPREHENSIVE GIS-BASED FRAMEWORK FOR PHOTOVOLTAIC ENERGY PLANNING AND MANAGEMENT IN RURAL ASSAM**" has been submitted to the Department of Energy, Tezpur University, Assam, India, under the School of Engineering for partial fulfilment for the award of the degree of Doctor of Philosophy in Energy. This is an original work carried out by me under the supervision of Prof. Debendra Chandra Baruah. The research was conducted at the Energy Conservation Laboratory, Department of Energy, Tezpur University.

Additionally, I declare that no part of this work has been reproduced elsewhere for the award of any other degree from another university or institute.

All the assistance and support received from various sources have been duly acknowledged.

Date:

(Bharat Terang)

Place: Tezpur



TEZPUR UNIVERSITY

(A Central University Established by an Act of Parliament of India)

Napaam, Tezpur - 784028
Assam, India

Prof. Debendra Chandra Baruah
Professor
Department of Energy, Tezpur University
E-mail: baruahd@tezu.ernet.in

Ph. No. : +91 3712 27 5301 (O)
+91-6001007767 (M)
Fax: +91-3712 267005/6

CERTIFICATE BY THE SUPERVISOR

This is to certify that the thesis entitled "**A COMPREHENSIVE GIS-BASED FRAMEWORK FOR PHOTOVOLTAIC ENERGY PLANNING AND MANAGEMENT IN RURAL ASSAM**" submitted to Tezpur University in the Department of Energy under the School of Engineering, in partial fulfillment for the award of the degree of Doctor of Philosophy in Energy, including coursework, is a record of original work carried out by Mr. Bharat Terang under my supervision and guidance. He has complied with all the requirements stipulated in Tezpur University's regulations.

All assistance and support he received from various sources have been duly acknowledged.

No part of this thesis has been reproduced elsewhere for the award of any other degree.

Date:

(Prof. Debendra Chandra Baruah)

Place:



TEZPUR UNIVERSITY

(A Central University Established by an Act of Parliament of India)

Napaam, Tezpur - 784028

Assam, India

Ph. No. : +91 3712 27 5301 (O), Fax: +91-3712 267005/6

CERTIFICATE

This is to certify that the thesis entitled "**A COMPREHENSIVE GIS-BASED FRAMEWORK FOR PHOTOVOLTAIC ENERGY PLANNING AND MANAGEMENT IN RURAL ASSAM**" submitted to Tezpur University in the Department of Energy under the School of Engineering, in partial fulfillment for the award of the degree of Doctor of Philosophy in Energy, by Mr. Bharat Terang, has been examined by us on.....and found to be satisfactory.

The committee recommends the award of the degree of Doctor of Philosophy.

Supervisor

External Examiner

Date:

Date:

ACKNOWLEDGEMENT

"From patience comes wisdom, from humility comes honour, from absence of envy comes knowledge, and from knowledge comes liberation." - Bhagavad Gita 13.8

First and foremost, I express my deepest gratitude to the Almighty for guiding my steps and showering blessings upon me throughout this journey.

To my beloved family, especially my father Mukut Terang, mother Rengka Rongpipi, younger sister Rupmili, and younger brother Kiri, your boundless love, understanding, and support have been my rock and my refuge, sustaining me through the highs and lows of this academic endeavour. I am deeply thankful for your encouragement and sacrifices.

To my esteemed PhD supervisor, Prof. Debendra Chandra Baruah, your guidance has been the compass steering me through the seas of research. Your wisdom, patience, and belief in my potential have been the guiding stars illuminating my path, and I am truly grateful for the mentorship you have provided.

I extend my sincere gratitude to my Doctoral Committee, Prof Sadhan Mahapatra (Head of Department), Dr. Nabin Sarmah, and Prof. Bhogeswar Borah (External). Special thanks also to the faculty members, Prof. Dhanapati Deka, Prof. Rupam Kataki, Dr. Pradyumna Kumar Chaudhury, and Dr Vikas Verma, your insightful feedback and encouragement have been the wind beneath my wings, propelling me forward with renewed vigor and determination. I also express my gratitude to the non-teaching staff of the Department of Energy for their support throughout this journey.

My heartfelt thanks go to Prof. Marco Fiala and Dr. Luca Nonini at the University of Milan, Italy for hosting me in their lab and enriching my academic journey during my time as a Visiting Scholar under the AdaptNET Erasmus+ Capacity Building Project in Higher Education program (May 2022 to July 2022). Your hospitality and guidance greatly enhanced my research experience.

I am grateful to my colleagues from the State Innovation and Transformation Aayog (SITA) project team, Dr. Moonmoon Hiloidhari, Dr. Dipal Baruah, and Miss. Sherlyn Teronpi, for their assistance in GIS work.

The successful completion of this study was made possible through the invaluable assistance and cooperation extended by various individuals and organizations. I extend my gratitude to the North Eastern Space Application Centre (NESAC), Meghalaya, for their training program, and National Remote Sensing Centre (NRSC), Hyderabad, for providing essential data critical to my analysis. Special appreciation goes to Miss. Pirbi Tissopi, Mr. Rangbamon Teron, and Mr. Saiful Islam for their generous contribution of agricultural and field-level data, which has significantly enriched the depth and breadth of this academic research.

I am deeply grateful to the Ministry of Tribal Affairs, Government of India, for providing financial assistance through the NFST fellowship from 2018-2023, which enabled me to pursue my academic aspirations.

To my labmates in the Energy Conservation Laboratory, including Dr. Barkhang Brahma, Dr. Trinakshee Sarmah, Mr. Isfakur Rasul, Mr. Zipshit Saikia, Mr. Dipjyoti Gowala, Mr. Shubhajeet Barman and Mr. Ankit Das for their support and encouragement.

To all my friends from the department, thank you for infusing each day with joy and making this academic journey both enjoyable and enriching.

In the grand symphony of academia, each of you has played a vital melody, enriching my experience and shaping my growth. For this, I am eternally grateful.

Lastly, I want to thank me for believing in myself, for putting in all those long hours, for staying focused, and for never giving up when it got tough. I want to thank me for pushing through the late nights, the setbacks, and the sacrifices. I want to thank me for the hard work, dedication, and perseverance that got me here today. Most of all, I want to thank me for finishing what I started.

***With heartfelt appreciation,
Bharat Terang***

LIST OF TABLES

| Table Number | Description | Page No. |
|---------------------|--|-----------------|
| Table 1.1 | Estimated renewable energy potential by State/UT | 7 |
| Table 1.2 | State-wise installed capacity of renewable power | 8 |
| Table 3.1 | Village demographics and household survey data | 68 |
| Table 3.2 | PV technology types with efficiency, area requirements, and key features | 70 |
| Table 3.3 | Data sources and parameters considered for the study | 82 |
| Table 3.4 | Characteristics of the sentinel 2A data used in this study | 83 |
| Table 3.5 | Land Use Land Cover (LULC) classes, classification criteria, and descriptions | 96 |
| Table 3.6 | Total energy production and utilization metrics for different energy systems in the study area | 105-106 |
| Table 3.7 | LCA phases and assumptions parameters for RTS, GMS, and SWP systems | 137 |
| Table 3.8 | The assumptions made in the study are summarised | 139 |
| Table 3.9 | The key limitations considered in the study are summarized | 140 |
| Table 3.10 | Lifecycle GHG emissions by phases for RTS, GMS and, SWP systems | 140 |
| Table 3.11 | Net GHG reductions for RTS, GMS, and SWP systems | 140 |
| Table 4.1 | Irrigation schemes in Assam, India | 149 |
| Table 4.2 | Crop selection for the analysis | 152 |
| Table 4.3 | Cost calculation and assumptions for the pumping options | 157 |
| Table 4.4 | Emission factors for the energy sources for pumping options | 158 |
| Table 4.5 | Description of pumping options considered | 162 |
| Table 4.6 | Annual cost of irrigation (₹) | 163 |
| Table 4.7 | Estimated CO ₂ emission of the pumping options (kg/y/ha) | 163 |
| Table 4.8 | Specifications and considerations of SWP | 164 |
| Table 4.9 | Estimated value of CO ₂ emission for the pumping options | 165 |
| Table 4.10 | Revenue per year for different pumping options | 165 |

| Table Number | Description | Page No. |
|--------------|---|----------|
| Table 4.11 | Net Present Value for 10 years | 166 |
| Table 4.12 | The payback period for pumping options | 166 |
| Table 4.13 | Ranking based on <i>CoI</i> by <i>Rt</i> | 167 |
| Table 4.14 | Battery specifications and energy requirements for charging | 174-175 |
| Table 5.1 | Analysis of barriers and enablers for scaling solar PV systems | 190-191 |
| Table 5.2 | Key parameters used for business model analysis | 202-203 |
| Table 5.3 | Consolidated data sources for financial assessment of RTS systems in India | 205-206 |
| Table 5.4 | Component-wise capital expenditure analysis for RTS systems | 206 |
| Table 5.5 | Financial analysis of RTS systems | 207 |
| Table 5.6 | Costing and sales analysis of (1-3 kW) RTS systems with targeted sales 48 units | 210 |
| Table 5.7 | 10-Year revenue projections | 210 |
| Table 5.8 | Case study - analysis for 3 kW RTS system | 212 |
| Table 5.9 | Calculated levelized cost of electricity for 1–10 kW RTS systems | 214 |
| Table 5.10 | NPV analysis for 1–10 kW RTS systems | 215 |
| Table 5.11 | Simple payback period for 1–10 kW RTS systems | 216 |
| Table 5.12 | Cost breakdown of GMS systems across different capacities | 219 |
| Table 5.13 | Revenue streams analysis for GMS systems across various capacities | 220 |
| Table 5.14 | Payback period analysis for GMS systems across different capacities | 221 |
| Table 5.15 | Land use efficiency analysis for GMS systems across different capacities | 221-222 |
| Table 5.16 | Sensitivity analysis of GMS revenue and payback period under varying financial and operational parameters | 222-223 |

LIST OF FIGURES

| Figure Number | Description | Page No. |
|---------------|--|----------|
| Fig. 1.1 | Total energy supply by source, World, 1990–2022 | 1 |
| Fig. 1.2 | Total energy supply by source, India, 1990–2022 | 2 |
| Fig. 1.3 | Sector-wise India’s installed capacity of electricity | 3 |
| Fig. 1.4 | Percentage of renewable energy sources | 5 |
| Fig. 1.5 | Trend in RES cumulative installed capacity | 6 |
| Fig. 3.1 | Conceptual framework representing a description of physical systems | 58 |
| Fig. 3.2 | PV potential assessment framework for RTS, GMS, and SWP systems | 64 |
| Fig. 3.3 | Location map of the selected study area | 66 |
| Fig. 3.4 | Layout map of villages in the study area with names and boundaries | 67 |
| Fig. 3.5 | Distribution of the number of households across villages | 68 |
| Fig. 3.6 | PVlib simulation flowchart: Steps for photovoltaic energy system modelling | 78 |
| Fig. 3.7 | Road network of the study area | 85 |
| Fig. 3.8 | Methodology for solar data analysis | 86 |
| Fig. 3.9 | Validation of NASA data with ground data for Tezpur | 87 |
| Fig. 3.10 (a) | Daily solar irradiance incident on a selected location in the study area | 88 |
| Fig. 3.10 (b) | Time series of daily all sky surface shortwave downward irradiance | 88 |
| Fig. 3.11 (a) | Solar insolation map of India | 90 |
| Fig. 3.11 (b) | Solar insolation map of Assam | 90 |
| Fig. 3.11 (c) | Solar insolation map of Sonitpur district | 91 |
| Fig. 3.11 (d) | Solar insolation map of the study area (10 km ²) | 91 |
| Fig. 3.12 (a) | Five-year daily average of ambient temperature (T2M) | 92 |
| Fig. 3.12 (b) | Five-year time series of ambient temperature (T2M) | 93 |

| Figure Number | Description | Page No. |
|----------------------|---|-----------------|
| Fig. 3.13 (a) | Five-year daily average of wind speed at 10 m (WS10M) | 94 |
| Fig. 3.13 (b) | Five-year time series of wind speed at 10 m (WS10M) | 95 |
| Fig. 3.14 (a) | Identifying ground mounted options based on RFC method | 98 |
| Fig. 3.14 (b) | Identifying built-up area for RTS options based on MLC | 99 |
| Fig. 3.14 (c) | Distribution of cropland in the study area (on-screen digitization) | 100 |
| Fig. 3.15 (a) | Map representing area available for installation of RTS in the study area | 101 |
| Fig. 3.15 (b) | Map representing area available for installation of GMS in the study area | 102 |
| Fig. 3.15 (c) | Map representing cropland for installation of SWP in the study area | 104 |
| Fig. 3.16 | Annual average PV system output | 105 |
| Fig. 3.17 (a) | Map of village-wise spatial distribution of RTS installation capacity | 106 |
| Fig. 3.17 (b) | Map of village-wise spatial distribution of RTS generation capacity | 108 |
| Fig. 3.18 (a) | Map of village-wise spatial distribution of GMS installation capacity | 109 |
| Fig. 3.18 (b) | Map of village-wise spatial distribution of GMS generation potential | 110 |
| Fig. 3.19 (a) | Map of village-wise SWP installation capacity | 111 |
| Fig. 3.19 (b) | Map of village-wise SWP generation potential | 112 |
| Fig. 3.19 (c) | Map of village-wise surplus energy from SWP systems | 113 |
| Fig. 3.20 (a) | Monthly energy generation for RTS system | 114 |
| Fig. 3.20 (b) | Monthly energy generation for GMS system | 115 |
| Fig. 3.20 (c) | Monthly energy generation for SWP system | 115 |
| Fig. 3.20 (d) | Monthly surplus energy from SWP system | 116 |
| Fig. 3.21 | Layout map of proposed EV charging infrastructure utilizing surplus energy from SWP systems | 120 |
| Fig. 3.22 | Framework for lifecycle GHG emission estimation | 128 |

| Figure Number | Description | Page No. |
|----------------------|---|-----------------|
| Fig. 4.1 | Flowchart for the comparative assessment of SWP with DWP and EWP. | 151 |
| Fig. 4.2 | Location map of the study area | 152 |
| Fig. 4.3 | Basin irrigation | 153 |
| Fig. 4.4 | Furrow irrigation | 153 |
| Fig. 4.5 | Flowchart for selection of pump | 155 |
| Fig. 4.6 | Daily incident solar insolation in Jhawani-3 village | 156 |
| Fig. 4.7 | Rate of subsidy for SWP to match the capital cost of DWP and EWP | 168 |
| Fig. 4.8 | Rate of subsidy for SWP to match the annual ownership cost of DWP and EWP | 168 |
| Fig. 4.9 | Energy management algorithm | 177 |
| Fig. 5.1 | Cost-benefit analysis of RTS system for capacities ranging from (1 to 10 kW) | 208 |
| Fig. 5.2 | Cost breakdown of RTS systems (1 to 10 kW) | 208 |
| Fig. 5.3 | Profit margin analysis of RTS systems for capacities ranging from 1 to 10 kW | 209 |
| Fig. 5.4 | Cumulative profit analysis across RTS systems ranging from 1 to 10 kW | 209 |
| Fig. 5.5 | Annual revenue analysis for 1-3 kW RTS systems with a targeted sales volume of 48 units per year | 211 |
| Fig. 5.6 | Cumulative revenue analysis over 10 years for 1-3 kW RTS systems with a targeted sales volume of 48 units per year | 211 |
| Fig. 5.7 | Sensitivity analysis of total revenue (Million ₹) and payback period (Years) for GMS systems at varying CUF, interest rates, and tariff rates | 223 |

LIST OF ABBREVIATIONS

| Abbreviation | Full form |
|--------------|--|
| AC | Alternating current |
| AI | Artificial intelligence |
| BESS | Battery energy storage systems |
| BOS | Balance of system |
| CEA | Central electricity authority |
| CFA | Central financial assistance |
| CR | Crop rotation |
| DC | Direct current |
| DI | Duration of irrigation |
| DISCOMs | Distribution companies |
| DOI | Days of irrigation |
| DWP | Diesel water pump |
| EMS | Energy management system |
| EOL | End-of-life |
| EV | Electric vehicle |
| EWP | Electrical water pump |
| FiTs | Feed-in-tariffs |
| FL | Frictional lift |
| FPO | Farmer producer organizations |
| GHG | Greenhouse Gas |
| GMS | Ground mounted solar |
| GW | Gigawatt |
| INDC | Intended nationally determined contributions |
| kWh | Kilowatt-hour |
| LCA | Lifecycle analysis |
| LULC | Land use land cover |
| MFI | Microfinance institutions |
| MNRE | Ministry of new and renewable energy |
| MPPT | Maximum power point tracking |

| Abbreviation | Full form |
|--------------|---|
| MSP | Minimum support prices |
| MW | Megawatt |
| NGO | Non-governmental organization |
| O&M | Operation and maintenance |
| PAYG | Pay as you go |
| PM-KUSUM | Pradhan Mantri Kisan Urja Suraksha evam Utthan Mahabhiyan |
| PPA | Power purchase agreement |
| PPP | Public-private partnerships |
| PR | Performance ratio |
| PV | Photovoltaic |
| REPP | Renewable energy-based power plants |
| ROI | Return on Investment |
| RTS | Rooftop solar |
| SHG | Self-help groups |
| STC | Standard test conditions |
| SWP | Solar photovoltaic water pump |

LIST OF SYMBOLS

| Symbol | Meaning |
|--------------------|---|
| A_{SWP} | Area of solar PV |
| $B_{capacity}$ | Battery capacity |
| $C_{O\&M}$ | Operation & maintenance cost |
| CO_2 | Carbon Emission reduction |
| C_{cap} | Capital cost |
| C_{net} | Net consumer cost |
| C_t | Capital cost at time t |
| C_{total} | Total system cost |
| $D_{transport}$ | Transportation distance |
| E_h | Hydraulic energy |
| E_{EV} | EV energy demand |
| $EF_{battery}$ | Emission factor of the battery |
| EF_{diesel} | Emission factor for diesel |
| $EF_{disposed}$ | Emission factor for disposal process |
| $EF_{install}$ | Installation emission factor |
| $EF_{inverter}$ | Emission factor of the inverter |
| $EF_{maintenance}$ | Emissions factor from maintenance activities |
| EF_{pv} | Emission factor of PV module |
| $EF_{recycle}$ | Emission factor during recycling process |
| $EF_{transport}$ | Transportation emission factor |
| E_{SWP} | Energy generated by solar photovoltaic water pumping system |
| $E_{charged}$ | Energy stored in the battery |
| E_e | Electrical energy |
| E_{grid} | Grid energy |
| $E_{irrigation}$ | Energy requirement for irrigation |
| E_{pump} | Energy required for water pumping |
| E_{req} | Energy requirement of the battery |

| Symbol | Meaning |
|---------------------|--|
| E_{sol} | Solar insolation |
| E_{sol} | Solar insolation |
| E_{solar} | Solar energy generation |
| $E_{supplied}$ | Energy supplied to the battery |
| $E_{surplus}$ | Excess energy available from SWP |
| E_t | Energy generated at time t |
| F_{tilt} | Panel tilt angle |
| $GHG_{O\&M}$ | GHG emissions during operation and maintenance phase |
| GHG_{end} | End of life GHG emissions |
| $GHG_{install}$ | GHG emissions during installation phase |
| $GHG_{manufacture}$ | GHG emissions during manufacturing phase |
| $GHG_{reduction}$ | Reduction in GHG emission |
| GHG_{total} | Total lifecycle GHG emissions |
| $GHG_{transport}$ | GHG emission during transportation |
| I_0 | Leakage current |
| I_L | Light generated current |
| I_{batt} | Current of battery |
| $I_{capacity}$ | Inverter capacity |
| L_n | Diffusion length of electrons |
| L_p | Diffusion length of holes |
| $L_{shading}$ | Energy loss due to shading |
| M_t | Maintenance cost at time t |
| O_t | Operating cost at time t |
| P_{annual} | Annual profit |
| P_{inv} | Inverter capacity |
| P_{margin} | Profit margin |
| $P_{monthly}$ | Monthly profit |
| P_{pv} | PV system capacity |
| P_{solar_max} | Maximum power generated by the solar panels |
| R_t | Annual net cash flow at in year t |
| $T_{charging}$ | EV charging time |

| Symbol | Meaning |
|-------------------|---|
| T_{life} | Total lifespan of PV system |
| T_{module} | Module temperature |
| V_{batt} | Voltage of battery |
| $W_{disposed}$ | Weight of disposed components |
| W_{labor} | Total labour hours for installation |
| $W_{recycled}$ | Total weight of recycled PV system components |
| W_{weight} | Total weight of all PV system |
| t_c | Battery charging duration |
| η_{PV} | Efficiency of PV module |
| $\eta_{charging}$ | EV charging efficiency |
| η_{inv} | Inverter efficiency |
| $\eta_{storage}$ | Efficiency of the battery storage system |
| η_{surf} | Surface efficiency |
| ω_o | Solar hour angle |
| ₹ | Rupees |
| °C | Degree Celsius |
| A | Area |
| CUF | Capacity utilization factor |
| $E_{storage}$ | Battery energy storage requirements |
| I | Current |
| k | Boltzmann constant |
| L | Project lifetime |
| $LCOE$ | Levelized cost of energy |
| n | Number of days |
| NPV | Net present value |
| PBP | Payback period |
| q | Charge on an electron |
| T | Temperature of the solar cell |
| V | Voltage |
| W | Width of depletion layer |
| ϕ | Latitude angle |

| Symbol | Meaning |
|-----------|---|
| Col | Cost of irrigation |
| $G(\tau)$ | Carrier generation rate |
| H | Hydraulic head of pump |
| $L(i, j)$ | Load requirement for EV charging at location i and time j |
| Q | Rate of flow of water |
| S | Government subsidy |
| g | Acceleration due to gravity |
| n | System lifetime |
| r | Discount rate |
| δ | Solar declination angle |
| ρ | Density of water |