Initiative for the Roads and Highways Department,
Government of the People's Republic of Bangladesh

Implemented by

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BANGLADESH: NATIONAL HIGHWAYS SOLAR POWER POTENTIAL IN RIGHT-OF-WAYS

Group Design Project

MSc Transport/Transport with Data Science

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23rd June 2025

Executive Summary

This report assesses the feasibility and potential for solar power generation within the right-of-way (ROW) of Bangladesh's national highways, focusing on maximizing land use efficiency in a densely populated country facing escalating electricity demand. The study, commissioned at the request of the World Bank, provides a macro-level evaluation with the aim of guiding the Roads and Highways Department (RHD) in future solar infrastructure planning and policy development.

Bangladesh's rapid development and limited available land pose significant challenges for expanding energy infrastructure. Using highway ROW for solar installation, an approach proven in international contexts, offers the dual benefit of powering roadside infrastructure (such as lighting and traffic systems) and potentially injecting surplus electricity into the grid, ultimately enhancing road safety and supporting national energy goals.

A multi-criteria methodology was adopted to rigorously assess the suitability of ROW segments for solar panel installation. First, exclusion criteria were applied to eliminate areas unsuitable for development due to factors such as environmental protection, flood and seismic risks, population density, topography, land constraints, and proximity to infrastructure such as pipelines and railways. Remaining segments were then scored using an Analytic Hierarchy Process (AHP), a robust method that assigns weights through pairwise comparisons of seven key criteria: flood risk, seismic risk, population density, solar irradiation, land area, proximity to the electric grid, and night light intensity (as a proxy for local power need). Distinct scoring systems were employed for grid-connected and off-grid deployment scenarios.

The analysis identified 27 candidate highway segments. The highest-priority segments (notably on the Dhaka-Cumilla-Chattogram-Teknaf and Daulatdia-Faridpur-Jhenaidah-Jashore-Khulna-Mongla routes) offer an optimal balance of solar resource quality, grid access, available land, and local electricity need. Solar generation calculations accounting for various panel suppliers and real-world efficiency-reducing conditions (e.g., monsoon season performances and dirt build-up) demonstrate that installing panels on only the top four ranked segments can generate enough electricity to meet or exceed the entire national highway lighting demand (over 40.7 million kWh annually). Even in the worst-case scenario, expanding to the top six or seven segments maintains this sufficiency.

Both grid-connected and off-grid solar systems are viable options for deployment along Bangladesh's highway corridors. Grid-connected systems should be strategically located near existing transmission infrastructure to optimize connectivity, while off-grid systems are recommended for regions with substantial unmet lighting needs.

The literature review underscores the recommendation to continue utilizing Public-Private Partnerships (PPPs), leveraging Bangladesh's successful history with PPPs and power purchase agreements (PPAs). Implementing transparent and competitive tendering processes, particularly through bundling grid-connected projects, will enhance efficiency and reduce overall costs. Effective execution of highway-integrated solar initiatives requires robust coordination across relevant government agencies, including transport, energy, and environmental ministries as well as active participation from private sector entities, development organizations, and local communities. Comprehensive stakeholder mapping combined with inclusive engagement strategies is crucial for long-term success.

Bangladesh's highway rights-of-way (ROW) offer significant solar generation potential capable of addressing national highway lighting requirements and contributing substantially to broader energy demands. By adopting structured PPP frameworks, transparent procurement processes, and inclusive governance models, Bangladesh is well-positioned to become a regional leader in sustainable, infrastructure-integrated solar energy initiatives. Recommendations have been made on adopting an initial trial site as a pilot project along the N1 national highway, delineation and quantification of ROW, and Battery as a service for areas that are further away from power grid lines.

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1. Introduction

This report conducts a study about the potential for solar power generation within the right-of-way (ROW) in Bangladesh.

Bangladesh is a developing nation with the 7th most densely populated country (The World Bank, 2025b) on the planet and so there is a growing demand for resources with land at a premium. Electricity consumption per capita is at 17.3% of the world average (The World Bank, 2025a), with rapidly growing demand which leads to questions of how to fulfil this in a sustainable manner.

The World Bank is already heavily involved in transport in Bangladesh through the US$1.1 billion Accelerating Transport and Trade Connectivity in Eastern South Asia (ACCESS) and US$758 million Western Economic Corridor and Regional Enhancement (WECARE) (The World Bank, 2020) programs. These are looking to enhance trade and transport by upgrading major highways from single to dual carriageways, whilst also introducing intelligent transport systems (ITS) and laying fibre optic cables. In addition to the World Bank, Japan International Cooperation Agency (JICA), a partner organisation, is also active in Bangladesh (Japan International Cooperation Agency (JICA), 2025).

In a country with little available land, of the few areas where solar panels can be placed is ROW of major highways. This has been done in the United States, with the earliest project dated to 2008. The electricity produced by such an installation could be used to power road lighting, traffic lights and ITS equipment as well as putting power back into the grid. Adding road lighting and traffic lights would reduce road accidents and their attendant effects, which was estimated to cost 5.1% of GDP in 2016. It is hoped that these advantages can be achieved with much lower upfront capital expenditure by arranging the solar power installation as a Public Private Partnership with a Power Purchase Agreement.

In 2023 it is estimated 0.65% of Bangladesh's energy came from solar power, despite its location close to the equator. Bringing the placing of solar panels in the highway ROW to Bangladesh would trial this innovated, environmental and cost-efficient method to lower operating costs of modernised highways as well as delivering electricity to a population that is underserved.

1.1 Scope of Project

This project aims to conduct a macro-level assessment to identify areas with high solar generation potential along the ROW of national highways (N1 to N8) in Bangladesh, as requested by the World Bank, and to support the Roads and Highways Department's (RHD) future planning and guidance.

1.2 Deliverables

The report will deliver the following:

i. Literature Review of the best practices of roadside renewable power generation for transport facilities with a particular focus on experiences in South Asia or Asia.
ii. Review of policies and regulations related to roadside renewable power generation within ROW of Bangladesh's Road & Highways Department, and preparation for stakeholder mapping.
iii. Solar and wind resource mapping of Bangladesh's national highway corridors to identify and evaluate suitable land areas. The analysis should exclude environmentally sensitive areas, habitat migration sites, conservation and protected areas, high-risk flood zones, wetlands, and areas within certain distances of natural gas and other pipelines, transmission lines, rail lines and the roadway clear zones.
iv. Night-time light intensity mapping of Bangladesh's national highway corridors to identify and prioritise areas with greater electric power needs.
v. Prepare a list of priority sections of the national highway corridor for piloting roadside renewable power generation for pre-feasibility studies.

An amendment was made to deliverable iii. removing wind power generation from the project scope as the World Bank determined wind generation to be insufficient given the characteristics of Bangladesh.

1.3 Terms, Acronyms and Abbreviations

The following tables provide definitions for acronyms and abbreviations and for terms used in this document.

Abbreviation	Meaning
AADT	Annual Average Daily Traffic
ACCESS	Accelerating Transport and Trade Connectivity in Eastern South Asia
ADB	Asian Development Bank
AHP	Analytic Hierarchy Process
BERC	Bangladesh Energy Regulatory Commission
BESS	Battery Energy Storage System
BOO	Build-Own-Operate (a type of public private partnership model)
BOS	Balance-of-System
BOT	Build-Operate-Transfer (a type of public private partnership model)
BPDB	Bangladesh Power Development Board
DDM	Department of Disaster Managment (Bangladesh)
DOE	Department of Environment (Bangladesh)
EIA	Environmental Impact Assessment
EOL	End-of-Life
ECR	Environmental Conservation Rules
ESF	Environmental Social Framework
ESS	Environmental Social Standards
GIS	Geographic Information System
GIS	Geographic Information System
ITS	Intelligent Transport Systems
IEE	Initial Environmental Examination
JICA	Japan International Cooperation Agency
LCOE	Levelized Cost of Electricity
LED	Light Emitting Diode
LGEC	Local Government Engineering Department (Bangladesh)
MPPT	Maximum Power Point Tracking
MOEFCC	Ministry of Environment, Forest and Climate Change (Bangladesh)
NMT	Non-Motorised Traffic
NSM	National Solar Mission
NISE	National Institute of Solar Energy
ODOT	Oregon Department of Transportation
O&M	Operation and Maintenance
PCU	Passenger Car Unit
PGE	Portland General Electric
PPA	Power Purchase Agreement
PPP	Public Private Partnership

Abbreviation	Meaning
PSPU	Power-sector public utilities
PV	Photovoltaic
REC	Renewable Energy Credit
RHD	Roads and Highways Department (Bangladesh)
ROW	Right-of-Way
SREDA	Sustainable and Renewable Energy Development Authority (Bangladesh)
USDOT	United States Department of Transportation
WECARE	Western Economic Corridor and Regional Enhancement

2. Literature Review of Best Practices of Roadside Renewable Power Generation

This literature review aims to identify best practices for renewable energy generation along highway corridors. First, a study was conducted on the different types of solar energy generation technologies. After that, general and technical concepts were identified for integrating a solar generation system within the highway ROW. Then an examination of various business models was conducted. Lastly, specific case studies were analysed to assess whether these concepts were considered and how they were implemented. The goal is to compare cases to identify best practices and assess their transferability to Bangladesh.

2.1 Types of Solar Technology

2.1.1 Solar Panel Mounting Technology

Technology	Description
Ground Mounted Solar Photovoltaics (PVs)	• Simplest approach of installing PVs on unused land on the side of highways and interchanges • Low profile, fixed tilt arrays set back to meet safety clear zone • Narrow roadside strips can accommodate this type of PV with various limitations and • Example: Oregan built a 104-kW solar array at an Interstate-5 interchange in 2008 (Oregon Department of Transportation (ODOT), a) • Example: 2020 study by University of Texas found highway interchanges in the US had 127,500 acres of abundant land which could support 36 TWh of solar generation annually

Vertical Bifacial Solar PVs	• Placing solar modules vertically along highway medians and edges
	• Bifacial panels can capture sunlight on both sides and avoids shading between panels
	• (Mahmud et al., 2018-11-29)
	    o Introduced the concept of a solar highway in Bangladesh
	    o Vertical orientation minimises land footprint – important in space-scares Bangladesh
	• Example: Netherlands (LIFE Solar Highways) pilot shows vertical solar panels can be integrated into 5 m high noise barriers
	• 400 m long stretch generated enough energy to power 40-60 households

Solar Canopies and Pavements	• Solar canopies can be installed over infrastructure such as rest-stops and roadways (Hyder, 2025) • Solar roads have photovoltaics embedded into the road surface • Example: Solar road on Route 66 in Missouri and Wattway in France showed low energy output and durability issues • Example: 0.6-mile PV highway segment closed after five days when thieves managed to steal a portion of embedded solar panels • Consensus that on-road PV is expensive and prone to failure

Table 1 - Solar Panel Mounting Technology

2.1.2 Solar Tracking Technology

Solar tracking technology enhances the efficiency of PV systems by dynamically adjusting the orientation of solar panels to follow the sun's path across the sky. This alignment ensures that panels maintain an optimal angle relative to incoming sunlight, thereby maximising energy capture throughout the day. There are two types of solar tracker: single axis and dual axis systems. Single-axis trackers rotate the panels along one axis, typically east to west, to follow the sun's daily movement. In contrast, dual-axis trackers adjust both the horizontal and vertical angles, accommodating seasonal variations in the sun's position (REPSOL, 2023).

Solar trackers can significantly boost energy production. Single-axis systems can increase output by 25% to 35%, while dual axis systems offer gains up to 45% compared to fixed installations. However, these benefits come with increased costs and maintenance requirements. The added complexity and moving parts of tracking systems can lead to higher installation expenses and maintenance challenges (Treehugger, 2021).

Trackers typically function through:

- Sensors and Control Systems:
    - Photodiodes (light sensors) detect sunlight intensity and direction
    - Control units (microcontrollers) process sensor inputs and drive motors
- Mechanical systems:
    - Motors and actuators adjust the panel angles
    - Gearboxes keep the motion of the panel smooth
- Algorithms calculate the sun's path based on location, date, and time to ensure optimal alignment

2.1.3 PV Module Technology

Panel Type	Typical Efficiency	Configuration	Pros/Cons
Monocrystalline (Mono-Si)	17-24%	Ground-mounted tilted or on canopies above carriageways	Highest efficiency and longevity but premium cost
Polycrystalline (Poly-Si)	13-17%	Similar mounting as mono-Si but lower yield per m^2	Lower cost, less efficient; better for areas with more space
Thin-film (CIGS, CdTe, a-Si)	10-13%	Usually deposited onto a substrate such as glass metal or plastic	Good for installations where space is plentiful – cheaper
Bifacial Crystalline	19-22%	Vertical panels east-west along highway median/edges so both faces harvest light	Suited for ROW due to vertical orientation
Perovskite/HJT/CPV	25-30%	CPV needs trackers	Emerging technology – not commercially available

Table 2 - PV Module Technology (Aurora Solar, 2024)

Panel Type, Efficiency & Wattage Rating:

The use of monocrystalline commercial panels is preferred as these panels are distinguished by their single-crystal silicon structure, which results in a uniform dark appearance and superior efficiency rates, typically exceeding 20%. Their efficiency generally ranges from 15% to 25%, outperforming polycrystalline alternatives, particularly in low-light conditions. The compact footprint of monocrystalline panels makes them particularly well-suited for installations where space is a constraint.

Three solar panels have been considered below in terms of their efficiency, cost and year-on-year efficiency degradation. These have been selected based on having a high rating from Solar Magazine and an existing supply base in Bangladesh.

Type of Solar Panels	Efficiency	Size of Panels	Power	Typical Cost per Watt (USD)	Degradation per year
Company 1 - Sharp Solar (NB-JD580)	22.45%	2.28m x 1.13m	580W	0.14	-1% on year 1 & -0.4% $year^{-1}$ for 29 years
Company 2 - LONGi Hi-MO 5	21.1%	2.26 m x 1.13 m	540W	0.107	-1% on year 1 & -0.55% $year^{-1}$ for 29 years
Company 3 - Trina Solar Vertex N i-TOPCon Ultra	24.5%	2.384m x 1.303m	760 W	0.11	-1% on year 1 & -0.4% $year^{-1}$ for 29 years

Table 3 - Selected Solar panel technical specifications (Bellini, 2024; Sharp Corporation, 2025)

2.1.4 General Irradiation Thresholds for Solar Viability

Irradiation ($kWh/m^2/day$)	Solar PV Viability	Notes
>5.0	Excellent	High energy yield, rapid payback, supports all system types
4.0-5.0	Good	Commercially viable, typical for many tropical regions
3.5-4.0	Marginal but feasible	Requires optimised design, may need subsidies or storage support
<3.5	Poor	Generally uneconomical unless heavily subsidised for micro loads

Table 4 - Insolation Thresholds (Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) & Food and Agriculture Organization of the United Nations (FAO), 2018)

2.1.5 Factors Affecting Solar Panel Efficiency

Solar panel efficiency refers to how effectively a solar panel converts sunlight into usable electricity. It is expressed as a percentage using this formula:

$$\boldsymbol{Efficiency = \frac{Electical\ power\ output}{Solar\ power\ input} \times 100}$$

What this means practically:
If 1000 watts (W) of sunlight hits 1 square meter of a solar panel:

- A 20% efficient panel will convert 200 W of that sunlight into electrical power
- The remaining 800 W is lost as heat or reflected light

The table below shows the various factors that must be considered in setting the solar power generation project on RHD's ROW.

Factor	Description	Impact of Efficiency	Relevance to Bangladesh ROW
Panel Type	Mono-Si, Poly-Si, thin-film, bifacial etc	Varies from ~10%-22%+	Influences energy yield per area
Temperature	High ambient heat reduces voltage output, lowering panel	Efficiency drops 0.3-0.5% per °C over 25°C	Bangladesh's hot climate necessitates

Factor	Description	Impact of Efficiency	Relevance to Bangladesh ROW
	efficiency (typically above 25^{o}C)		temperature-tolerant panels
Solar Irradiation	Amount of solar energy received per square meter over a given time period (kWh/m^2)	More sunlight means higher energy output	Bangladesh gets 4-6.5 kWh/m^2/day
Angle of tilt of the solar panel mountings	Angle at which panels face the sun, ideally close to the latitude of the location	Misalignment reduces effective exposure	Fixed-tilt or tracking systems can improve yield in ROW setups
Shading	Shadows block light on all or part of a panel	Significant drop, especially in string setups	Must avoid tree overhangs or place panels in elevated ROW canopies
Soiling	Dust, pollution, bird droppings reduce light absorption	Up to 20-30% loss if uncleaned	Frequent cleaning or anti-soil coatings necessary
Degradation	Gradual decline in output due to aging of materials (e.g. UV damage, corrosion)	High-grade cells mean more consistent output. About -1% on the first year and thereafter -0.5% year^{-1} as per manufacturers datasheet.	Tier 1 panels for better long-term returns
Tracking System	Single/dual axis systems track sun movement to increase exposure	Gains of 10-45% vs fixed tilt	Adds huge complexity but boosts yield – can be viable in wide ROWs

Table 5 - Factors Affecting Solar Panel Efficiency *(Ghazi et al., 2014; Richard et al., 2024)*

2.2 Integration of Solar Power Generation into ROW

Identification of the key factors that support the successful integration of a solar energy generation system within the highway ROW.

2.2.1 Site Feasibility

It is essential to assess various aspects of a site before implementation. First the natural characteristics of the land must be studied (Oregon Department of Transportation (ODOT), 2016). This includes:

i. The topography of the site – ideally, the terrain should be flat (with a slope of less than 5%)
ii. Solar exposure – sites should be free of shading from vegetation, as higher exposure increases generation potential
iii. Soil conditions –presence of wetlands or unsuitable substrates
iv. Environmental risks – flooding, landslides, erosion

Next, constraints related to the feasibility and efficiency of project developments must be considered. These include:

v. The available land area – site must be large enough to benefit from economies of scale (typically 5 acres or more). For Bangladesh context, the ROW widths are a constraint due to the limitations on the availability of ROW. As such two (2) metre width was selected for use in analysis.
vi. Proximity to a grid connection point – ideally within half a mile of the electrical grid
vii. Site accessibility
viii. Surrounding population density which may limit or complicate development

Natural Characteristics Constraints	Infrastructure Implementation Constraints
Topography (slope < 5%)	Size of land available (5 acres or more)
Solar exposure	Proximity to the electric grid
Soil conditions	Accessibility
Environmental risks (flooding, landslides, seismic…)	Population density in surrounding area

Table 6 – Site Feasibility Constraints

2.2.2 Sustainability and Resilience

To ensure the sustainability and resilience of a solar energy generation project, two main components must be taken into consideration (Oregon Department of Transportation (ODOT), 2016; U.S. Federal Highway Administration (FHWA), 2016).

The first concerns the infrastructure and technologies employed: solar installations must be designed to withstand extreme weather conditions such as high heat, humidity, strong winds, or storms. The quality of materials (frames, glazing, supports) and electrical components (inverters, connectors) is critical to ensuring a lifespan of over 20 years. end-of-life considerations must be addressed: recycling of waste, etc. Sustainability also depends on good infrastructure design (foundations, drainage) and the ability to operate in a road environment without creating hazards or undergoing damage.

Another consideration is ensuring that the chosen public land is not in competition with other infrastructure projects, which could undermine the project's longevity.

2.2.3 Solar Panel Configuration on the ROW

Justification for Panel Rating Optimizing LCOE for Available Space

The defining characteristic of this project is the spatial constraint of the ROW: a fixed 2-metre (2000mm) width available for installation of solar panel. To maximise power generation within this narrow right-of-way, it is crucial that the panels with the highest possible power output per unit area are selected. Monocrystalline panels offer inherently superior efficiency rates, which translates directly into greater wattage output for every square metre of installed area. This attribute is especially important for a linearly constrained installation, where the ability to generate more power from a limited footprint directly contributes to minimising the Levelized Cost of Electricity (LCOE). By opting for a high wattage rated panel, the power density along the 2-meter width corridor is maximised. This higher power output from a restricted physical space directly impacts the LCOE by increasing the total energy yield (kWh) for a given set of fixed balance-of-system (BOS) costs, such as mounting structures and cabling per linear metre. The smaller footprint advantage of monocrystalline panels is thus directly leveraged to optimise the project's economic viability.

Optimal Fixed Tilt Angle

Bangladesh is situated between 20°34' and 26°38' North latitude. For Dhaka, a central location, the latitude is approximately 23.7° to 23.8° North. For fixed-tilt solar PV systems in the Northern Hemisphere, the optimal annual tilt angle is typically set close to the site's latitude to maximize overall energy capture throughout the year. Recommendations for Dhaka suggest a fixed tilt angle around 23.7° to 24°, (Profile Solar, 2024) while some academic studies propose an average yearly optimal tilt angle of 27.92°(Sharma et al., 2020).

Although adjusting the tilt angle seasonally (e.g., lower in summer, higher in winter) can enhance energy yield by 7-8%, the project specifies a fixed-tilt system for simplicity and cost-effectiveness. Therefore, a fixed tilt angle of 25 degrees (south-facing, 0° azimuth, which is standard for Northern Hemisphere fixed arrays) has been selected as a practical compromise that aligns well with the local latitude and general recommendations for maximizing annual energy production in Bangladesh.

Single Row Panel Layout
The project's unique constraint of a 2-meter (2,000mm) wide right-of-way dictates specific panel orientation and layout considerations.

Panel Dimensions and Orientation: Given the 2,000mm width constraint of the installation area, the panels must be installed in landscape orientation (1.13 - 1.3m width fits within 2,000mm). Installing them in portrait orientation (2.26 - 2.38m length) would exceed the available width.

Structural Support Requirements for Linear Installation:
Ground-mounted solar systems typically employ metal framing secured with ground anchors such as concrete piers, helical piles, or driven piers. For a narrow strip like a highway right-of-way, driven piers or helical piles are more suitable due to their smaller footprint compared to wide concrete foundations, offering strong load-bearing capacity with minimal site disturbance. The linear nature of the installation along a highway means the structure needs to be continuous and exceptionally robust to withstand lateral wind forces and potential ground vibrations from heavy traffic. The mounting structure should be constructed from durable, rust-proof materials like mild steel or aluminium. The proximity to the highway implies potential ground vibrations from heavy traffic and unique wind load considerations along a long, narrow strip. This requires a foundation design that is not only stable but also resilient to these dynamic forces, potentially favouring driven piers or helical piles over traditional concrete pads.

2.2.4 Maintenance

Preventive and corrective maintenance is essential to maintain optimal performance. This includes regular panel cleaning (especially to prevent losses from dust), remote monitoring, periodic inspections, and replacement of defective components.

Access Pathways and Maintenance Limitations: The 2-meter width must accommodate the panel (1.13 - 1.3m), structural support, and any necessary maintenance access. This leaves a remaining width of 2,000mm – 1,300mm = 700mm (0.7m) for these other elements. While general recommendations for ground-mounted systems suggest 3-5 feet (0.91 - 1.52m) between rows for maintenance or 10 feet (3.05m) minimum clearance around arrays, these are not directly applicable to a single-row installation within such a narrow strip. The limited space means that pathways alongside the panels within the 2m width are severely constrained. Maintenance access will likely involve personnel walking along the non-tilted side of the panels or requiring temporary access from the highway side, which introduces significant safety implications. The spatial constraint forces landscape panel orientation and severely limits options for structural support and maintenance access within the right-of-way. This will likely necessitate custom, more expensive mounting solutions and specialized, potentially more costly, operation and maintenance (O&M) procedures.

The project should include a training and mobilization plan for local technicians and upskilling of communities along the highways ROW. The results are twofold: efficient maintenance and massive job creation in the renewable energy sector. In addition, project ownership is fostered and may likely reduce cases of vandalism.

Routine Maintenance:
Routine maintenance activities will include **regular visual inspections, continuous performance monitoring, and scheduled cleaning of the PV modules**, ensuring that the array operates at peak efficiency, minimises avoidable energy losses, and maintains warranty-compliant performance levels throughout its service life.

The activities are summarized in the table below:

Task	Details	Frequency	Upskilling of Women
Visual Inspection	Inspect panels for cracks, discolouration, delamination, hotspots, loose wires, corrosion and pest damage.	Monthly	Easy to upskill and train
Performance Monitoring	Log inverter data (MPPT efficiency, fault codes), compare actual output vs. predicted yield.	Continuous/Monthly	More difficult as these are highly technical skills and would likely require a technician
Cleaning of Modules	Removal of dust	Bi-Monthly (Dry Season); As needed (Monsoon)	Easy to upskill and train

Table 7 - Routine Maintenance

Seasonal Maintenance

Bangladesh's tropical monsoon climate presents unique challenges for solar farm operations, requiring a carefully planned maintenance strategy that adapts to the country's distinct seasonal weather patterns. By tailoring maintenance activities to each season's characteristics, solar projects can minimize downtime, prevent weather-related damage, and maintain consistent energy generation despite Bangladesh's challenging climate conditions. The following maintenance schedule outlines the key areas and specific tasks required during each seasonal phase to maximize solar project's reliability and efficiency.

Season	Key Focus Areas	Tasks
Pre-Monsoon (Apr – May)	Prepare for storms and reduced irradiation.	Deep cleaning, structural check, cable sealing, vegetation trimming, anti-corrosion treatment
Monsoon (Jun – Sep)	Address waterlogging, lightning and efficiency drop.	Drainage inspection, inverter humidity checks, grounding resistance test, lightning/surge protection check.
Post-Monsoon (Oct – Nov)	Recover from debris and rain-related soiling.	Algae/mud removal, thermal scan for microcracks, alignment check, IV curve testing.

Table 8 - Seasonal Maintenance

Annual Maintenance Activities

Effective solar farm maintenance requires a diverse range of specialized activities that go beyond basic cleaning and visual inspections. These technical maintenance procedures are essential for ensuring optimal performance, preventing costly failures, and maximizing the 25+ year lifespan of solar installations. The following table outlines key maintenance activities, their technical requirements, and the potential for skills development and inclusive employment opportunities within Bangladesh's growing solar industry

Activity	Method/Tools	Purpose	Upskilling of Women
IV Curve Testing	Portable IV Tracer	Detect mismatch, degradation or shading losses	Requires a technician

Activity	Method/Tools	Purpose	Upskilling of Women
Insulation Resistance Testing	Megger Test (IEC 62446-1)	Identify leakages or aging cables	Requires a technician
Thermal Imaging	Infrared Camera	Detect hotspots and PID-prone areas	Possible with specialised training
Firmware/Software Update	OEM-provided updates	Improve inverter performance and monitoring integration	Requires a technician
Structural Recoating	Zinc/aluminium paint on mounts and foundation	Prevent corrosion and ensure 25+ year asset life	Easy to upskill / train

Table 9 - Annual Maintenance

2.2.5 Estimation of Manual Cleaning Cost

Dust and dirt substantially imped the production of electricity from the PV panels, with losses in the region of 10% to 70% depending on the quantity of dust in the region (Ghazi et al., 2014). This is substantial problem in areas which a lot of dust and little rain to help clean the panels resulting in annual global losses estimated at 3-5 billion € (Ilse et al., 2019).

The usual way to clean solar panels is with water, specialised soap and microfibre cloths. This is both labour and water-intensive (Jones et al., 2016), which causes difficulty and expense in areas with limited potable water, such as Bangladesh, which is under medium to high stress according to the World Resources Institute (World Resources Institute, 2023).

This problem has attracted interest and there have been technical solutions developed for it. The use of electrostatics methods for dust removal has been used in space exploration having been first devised at NASA in 1967 (Jones et al., 2016). This technique has had much research into it for terrestrial use to refine it such as in (Panat & Varanasi, 2022). This technology has made it out of the laboratory and a commercial implementation is available from a company called CleanFIZZ (*CleanFIZZ*).

The other techniques include using air jets to blow the dust off and wiping with microfibre cloths. These techniques have been combined together and automated with robots. The technology is sufficiently developed that it has been deployed on multiple sites with the company Airtouch on their fourth iteration of their solution (*Airtouch AT 4.0*).

Since Bangladesh is a country that has low labour costs and does not have a surfeit of capital, manually cleaning the solar panels is preferred. This would be done using microfibre cloths to remove the dust (Ilse et al., 2019) whist wearing face masks to reduce inhalation.

To make an estimate of the cost per solar panel per year the following equations where used:

$$n_{panels\ cleaned} = \frac{t_{panel}}{60 - r} \times t_{wd} \times y \times l_{week} \times h$$
$$C_{panel\ cleaner} = W_{annual} \times (1 + T + M + P) + E$$
$$= C\left(\frac{C_{panel\ cleaner}}{n_{panels\ cleaned}}\right) \times \frac{y}{f}$$

Where:

- $n_{panels\ cleaned}$ = Total number of panels cleaned per annum

- t_{panel} = Time to clean one panel = 2 minutes
- r = Rest time per hour = 10 minutes per hour
- t_{wd} = Hours worked per day = 7 hours per day
- y = Weeks per year = 52 weeks per year
- l_{week} = Days in a working week = 5 days per week
- h = Holiday allowance fraction = 18/19, one day for every 18 workdays.
- $C_{panel\,cleaner}$ = Annual cost of a panel cleaner
- W_{annual} = Annual wage = 175000 BDT (Minimum Wage)
- T = Training cost fraction = 1/10
- M = Management cost fraction = 3/10
- P = Transport cost fraction = 1/10
- E = Equipment cost per annum.
- f = weeks between cleaning = 2 weeks

Inputting the values we have yields a cleaning cost of 160.14 BDT per panel per year.

This costing is for dry dust. Post the monsoon season there will be a need to clean off damp dust which might necessitate the use of water as well as chemical cleaning agents. This may increase the equipment costs.

2.2.6 Road Safety

The integration of solar infrastructure must never compromise road user safety. To that end, two types of measures must be considered.

First, **technology-related measures** should be implemented. These include, for instance, the use of **anti-glare panels** and appropriate panel orientation to prevent visual disturbance for drivers.

Second, **infrastructure-related measures** must be considered. This includes ensuring that **maintenance access** for personnel does not interfere with road traffic, as well as the road clearance zone or setback requirements. The size of this zone depends on traffic speed and volume as well as road geometry; however, a recommendation is that project boundaries be at least 30 feet (about 9 meters) from the road edge (Oregon Department of Transportation (ODOT), 2016).

2.3 Battery Energy Storage Systems (BESS)

The predominant battery technology for energy storage applications is lithium-ion batteries, particularly lithium iron phosphate ($LiFePO_4$) variants, due to their high energy density and efficiency. They are suitable for applications requiring rapid response and high-power output. However, they can be sensitive to temperature variations and may require thermal management systems. (Gupta et al., 2021). Redox flow batteries (RFB) such as vanadium redox flow batteries store energy in liquid electrolytes, allowing for scalable energy capacity. They are well-suited for large-scale, long duration storage needs and have a long cycle life (Stauffer & MIT Energy Initiative). Another option is sodium-sulphur (NaS) batteries, which have a high energy density and are effective for grid-scale storage. They operate at high temperatures and have been used in various large-scale applications.

The sizing of the battery energy storage systems (BESS) depends on the scale of the solar PV installation and the intended application. Tesla's Megapack offers capacities up to 3.9 MWh per unit, suitable for large-scale deployments. Smaller systems, like the Tesla Powerwall, provide around 13.5 kWh, appropriate for localised energy needs (Wikipedia, 2025).

Installing BESS along highway ROW should consider the following:

- Site selection – areas that are secure, accessible for maintenance and have minimal environmental impact/exposure
- Structure can withstand local weather conditions and comply with relevant building codes
- Grid compatibility and interconnection

2.4 Lighting Demand Calculations

As referenced by the project brief, one of the uses of Solar power generation on highway right-of-way in Bangladesh is to illuminate road sections with no existing road lighting and underlit sections on roads. This led to the formation of the first basis for power demand requirements generated by the solar panels, which can then be used to size the solar power supply requirements objectively.

It is essential to consider the typical road cross-section and lighting requirements to meet international illuminance standards. For consideration, the widest cross-section has been considered with reference to the typical road cross-section designs on the Western Economic Corridor and Regional Enhancement Program - TCS-1 Typical Road Cross Section in an Urban Area. In addition, a new lighting plan has also been considered here.

The following are the general principles that should be considered for road lighting:

1. Driver requirements - Drivers rely heavily on visual contrast to detect objects on the road, perceiving them either as dark shapes against a light background or vice versa. The need for higher lighting levels increases with driving speed, as faster speeds require drivers to see finer details at greater distances and respond more quickly. Rather than illuminating objects to appear bright against their background - which is inefficient - road lighting is designed to create a bright road surface that contrasts with darker objects, effectively revealing hazards through silhouette. This is achieved by directing light beams along the road surface to enhance reflection, while minimising glare that could impair the driver's vision and reduce contrast.
2. Pedestrian requirements - Pedestrians need to see not only objects on the ground but also other people and surroundings. Their lighting needs are less urgent than drivers' because they have more time to react. Therefore, overall lighting levels for pedestrians can be lower, with light directed more vertically to enhance visibility of other pedestrians rather than just horizontal surfaces.
3. Lighting the surroundings - Lighting the surroundings benefits all road users by providing visual context. For drivers, it highlights stationary objects near the carriageway; for pedestrians, it creates a pleasant nighttime environment by illuminating buildings and landmarks. The human eye adapts to a wide range of lighting, and a well-lit street is significantly brighter than moonlight - though still much dimmer than daylight. (The Institution of Lighting Engineers, 1987)

In summary, the road lighting objectives are:

- **Safety:** Ensure good visibility for drivers, pedestrians, and service road users.
- **Uniformity:** Minimise glare and shadows, maintaining consistent lighting levels.
- **Energy Efficiency:** Use LED or energy-saving light bulbs.

2.5 Public-Private Partnership Models for Renewable Energy Projects in ROW

Various public-private partnership (PPP) models have been used when implementing renewable energy projects within highway rights-of-way. Various States in the USA use federal tax credits and partnership arrangements to effectively minimise capital and operational expenditures for transportation agencies while enabling renewable energy development.

2.5.1 Overview of PPP Implementation Approaches in the USA

Transportation agencies can leverage public-private partnerships to reduce financial exposure while advancing energy objectives within highway corridors. Tax credit availability and strategic partnership arrangements can provide mechanisms to optimise project economics and risk allocation. Each renewable energy initiative examined demonstrates unique business model characteristics that influence permitting processes and contractual frameworks.

Model	Description	Implementation Mechanism	Financial Structure	Agency Role & Benefits	Case Example
1. Transportation Agency as Electricity Purchaser	Third-party developer installs and operates renewable system; agency agrees to purchase the electricity	- Site Access Agreement (e.g., utility permits, leases) - Power Purchase Agreement (PPA) (20–25 years)	- Private capital raised through tax incentives - Fixed-term PPAs enable cost recovery and returns	- Agency receives electricity at fixed rate - Cost-neutral model with predictable pricing	Oregon DOT's Solar Highway Demonstration Project (PPA with SunWay 1, LLC)
2. Third-Party Electricity Utilisation	Developer installs system in ROW; electricity sold to utility or public entity, not transportation agency	- Airspace lease or special use permit - No electricity purchase by agency	- Developer gains from power sales - Agency receives lease payments only	- No operational burden - Lease revenue without electricity obligations	Massachusetts DOT solar/wind proposals; California DOT solar projects
3. Renewable Energy Credits (RECs) Acquisition	Agency gains environmental credits (not electricity) through REC-sharing with utility or developer	- Site license agreement - RECs traded in compliance or voluntary markets	- Developer retains electricity revenue - Agency gets RECs and nominal fees	- Agency supports sustainability goals-Public image enhancement - Partial REC ownership	Oregon DOT's second solar highway (with Portland General Electric)
4. Agency Ownership and Operation	Agency builds, owns, and operates renewable system directly	- Full project ownership - In-house operation	- High upfront costs - Limited access to tax incentives	- Complete control over energy use - Sustainability branding but often financially unsustainable	Early agency-owned projects; later shifted to private partnership models

Table 10 - PPP Models

2.6 Case Studies

2.6.1 Case Study 1: Oregon Solar Highway Program (USA)

In December 2008, Oregon launched the first solar highway project in the United States, a landmark initiative combining renewable energy generation with transportation infrastructure. This 104 kW ground-mounted solar array, located at the interchange of Interstates 5 and 205 near Portland, was installed on a triangular parcel of unused ROW and consists of 594 solar panels. It produces approximately 122,000 kWh annually, offsetting more than one-third of the energy used for freeway lighting at the site.

Building on the success of this initial pilot, ODOT and Portland General Electric (PGE) expanded the model in 2011 with the construction of the Baldock Solar Station (also known as the French Prairie Solar Station). This second installation, also within the highway ROW, features a 1.75 MW array with nearly 7,000 fixed-tilt panels spread over 7 acres near Wilsonville, Oregon. It generates over 1.9 million kWh per year, supplying power to ODOT and further contributing to Oregon's renewable energy targets.

These two projects are especially relevant for the Bangladeshi context. They illustrate how existing highway ROW can be effectively repurposed for solar generation without disrupting traffic or requiring new land acquisition – an approach well aligned with Bangladesh's dense geography and infrastructure constraints.

2.6.2 Case Study 2: Jawaharlal Nehru National Solar Mission (India)

India's Jawaharlal Negru National Solar Mission (NSM) is a nationwide initiative, launched in 2010, to rapidly scale up solar PV deployment across the country. This mission, initially aimed for 20 GW of installed solar energy by 2022, later increased to 100 GW in 2015. It was implemented in three phases, combining grid-connected projects, off-grid, rooftop solar and rural applications. Unlike the other case studies which are specific highway projects, the NSM is a broad policy mission that has led to numerous solar installations under a unifying framework. However, the geographical proximity and similar weather conditions of India and Bangladesh make this case study a good starting point for examining how solar energy potential has been exploited through the deployment of solar energy production technologies. (Ministry of New and Renewable Energy (MNRE), 2012; Upadhyay, S. P., & Singh, U, 2021)

2.6.3 Case Study 3: Tarim Desert Highway (China)

The Tarim Desert Highway Zero Carbon Demonstration Project, situated in the Taklamakan Desert within China's Xinjiang Uyghur Autonomous Region, is recognised as China's longest photovoltaic irrigation and desertification control project. It integrates renewable energy within highway infrastructure, significantly contributing to environmental protection, desert management and sustainable development. To date, it has produced over six million kWh of renewable electricity, illustrating substantial progress in China's transition to green energy (Tianshannet, 2024). This case study was selected because it showcases the successful implementation of a solar project in a highly challenging environment, supplying energy to infrastructure along an extended highway through an off-grid system. Such an approach may offer valuable insights and transferability for the development of solar infrastructure along Bangladesh's national highway network.

The project strategically used a 522 km stretch of land along the desert highway, transforming otherwise unproductive flat desert areas into ecological shelter forests. A network of 86 PV-powered water well stations facilitate the irrigation of over 3,100 hectares (Yicai Global, 2024). Grid access is not a factor here, as the concept was to create a self-sustaining off-grid power network using battery storage, which can provide up to 7 hours of power when sunlight is unavailable (The State Council of the People's Republic of China, 2024).

2.6.4 Summary and Lessons

Category	Tarim Desert Highway – China	Jawaharlal Nehru National Solar Mission – India	Oregon Solar Highway – USA
Location	Taklamakan Desert, Xinjiang	Nationwide (India)	Oregon, USA (Interstate ROW)
Purpose	Desert control, off-grid irrigation, highway power	National solar capacity expansion (grid & off-grid)	Repurpose highway ROW for grid-connected solar
Significance	China's longest PV desert project	India's flagship solar initiative (100 GW target)	First US solar highway; model for ROW deployment
Energy Output	>6 million kWh total; 1.1 million kWh/day	CUF 18–24%; e.g., 873,826 kWh from 5 MW site	~122,000 kWh (pilot); ~1.9 million kWh/year (Baldock)
Land Use Feasibility	Flat, uninhabited desert; ideal for off-grid PV	Arid or non-agricultural lands preferred; some land disputes	Unused highway ROW; no habitat impact; good solar gain
Scale	3,540 kW over 522 km	Up to 100 GW across India	104 kW (pilot); 1.75 MW (Baldock site)
PV Technology	Monocrystalline, single-sided; $LiFePO_4$ batteries	Poly/monocrystalline and thin film; minimal CSP use	Fixed-tilt crystalline PV with durable ground mounts
Storage	$LiFePO_4$ batteries (7-hour backup)	Limited; large-scale storage lacking	Grid-tied; no storage deployed
Operator	PetroChina's Tarim Oilfield Co.	MNRE & NTPC (via NVVN)	Public-private: ODOT & Portland General Electric
Business Model	Eliminates diesel use; off-grid savings	Competitive PPAs with bundling; lower tariffs	Utility-financed, built, and maintained via PPP
Tariff/Cost Impact	Saves ~4 million yuan/year	Tariffs cut from ₹17.91 to ₹7.49 (2010–2012)	Reduces ODOT's electricity costs; no public ops cost
Sustainability Features	Reduces diesel use by 1,000 tons/year; CO_2 by 3,410 tons	National Institute of Solar Energy (NISE) handles testing, R&D	Lifecycle sustainability - EOL recycling encouraged
Climate Resilience	Designed for 70°C heat & sandstorms	Heat-resistant design: storage gaps persist	Weather-resilient (rain, wind); simple fixed mounts
Challenges	High temperatures and risk of solar panels being covered by sandstorms reducing efficiency	Land conflict, monsoon variability, PV waste, CSP issues	Limited capacity; no on-site storage; depends on utility support
Maintenance & Workforce	On-site staff for well ops and PV repair	Project-dependent maintenance	Utility (PGE) owns/maintains array; low-maintenance design

Table 11 - Comparison of Case Studies (Ministry of New and Renewable Energy (MNRE), 2012; Oregon Department of Transportation (ODOT), 2016, a, b, c; The State Council of the People's Republic of China, 2024; Tianshannet, 2024; U.S. Federal Highway Administration (FHWA), 2016, a, b; Upadhyay, S. P., & Singh, U, 2021; Yicai Global, 2024)

2.6.5 Transferability to Bangladesh

The analysis and comparison of the three case studies enable the evaluation of best practices and the identification of lessons that are transferable to the Bangladeshi context.

First, the sites chosen in all three projects were strategically selected, considering solar exposure, topography, population density, and proximity to the national grid (for connected systems). Given the geographical and climatic similarities between India and Bangladesh, it is reasonable to expect similar success for the same type of solar installation.

Second, a key distinction can be made between two major options for integrating solar energy: grid-connected vs. off grid systems. Among the three cases, different models were adopted. On the one hand, the Oregon project and Indian solar parks are grid connected systems that require proximity to electrical infrastructure. However, the Chinese project uses an off-grid system that eliminates the need for grid proximity but requires energy storage solutions to ensure stable power delivery and respond to demand fluctuations. Both system types proved successful and are potentially replicable in Bangladesh. Thus, the study of the most suitable ROW segments for solar panel installation (see Section 4) will consider both options: grid-connected and off-grid systems. The evaluation and ranking criteria will be adapted accordingly, as certain factors differ depending on the chosen system type.

Third, the PPP model appears to be a strong strategic option. All three case studies adopted some form of PPP. Bangladesh is already familiar with this business model, having implemented several PPP-based solar projects such as those supported by the Asian Development Bank and Dynamic Sun Energy Private Limited (Asian Development Bank (ADB), 2024). Similar to the National Solar Mission in India, Bangladesh launched large-scale tenders for solar development, most recently in March 2025 when the Bangladesh Power Development Board (BPDB) issued a call for bids to develop 14 solar power plants totalling 2,605 MW (AC), with individual projects ranging from 105 to 250 MW. Selected developers are to be awarded 20-year power purchase agreements (PPAs), with the submission deadline set for 28 May 2025 (EnergyNews, 2025). Moving forward, the use of competitive tenders is a good strategy for selecting developers and could be more cost-effective than appointing a single local operator, as was done in Oregan with PGE. If a grid-connected approach chosen, the bundling mechanism (as used in India) should be carefully considered.

Fourth, the three case studies illustrate different approaches to ensuring sustainability and resilience in solar infrastructure. The Chinese case demonstrates that solar installations can withstand extreme heat conditions, while the Oregon and Indian cases highlight the importance of system validation, testing and performance monitoring over time.

Finally, in terms of maintenance, two distinct approaches emerge. In China and India, projects emphasised the training of local technicians, whereas in Oregon, the private developer is contractually responsible for ongoing operations and maintenance. In the case of Bangladesh, investing in the large-scale training of local technicians could yield dual benefits by both ensuring the long-term maintenance capacity and stimulating employment in the renewable energy sector.

3. Policy and Regulations in Bangladesh

This chapter examines the policy and regulatory frameworks in Bangladesh that influence the deployment of renewable energy technologies (particularly solar power) within the highway ROW. It provides a descriptive and analytical overview of four major regulatory domains: transport, energy, environment, and procurement & financing. Relevant Bangladeshi policies, laws, and institutional arrangements are highlighted for each.

3.1 Transport Domain

The transport domain governs the use of highway infrastructure and associated land. In Bangladesh, the institutional framework for roads and highways, land use regulations, and geometric design standards collectively shape what can be done within highway ROW. Key considerations include: The official classification of roads, which determines jurisdiction and management responsibility; the design parameters (such as cross-section widths, lane configurations, and shoulder dimensions) that define how much usable space is available within the ROW; and the legal restrictions on non-road uses of highway land, which regulate how this space can be utilized for purposes such as renewable energy generation.

These factors directly impact the feasibility of installing renewable energy systems such as solar PV arrays along road corridors. For instance, wider road classifications (e.g., National Highways with Design Type 1 or 2) tend to have broader ROWs and shoulders, potentially offering more opportunity for solar integration without compromising safety or future expansion. Conversely, roads with narrower cross-sections limit usable space and impose tighter constraints on infrastructure placement.

The following are the three main policy documents which have been guiding the policies of transport agencies while selecting road development and improvement projects.

Year	Policy/Regulation	Applicability
2004	National Land Transport Policy	Sets overarching transport policy goals including multimodal integration, road safety, and sustainability. Establishes institutional responsibilities.
2004	Integrated Multi-modal Transport Study	Provides a strategic framework for coordinated development of road, rail, inland waterways, and port infrastructure.
2009	Bangladesh Road Master Plan Study	Defines national road classifications (e.g., national, regional, zila), outlines geometric design standards, ROW requirements, and upgrade strategies.

Table 12 -Policy documents guiding policies of transport agencies

3.1.1 Road Classification

Bangladesh's road network is organised into several tiers, each managed by specific authorities. The primary network consists of National Highways, Regional Highways, and Zila (district) Roads (see Table below), which are planned, constructed, and maintained by the Roads and Highways Department (RHD) under the Ministry of Road Transport and Bridges. National Highways (designated with "N" numbers) connect the national capital Dhaka with divisional headquarters, major ports, and international highways, forming the country's arterial routes. Regional Highways ("R" routes) link district headquarters and important locations not served by the national network, while Zila Roads ("Z" routes) connect district centres to upazila (sub-district) towns or to each other, acting as feeders to the higher highway system. Beneath this, a secondary network of rural roads (Upazila, Union, and Village roads) falls under the Local Government Engineering Department (LGED) and municipal authorities.

This hierarchical classification is important because the authority over a given road (RHD for highways vs. local agencies for rural roads) determines who can grant permission for any use of the ROW.

Road Naming	Road Type	Additional information	Length (km)
NXXX (N1, N2, N101…)	National Highway	Highways connecting National capital with Divisional HQ's or seaports or land ports or Asian Highway.	3,790
RXXX (R110, R151…)	Regional Highway	Highways connecting District HQ's or main river or land ports or with each other not connected by National Highways.	4,206
ZXXXX (Z2034, Z5063…)	"Zila" Roads	Roads connecting District HQ's with Upazila HQ's or connecting one Upazila HQ to another Upazila HQ by a single main connection with National/Regional Highway, through shortest distance/route.	13,121
Total (highways)			21,117

Table 13 - Classification of Highways (Road Master Plan, 2009)

For renewable energy deployment, the focus is on RHD-managed national highways as stated in the scope of the project. RHD, being the custodian of these roads, has the mandate to ensure their safe and intended use. Any initiative to install solar panels or other infrastructure along a highway must therefore align with RHD's policies and standards.

3.1.2 Roads and Highways Standards

The RHD defines six standard road design types, each based on expected peak-hour traffic volumes (expressed in Passenger Car Units, or PCU), and associated with specific cross-section widths, carriageway configurations, and shoulder dimensions. These geometric standards are essential when evaluating the spatial feasibility of installing solar infrastructure along highway corridors.

Design Type 1 roads, intended for the highest traffic volumes (4,500–8,500 PCU per peak hour, equivalent to 19,000–36,000 AADT), feature a wide 37.80-meter crest including dedicated lanes for non-motorized transport (NMT), dual 11-meter carriageways (6 lanes total), and 1.5-meter paved shoulders. These are typically classified as National Highways. As the design types of progress from 2 to 6, the cross-sectional width and number of lanes decrease, with Type 6 roads (under 530 PCU or 600 AADT) having a single 3.7-meter carriageway, 1.5-meter shoulders, and a total crest width of 10.70 meters, generally corresponding to Zila roads (see Table Below)

These design specifications help determine how much of the right-of-way is physically usable for solar installations. For instance, Design Types 1 and 2 may offer greater flexibility for siting solar panels without impeding traffic or safety buffers, while narrower configurations like Types 5 and 6 may pose significant spatial constraints. The inclusion or exclusion of non-motorised traffic (NMT) lanes also affects the available land profile.

Incorporating solar infrastructure must respect these spatial allocations, ensuring that clear zones, embankments, and shoulder access are preserved.

Design Type	Peak Hour Volume (PCU)	Total Width (m)	Carriageway (lanes)	Road Type
1	4,500–8,500	37.80	2 × 11.0 (6)	National
2	2,100–4,500	30.40 / 23.20	2 × 7.3 (4)	National
3	1,600–2,100	16.50 / 16.30	7.3 (2)	National, Regional
4	800–1,600	16.50 / 15.20	6.2 (2)	National, Regional, Zila
5	530–800	12.50	5.5 (2)	National, Regional, Zila
6	<530	10.70	3.7 (1)	Zila

Table 14 - Geometric Standards Manual (2005)

3.1.3 Land Use of Highways

The use of land within highway corridors in Bangladesh is governed by a combination of policy, engineering standards, and regulatory practice. This land, known as the ROW, is a legally protected corridor reserved for road infrastructure and associated public uses. The ROW defines the total width of land acquired or designated for a highway, including not only the carriageway and shoulders, but also any embankments, drainage systems, and space for future expansion.

According to the Road Master Plan (Road and Highways Department (RHD), 2009), Bangladesh has not yet acceded to the Asian Highway Design Standard, a regional framework that establishes technical and institutional guidelines for improving the quality, consistency, and efficiency of highway networks across member countries. However, the document notes that Bangladesh retains the option to formally join the agreement by submitting the relevant accession form through the United Nations.

The Asian Highway Standard defines the ROW as the total width of land reserved for road infrastructure, encompassing the carriageway, shoulders, medians, drainage systems, and space allocated for future expansion. This width is measured across the full corridor, symmetrically from the road's centreline. The table below presents the recommended minimum ROW widths by highway classification:

Highway classification	**Right of Way Width (metres)**
Primary	50
Class 1	40
Class 2	40
Class 3	30

Table 15 - Right of Way based on Asian Highway Standard

In parallel, the (Government of the People's Republic of Bangladesh et al., 2000) outlines Bangladesh's internal ROW design principles. It states that the required width varies with terrain conditions, such as embankment height or the presence of bridge approaches. For National and Regional Highways, the standard land acquisition width is generally 30 metres. However, where roads are likely to be expanded from two to four lanes or more, wider land reservations are recommended from the outset. A key aspect of the design policy is the prevention of unauthorised encroachment after land acquisition and construction. Infrastructure and roadside elements must be designed to protect the full ROW width and discourage informal occupation or development that could compromise road safety or future upgrades.

From a planning and regulatory perspective, these standards serve as a basis for evaluating the physical feasibility of roadside renewable energy projects. Any solar installation within the ROW must align with the official design envelopes, anticipate possible road widening, and strictly avoid interference with core roadway functions or safety margins. Understanding the official ROW framework is thus essential for determining which segments of the national highway system can host solar infrastructure in a secure and compliant manner.

3.2 Energy Domain

The energy domain encompasses the policies and regulations that promote and regulate power generation, especially from renewable sources. In Bangladesh, the Renewable Energy Policy framework and associated agencies like the Sustainable and Renewable Energy Development Authority (SREDA) form the backbone of efforts to increase solar energy deployment.

3.2.1 Renewable Energy

Bangladesh's renewable energy sector is governed by a set of evolving policies and regulations that support project development, private investment, and grid integration. The foundation was laid by the

Renewable Energy Policy of 2008, which introduced national targets and incentives for clean energy projects.

In 2012, the government established the SREDA as the key agency for coordinating renewable energy and energy efficiency initiatives. Since then, additional guidelines such as those for solar project implementation (2013), net metering (2018), and electric vehicle charging infrastructure (2022) have expanded the regulatory base. Newer instruments, like the Energy Audit and Labelling Regulations (2023), also help optimise demand and efficiency.

The Draft Renewable Energy Policy 2025, building on an earlier 2022 version, seeks to consolidate previous efforts by setting updated integration targets, introducing financing mechanisms, and standardising technical guidelines for scaling renewables. However, as the draft is still under review, it has received technical and institutional feedback from stakeholders, particularly regarding its implementation clarity, institutional roles, and enforcement mechanisms.

The table below summarises the relevant policies and their applicability:

Year	Policy/Regulation	Applicability
1972	Bangladesh Power Development Boards Order	Establishes the authority of the BPDB, including its authority to award generation concessions and purchase electricity from both private and public sectors.
2003	Bangladesh Energy Regulatory Commission Act	Empowers the Bangladesh Energy Regulatory Commission (BERC) to issue, renew, revise and revoke licenses to all entities involved in power generation, transmission and distribution
2008	Renewable Energy Policy of Bangladesh	Provides additional institutional arrangements, resource and technology development programmes, investment and fiscal incentives, and regulatory policies specifically for renewable power plants under private participation.
2012	The Sustainable and Renewable Energy Development Authority Act	SREDA as a statutory body to promote renewable energy and energy efficiency in Bangladesh. The Act outlines its mandate, including setting standards, coordinating policies, supporting R&D, and proposing renewable energy tariffs to BERC.
2013	Guideline for the Implementation for Solar Power Development Program	Describes the different modes for implementation solar power projects and details the process for setting up a Solar Park and the financial benefits for Solar Power Companies.
2018	Electricity Act	Principal legislation establishing the structure and implementation guidelines for the generation, transmission, and distribution of electricity in Bangladesh, including land/easement acquisition for such purposes.
2018	Net Metering Guidelines	Policy document about prosumers (people/companies that consume and produce electricity, e.g. a house with photovoltaic panels on the roof). It details the framework for how consumers can generate electricity from renewable sources for their own use and export excess energy to the distribution grid. The guidelines cover eligibility criteria, energy accounting and settlement procedures, tariff structures, metering arrangements, application procedures, and interconnection requirements, including technical and safety standards.

Year	Policy/Regulation	Applicability
2022	[Draft] Renewable Energy Policy	Covers all types of renewable energies in Bangladesh, very important document, there are details in there that explain that Wind power is a good energy source for Bangladesh
2022	Electric Vehicle Charging Guideline	definitions of charging infrastructure types, general operational requirements, safety standards, and application procedures for setting up charging stations.
2023	Energy Audit Regulation	Helps identify consumption profiles and energy-saving opportunities, enabling better sizing and targeting of solar PV systems.
2023	Energy Efficiency Labelling Regulation	Promotes the use of efficient appliances, which lowers demand and increases the relative contribution of solar generation.
2025	[Draft] Renewable Energy Policy	Updated version of the 2022 draft, incorporating financing strategies, technical standards, and renewable energy integration targets in the power system by 2030.

Table 16 - Relevant Policies in the energy sector

3.2.2 Land-Related Regulations

Land acquisition for renewable energy infrastructure, particularly when located within or adjacent to public corridors like highways, is governed by national legislation that outlines procedures and compensation mechanisms. The key legal instrument is the Acquisition and Requisition of Immovable Property Act (2017), which regulates the acquisition of land for public purposes. It provides the legal basis for determining compensation, handling objections, and ensuring due process during land transfer.

While most solar installations along highways are expected to be within existing rights-of-way and thus not require additional acquisition, this regulation remains relevant in cases where land beyond the ROW is can be potentially used or when clarifying legal ownership and use rights.

The table below summarises the applicable land-related regulation:

Year	Policy/Regulation	Applicability
2017	Acquisition and Requisition of Immovable Property Act	Governs the acquisition of land for public purposes, including determining compensation for acquired property.

Table 17 - Land related regulation

3.3 Environmental Domain

Environmental considerations are central to the development of renewable energy infrastructure along highway corridors. In Bangladesh, projects must comply with national environmental regulations, including permit procedures and restrictions related to protected areas and biodiversity conservation.

The environmental clearance process is managed by the Department of Environment (DoE) under the Ministry of Environment, Forest and Climate Change (MoEFCC), based on the Environmental Conservation Act (1995) and its associated rules. Projects are screened and categorised by potential impact, which determines the required level of assessment, ranging from basic registration to full Environmental Impact Assessment (EIA).
Additionally, roadside solar installations must consider the location of ecologically sensitive areas, such as national parks, wetlands, and wildlife sanctuaries. Bangladesh's legal framework includes multiple policies that protect these zones from encroachment or degradation.

For projects involving multilateral financing, such as World Bank support, compliance with international environmental and social safeguards is also mandatory. These include detailed requirements for risk assessment, biodiversity protection, and the application of the mitigation hierarchy.

The following sections outlines the permitting process and applicable regulatory instruments, followed by an overview of protected area considerations.

3.3.1 Environmental Permitting

The DoE, under the MoEFCC, is the central agency responsible for environmental planning, permitting, monitoring, and enforcement in Bangladesh. Under the Environmental Conservation Act 1995 and the Environment Conservation Rules (ECR) 1997 (Ministry of Environment, Forest and Climate Change, 1995, 1997), the DoE is mandated to issue environmental clearances for all categories of development projects. These rules define the EIA process, prescribe environmental quality standards for air, water, and soil, and regulate wastewater discharge, use of resources, and conservation of degraded ecosystems.

Projects are classified into four categories: Green, Yellow, Orange, and Red, depending on their environmental risk profile. The table below summarises these categories and their typical requirements:

Category	Impact Level	Key Requirements	Example Projects
Green	Negligible	Basic registration only	Small non-industrial facilities
Yellow	Low	Initial Environmental Examination (IEE)	Rooftop or roadside solar <50 MW
Orange	Moderate	IEE with potential for detailed review	Solar parks >50 MW near populated areas
Red	Significant	Full EIA + Environmental Management Plan	Thermal power plants, industrial zones

Table 18 - Classification of Environmental Areas

This classification is based on the ECR 1997 and may be further influenced by project location, especially in or near ecologically sensitive zones such as wetlands, rivers, forests, or wildlife habitats.

The permitting process is further supported by a comprehensive framework of environmental laws and policies, including:

- National Environmental Policy (1992, 2018)
- National Environmental Management Action Plan (1995)
- Environmental Conservation Act and Rules (1995, 1997, 2000, 2002, 2010)
- Environmental Court Act (2000)
- ECA Management Rules (2016)
- National Environmental Management Action Plan (NEMAP) 1995–2005
- National Water Policy (1999)
- Water Act (2013)
- Environmental Protection Bill (2010)
- National Agricultural Policy (1999)
- National Land Use Policy (2001)
- National Forest Policy (1994, amended 2010)
- The Embankment and Drainage Act (1952)
- National Fisheries Policy (1996)
- IUCN (1994) Protected Area Framework
- Dredged and Dredged Material Policy (2013)
- National Conservation Strategy (1992, updated 2013)
- National Biodiversity Strategy and Action Plan (NBSAP) (2007)

- Bangladesh Wildlife (Conservation & Security) Act (2012)
- The Protected Area Management Rules (2017)
- Integrated Biodiversity Assessment Tool (IBAT)
- Bangladesh Biological Diversity Act (2017)
- RHD Road Master Plan (2009)

For internationally funded projects, including those supported by the World Bank, compliance with the Environmental and Social Framework (ESF) is required(The World Bank, 2016). This includes:

- A Vision for Sustainable Development,
- Ten Environmental and Social Standards (ESSs),
- Policy and procedural directives for Investment Project Financing (IPF), and
- Specific provisions for disadvantaged or vulnerable groups.

Among these, two standards are particularly relevant:

- ESS-1: Requires identification, assessment, and management of environmental and social risks consistent with the ESF.
- ESS-6: Focuses on biodiversity conservation and sustainable management of living natural resources. It mandates the mitigation hierarchy, which includes:
  a) Anticipating and avoiding risks and impacts,
  b) Minimizing or reducing risks where avoidance is not possible,
  c) Mitigating residual impacts, and
  d) Compensating or offsetting significant impacts where technically and financially feasible.

3.3.2 Protected Areas

There are several types of protected areas, listed below (Forest Department, Government of the People's Republic of Bangladesh, 2025):

1. **Wildlife Sanctuary:** means an area closed to hunting, shooting or trapping of wild animals and declared as such under Article 23 by the government as undisturbed breeding ground primarily for the protection of wildlife inclusive of all natural resources such as vegetation soil and water (paragraph) (p) of Article 2).
2. **Special Biodiversity Area:** means specialised forest areas to consider for the conservation and development of biodiversity. For example, Ratargul Swamp forest of Sylhet.
3. **Vulture Safe Zone:** means areas considered for conservation and reproduction of critically endangered white-rumped Vulture (*Gyps bengalensis*).
4. **National Park:** means comparatively large areas of outstanding scenic and natural beauty with the primary object of protection and preservation of scenery, flora and fauna in the natural state to which access for public recreation and education and research may be allowed (paragraph) (p) of Article 2).
5. **Ecopark:** is an area of natural ecological habitat of flora and fauna with outstanding scenic beauties which is managed to provide recreational facilities for visitors, and which is declared as such through official gazette notification under section 19 of the Act.
6. **Botanical garden:** means an area where different native and exotic plan species are conserved or managed for education, research and conservation and improvement of source of gene pool introducing from another habitat and which is declared as such through official gazette notification under section 19 of this Act.
7. **Safari Park:** means an area where indigenous and exotic wild animal species are protected in an approximation of a natural environment for increasing the population and grazing openly and which is declared as such through official gazette notification under section 19.

Here is a comprehensive list of protected areas in Bangladesh, from Bangladesh's Forest Department:

Sl. No	Name	Location	Area (hac.)
1	Bhawal National Park	Gazipur	5,022.29

Sl. No	Name	Location	Area (hac.)
2	Madhupur National Park	Tangail and Mymensingh	8,436.13
3	Ramsagar National Park	Dinajpur	27.75
4	Himchari National Park	Cox's Bazar	1,729.21
5	Lawachara National Park	Moulavibazar	1,250
6	Kaptai National Park	Chittagong Hill Tracts	5,464.78
7	Nijhum Dweep National Park	Noakhali	16,352.23
8	Medhakachhapia National Park	Cox's Bazar	395.92
9	Satchari National Park	Habigonj	242.91
10	Khadimnagar National Park	Sylhet	678.80
11	Baroiyadhala National Park	Chittagong	2,933.61
12	Kadigarh National Park	Mymensingh	344.13
13	Kuakata National Park	Patuakhali	1,613
14	Nababgonj National Park	Dinajpur	517.61
15	Singra National Park	Dinajpur	305.69
16	Altadighi National Park	Naogaon	264.12
17	Birgonj National Park	Dinajpur	168.56
18	Rema-Kalenga Wildlife Sanctuary	Hobigonj	1,795.54
19	Char Kukri-Mukri Wildlife Sanctuary	Bhola	40
20	Pablakhali Wildlife Sanctuary	Chittagong Hill Tracts	42,069.37
21	Chunati Wildlife Sanctuary	Chittagong	7,763.97
22	Fashiakhali Wildlife Sanctuary	Cox's Bazar	1,302.42
23	Dudpukuria-Dhopachari Wildlife	Chittagong	4,716.57
24	Hajarikhil Wildlife Sanctuary	Chittagong	1,177.53
25	Sangu Wildlife Sanctuary	Bandarban	2,331.98
26	Tengragiri Wildlife Sanctuary	Barguna	4,048.58
27	Sonarchar Wildlife Sanctuary	Patuakhali	2,026.48
28	Dhangmari Wildlife Sanctuary	Bagerhat	340
29	Chadpai Wildlife Sanctuary	Bagerhat	560
30	Dudhmukhi Wildlife Sanctuary	Bagerhat	170
31	Teknaf Wildlife Sanctuary	Cox's Bazar	11,614.57
32	Nagarbari-Mohanganj Dolphine Sanctuary	Pabna	408.11
33	Shilanda-Nagdemra Wildlife (Dolphin) Sanctuary	Pabna	24.17
34	Nazirganj Wildlife (Dolphin) Sanctuary	Pabna	146
35	Sundarban (East) Wildlife Sanctuary	Bagerhat	122,920.90
36	Sundarban (West) Wildlife Sanctuary	Satkhira	119,718.88
37	Sundarban (South) Wildlife Sanctuary	Khulna	75,310.30
38	Swatch of No-Ground Marine Protected Area	South Bay of Bengal	173,800
39	Char-muguria Eco-park	Madaripur	4.20

Sl. No	Name	Location	Area (hac.)
40	Special Biodiversity Conservation Area (Ratargul)	Sylhet	204.25
41	Altadighi water based Special Biodiversity Conservation Area	Naogaon	17.33
42	National Botanical Garden	Dhaka	87.13
43	Tilagar Eco-Park	Sylhet	45.34
44	Madhabkundu Eco-Park	Moulavibazar	202.43
45	Inani National Park	Cox's Bazar	7,085.16
46	Pankhali Wildlife (Dolphin) Sanctuary	Khulna	404
47	Shibsha Wildlife (Dolphin) Sanctuary	Khulna	2,155
48	Vadra Wildlife (Dolphin) Sanctuary	Khulna	868
49	Padma Setu Wildlife Sanctuary	Madaripur, Shariotpur, Munshiganj, Faridpur	11,772.61
50	Dharmapur National Park	Dinajpur	704.70
51	Saint Martin Marine Protected Areas	Bay of Bengal	174,300
52	Baishari Bangdepa Wildlife Sanctuary	Cox's Bazar	2,234.01
53	Madhutila Ecopark	Sherpur	131.19
54	Special Biodiversity Area	Purbachal	58.30
55	Wetland-based Animal Sanctuary (Biljoania)	Tanore, Rajshahi	0.66
56	Wetland-based Animal Sanctuary (Bilvala)	Godagari, Rajshahi	6.10
	Total		818,305.75

Table 19 - Protected areas in Bangladesh

3.4 Procurement and Financing

3.4.1 Public Procurement

The following relevant policies and regulations are in place:

Year	Policy/Regulation	Applicability
2006	Public Procurement Act	Outlines the major considerations for public procurement, including different procurement methods (local, international, etc) and the processes involved
2008	Public Procurement Rules	Provide detailed methodological guidelines for each process. These regulations apply to all forms of public procurement (using public funds), regardless of the procuring authority.
2010	Quick Enhancement of Electricity and Energy Supply (Special Provisions) Act	Aims to facilitate the rapid increase of electricity production and transmission in Bangladesh. It primarily supersedes the Public Procurement Act 2006 and empowers the government and its entities to accept proposals for this purpose

Table 20 - Public Procurement Policies

3.4.2 Public-Private Partnerships (PPP)

Bangladesh recently announced significant policy changes to bolster investments in renewable energy-based power generation, reflecting a commitment to expand private sector participation in the power sector through effective PPPs.

Tax Incentives for Renewable Power Generation

On 27 November 2024, the Government of Bangladesh introduced a 10-year tax incentive program to promote renewable energy-based power facilities. This incentive, detailed in SRO No. 400-Law/Income Tax-54/2024, comes into effect on 1 July 2025. Under this program, eligible individuals and companies engaged in renewable electricity generation projects, whose commercial operations commence between 1 July 2025 and 30 June 2030, will benefit from a 15-year income tax exemption period. The exemptions are structured as follows:

- 100% exemption for the first 10 years from the date of commercial production.
- 50% exemption for the subsequent 3 years.
- 25% exemption for the final 2 years.

This policy aims to enhance the financial viability of renewable energy projects to attract significant private investment in the sector.

Reforms to Facilitate Private Sector Participation

The newly drafted Policy for Enhancement of Private Participation in the Power Sector, 2025 (The High Court Division of the et al., 2025) reflects the government's attempt to create a level playing field for private investors. Notably, the repeal of sections 6(2) and 9 of the Quick Enhancement of Electricity and Energy Supply (Special Provisions) Act, 2010 which eliminates the provision for procurement of power from the private sector through unsolicited proposals. This ensures that all procurement must now follow transparent and competitive processes, thereby fostering greater confidence among private investors and promoting fairness in project selection.

Joint Ventures and Partnerships

The 2025 policy also lays out a comprehensive framework for establishing joint ventures or partnerships between the Power Sector Public Utilities (PSPUs) and private investors to develop Merchant Power Plants on a Build-Own-Operate (BOO) basis. Key provisions include:

- Creation of a Special Purpose Vehicle to implement and operate the project
- Joint venture or partnership terms to be defined through a formal deed and subject to Bangladeshi laws and regulations
- Approval of the Board of the respective PSPU and the BERC prior to formation
- PSPU contributions (e.g., project land and assets) will be monetized and counted towards its share in the venture

3.5 Stakeholders

The successful implementation of renewable energy systems within Bangladesh's national highway corridors requires careful coordination among stakeholders including government institutions, private sector entities, development partners, and local communities. Given the pioneering nature of highway-integrated solar installations in Bangladesh and the complex regulatory environment surrounding both transportation infrastructure and renewable energy development; effective stakeholder engagement becomes critical to the projects success. The renewable energy project component intersects multiple sectors; transportation, energy, environment, and local development, each governed by different ministries, agencies, and regulatory frameworks. This stakeholder mapping identifies the key actors involved in decision-making, implementation, and oversight of highway renewable energy projects, while establishing a hierarchical engagement structure that recognises varying levels of influence, interest, and authority. Understanding these stakeholder dynamics is essential for navigating the institutional landscape, securing necessary approvals, managing implementation risks, and ensuring that the sustainable project outcomes align with Bangladesh's broader infrastructure development and renewable energy objectives.

3.5.1 Primary Stakeholders

Stakeholder	Role	Influence Level	Interest Level	Key Concerns	Engagement Strategy
RHD	Landowner, project implementer	Very High	Very High	Safety, liability, maintenance	Joint planning, regular coordination
Ministry of Power	Policy maker, strategic oversight	Very High	High	Energy security, grid stability	Policy alignment, regular updates
SREDA	RE coordination, standards	High	Very High	RE targets, technical compliance	Technical collaboration
BERC	Tariff regulation, market oversight	High	High	Market stability, fair pricing	Regulatory consultation
BPDB	Grid operator, power purchaser	High	High	Grid integration, technical standards	Technical coordination
World Bank	Primary funder, technical support	Very High	Very High	Development impact, sustainability	Partnership management, regular reporting

Table 21 - Primary Stakeholders

3.5.2 Secondary Stakeholders

Stakeholder	Role	Influence Level	Interest Level	Key Concerns	Engagement Strategy
Solar Developers	Technology, investment	Medium	Very High	Market access, contract terms	Market development, tender processes
Highway Contractors	Construction, maintenance	Medium	High	Contract opportunities, technical specs	Procurement planning, capacity building
Electric Mobility Companies	Future integration	Low	Medium	Infrastructure compatibility	Future planning consultation
Local Communities	Beneficiaries, social license	Medium	High	Employment, environmental impact	Community consultation, benefit sharing
Civil Society	Advocacy, monitoring	Low	Medium	Transparency, environmental protection	Information sharing, consultation

Table 22 - Secondary Stakeholders

The interest and influence levels were qualitatively ranked according to the group members' judgment and their relationship to the project. These rankings may be subject to change when applied.

4. Identification and Evaluation of Suitable Road Segments for Solar Generation

In this section, the objective is to identify which portions of public land along the national highway network have strong potential for the installation of solar energy generation infrastructure. The goal is primarily to illuminate road segments where lighting is very limited or non-existent, preferably, to generate enough energy to power the entire lighting system of the national highway network (see Figure below highways N1 to N8), and possibly related RHD operational facilities.

Figure 1 - National Highways (N1-N8)

To determine the ROW segments with the highest potential for solar generation, the methodology is divided into two main steps. The first step involves excluding all segments considered unsuitable based on specific criteria whereupon a list of potential candidate segments is compiled. The second step involves scoring and ranking the candidate segments through multi-criteria evaluation. Ultimately, this process identifies the segments with the highest potential for solar panel installation.

4.1 Exclusion of Areas Unsuitable for Solar Panel Installation

The exclusion criteria in Table 23 - Exclusion Criteria were defined in collaboration with the World Bank and the identified concepts.

Exclusion Criteria
Railways Crossings
Protected environmental areas
Critical Zones
Flooding Risk
Seismic Risk
Population density
Topography
Land Area
Pipelines and gas lines

Table 23 - Exclusion Criteria

In the following sections, binary maps will be presented using red and green colouring. Red areas represent zones deemed unsuited, and therefore excluded, whereas green areas represent zones considered suitable and potential candidates.

Case 1: Direct Exclusion (Blue category)
The first case concerns the following exclusion criteria: railway crossings, protected environmental areas and critical zones (airports/military bases). For each of these criteria, the unsuitable areas are clearly delineated on a national map of Bangladesh and following the next considerations:

Variable	Basis	Consideration
Railway Crossings	US safety standards for visibility requirements at road-railway crossings (U.S. Department of Transportation, 2023)	100m buffer zone around crossings
Protected Environmental Areas	Per the Environmental and Social Standards (ESS) for World Bank projects, in particular ESS1 & ESS6 (The World Bank, 2016)	Exclude all listed Bangladesh national parks
Critical Sites (Airports)	Obstacle Limitation Surfaces (OLS) (Ministry of Defence & Military Aviation Authority, 2018)	Buffer zone based on the radius of the runway

Table 24 - Direct Exclusion Areas

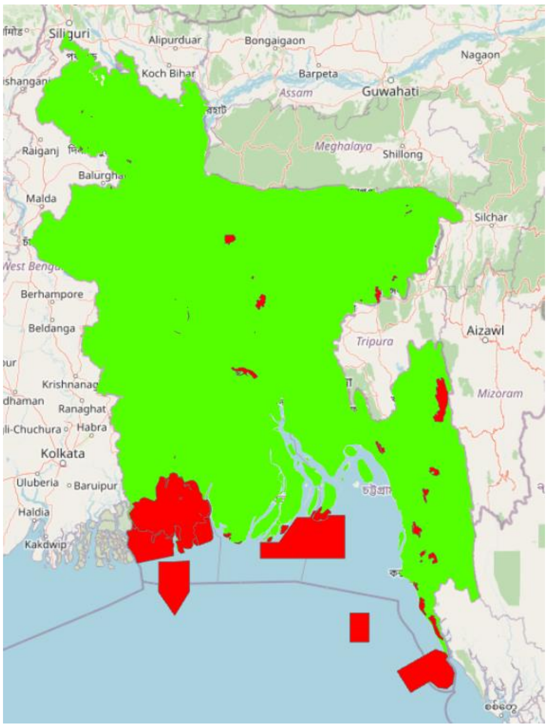

Figure 2 - Protected Areas - Binary Map

Case 2: Threshold-Based Exclusion (Amber category)
This second case concerns the following exclusion criteria: flooding risk, seismic risk, population density and topography. For each of these criteria, a threshold value is defined:

Variable	Threshold Basis	Threshold Value
Population Density	Definition of a city based on the European Commission's Degree of Urbanisation (United Nations Human Settlements Programme, 2020)	1,500 population/km^2
Flood Risk	High hazard and exposure areas for roads based on 150-year flood return periods as calculated by the Department of Disaster Management (DDM) (Department of Disaster Management (DDM) & Ministry of Disaster Management and Relief, 2023)	9 risk-matrix score
Seismic Risk	High hazard and exposure areas for roads based on 1,000-year earthquake return periods as calculated by the DDM	9 risk-matrix score
Topography - Slope	Site requirements recommended by the ODOT	5% gradient

Table 25 - Threshold-Based Exclusion

In the case of flooding and seismic risk, the following matrix was constructed using a numerical scoring method based on hazard and exposure based on the scale of colours provided from the source.

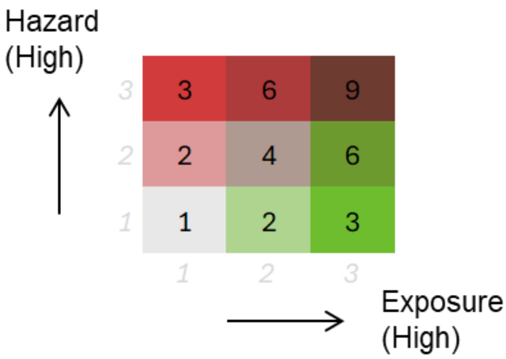

Figure 3 - Risk Matrix

Each row represents a level of exposure (from 1 to 3), while each column represents a level of hazard (also from 1 to 3). The risk score for each cell is calculated as the product of hazard and exposure (i.e., Risk Score = Hazard × Exposure). The final exclusion table is shown below.

Exclusion Criteria	Unit	Threshold
Flooding Risk	Unitless (scale 1 – 9)	9
Seismic Risk	Unitless (scale 1 – 9)	9
Population Density	inhab/km²	1,500 inhab/km²
Topography (slope)	%	5%

Table 26 - Exclusion Criteria

Thus, all areas in Bangladesh with a population density higher than 1500 inhab/km^2 are categorised as unsuitable, while areas with a population density lower than 1500 inhab/km^2 are categorised as suitable.

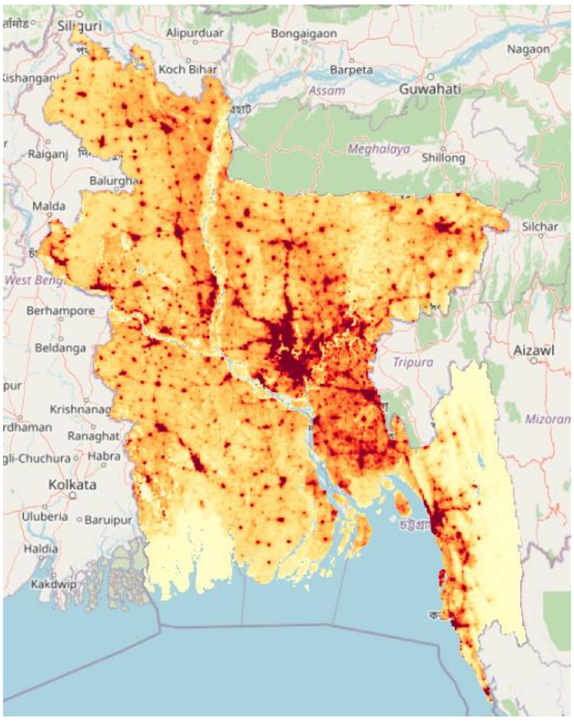

Figure 4 - Population Density - Continuous Map

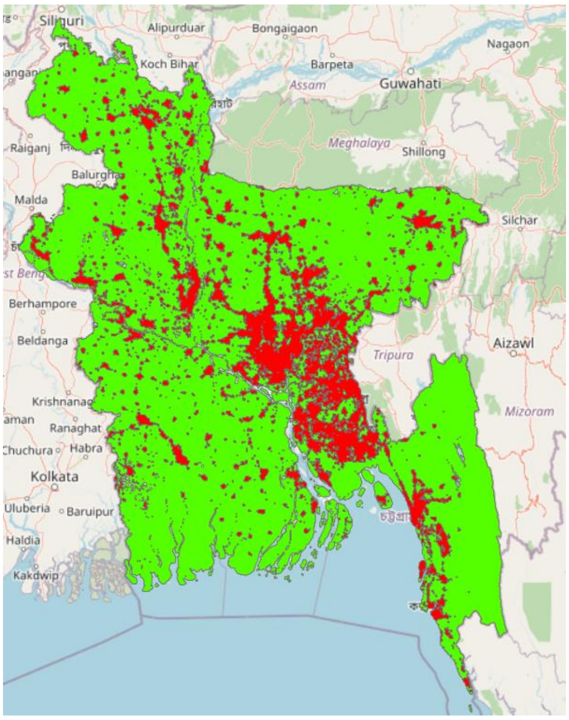

Figure 5 - Population Density - Binary Map

Overlaying the seven binary maps corresponding to the seven exclusion criteria: flood risk, seismic risk, population density, topography, railway crossings, protected environmental areas, and critical zones - we obtain the final binary map illustrating the remining suitable areas (in green) and the unsuitable areas (in red). The overlay of this final binary map with the national highway network results in a map of the remaining potential segments.

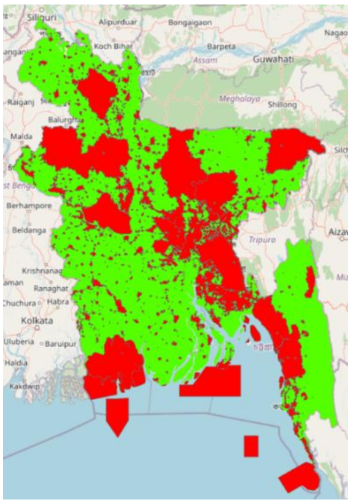

Figure 6 - Final Binary Map

Figure 7 - National Highways

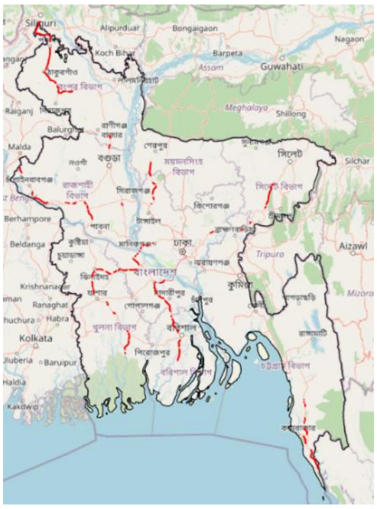

Figure 8 - Remaining Segments

The final step to obtain the definitive list of candidate segments is to apply the last two exclusion criteria - land area and pipelines.

An interactive map, reflecting the results of Case 1 and Case 2, is available here:

https://imperialcollege.maps.arcgis.com/apps/instant/atlas/index.html?appid=b82a478608f040c28e98566b898ae371&webmap=4a061b742e444960baaf1a338bfb0011

Case 3: Manual Exclusion (Green category)
Candidate segments intersecting with pipelines were removed, as well as those with a length under 5 kilometres. According to the recommendation in Section 2.1.1, only areas with a surface area greater than 5 acres should be considered suitable. Assuming a minimum width of 2 meters on each side of the road for installing solar panels, the following calculation for minimum segment length was used:

$$5\ acres = 20{,}000\ m^2$$

$$\text{Area on each side of the road:} \frac{20{,}000}{2} = 10{,}000^2$$

$$\frac{10{,}000}{2} = 5{,}000\ m$$

Therefore, all segments shorter than 5km are excluded.

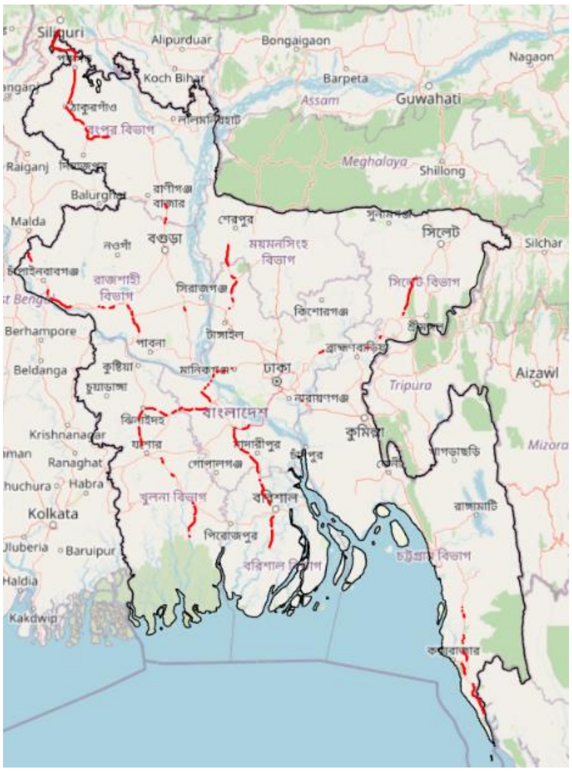

Figure 9 - Remaining Segments

Figure 10 - Final List of Candidate Segments

Thus, Figure 10 shows the list of 27 candidate segments that will be considered in the priority ranking.

4.2 Multi Criteria Scoring of Remaining Segments

4.2.1 Selection of Criteria

At the end of step 1, 27 suitable candidate segments (S_i) remain. The objective of this section is to score and rank these candidate segments through a multi-criteria evaluation.

Therefore, for each of the 27 candidate segments (S_i), a score is calculated as follows:

$$Score\ (S_i) = W_1 \times Value(C_{i1}) + \cdots + W_7 \times Value(C_{i7})$$

Evaluation Criteria C_j		Weights W_i
C_1	Flood Risk	W_1
C_2	Seismic Risk	W_2
C_3	Population Density	W_3
C_4	Solar Irradiation	W_4
C_5	Land Area	W_5
C_6	Proximity Electric Grid	W_6
C_7	Night Light Intensity	W_7

Table 27 - Assessment Criteria

The assumptions regarding these criteria are as follows:

- The lower the flood risk, the higher the priority of the segment.
- The lower the earthquake risk, the higher the priority of the segment.
- The lower the population density, the higher the priority of the segment.
- The higher the solar irradiation, the higher the priority of the segment.
- The larger the land area, the higher the priority of the segment.
- The shorter the distance to the electric grid, the higher the priority of the segment.
- The lower the night light intensity, the higher the electricity need, the higher the priority of the segment.

For each segment (S_i), two scores were calculated, one assuming a grid-connected project and another assuming an off-grid project. This has an impact on whether C_6 (proximity to electric grid), and C_7 (night light intensity) are taken into consideration.

Criterion C_6, was considered when calculating a score for a grid-connected project, but not in the scoring for an off-grid project.

Criterion C_7 will only be considered in the case of an off-grid project, since it is assumed that the energy produced by the solar panels will be used locally and not injected into the national energy grid. The primary goal in this case is to generate electricity for roads that need nighttime lighting the most, and the panels should be installed along the roads with the greatest need.

4.2.2 Determination of Weights

A critical point in this multi-criteria evaluation is the determination of weightings for each of the scores ($W_1, \dots W_7$). To determine these weights, the analytic hierarchy process (AHP) method has been used.

The objective of the AHP method is to compare the criteria C_j in pairs, allowing for a relative importance assessment of each criterion with respect to all others via the Saaty Scale. This method proves to be more effective than traditional approaches where the expert would simply assign a weight between 0 and 1 to each criterion without directly comparing them.

Importance Scale	Definition of Importance
1	Equally Important Preferred
2	Equally to Moderately Important Preferred
3	Moderately Important Preferred
4	Moderately to Strongly Important Preferred
5	Strongly Important Preferred
6	Strongly to Very Strongly Important Preferred
7	Very Strongly Important Preferred
8	Very Strongly to Extremely Important Preferred
9	Extremely Important Preferred

Table 28 - Saaty Scale

In practice, this pairwise comparison is carried out using the Pairwise Matrix P show below.

	Flood Risk	Seismic Risk	Population Density	Solar Irradiation	Land Area	Proximity Electric Grid
Flood Risk	1					
Seismic Risk		1				
Population Density			1			
Solar Irradiation				1		
Land Area					1	
Proximity Electric Grid						1

Table 29 - Pairwise Matrix P

In the matrix P, the coefficient P_{ij} represents the relative importance of criterion *i* compared to criterion *j*, according to the Saaty scale. In this sense, if, based on expert judgement, criterion *i* is "Very Strongly Important" compared to criterion *j*, the expert would enter 7 in cell P_{ij}. In other words, the expert consider criterion *i* to be seven times more important that criterion *j*.

The legitimacy of the selected experts may be subject to discussion. The determination of the weights through the application of the AHP method relies on the judgement of the eight members of the working group (Group 2). These judgements are therefore subjective and are based on the various analyses carried out throughout the project.

Each group member individually constructed a pairwise matrix according to their own judgement. Based on these eight pairwise matrices, a final pairwise matrix, denoted M, was built. This final matrix is constructed such that each coefficient of the matrix is the geometric mean of the eight corresponding individual coefficients.

$$M_{ij} = \left(\prod_{k=1}^{8} P_{ij,k} \right)^{1/8}$$

Following on, the final matrix M is normalised column-wise so that the sum of each column equals 1. The final weight for each criterion is then calculated by taking the average of the values in each row.

	Weight (%) Grid Connected	**Weight (%) Off Grid**
Flood Risk	7.54	6.96
Seismic Risk	5.54	6.30
Population Density	11.26	13.06
Solar Irradiation	39.35	33.78
Land Area	19.28	19.69
Proximity Electric Grid	17.05	-
Night Light Intensity	-	20.20

Table 30 - Criterion Weighting

Once the weights have been determined, the normalised values (C_{ij}) for each criterion $C_1, \dots, C_j, \dots, C_7$, and for each segment $S_1, \dots, S_i, \dots, S_{27}$, have to be collected.

Collection of raw data:

Segment	Flood Risk (scale 1 – 9)	Seismic Risk (scale 1 – 9)	Population Density (inhab/km²)	Solar Irradiation (kWh/m²/year)	Land Area (m²)	Proximity Electric Grid (km)	Night Light Intensity (kW/(m².sr))
S_1							
…							
S_i	$RawValue(C_{i1})$						
…							
S_{27}							

Table 31 - Collection of Raw Data

Normalisation of data (0-100):

Segment	Flood Risk (0 – 100)	Seismic Risk (0 – 100)	Population Density (0 – 100)	Solar Irradiation (0 – 100)	Land Area (0 – 100)	Proximity Electric Grid (0 – 100)	Night Light Intensity (0 – 100)
S_1							
…							
S_i	$Value(C_{i1})$						
…							
S_{27}							

Table 32 - Normalisation of Data

Solar for each of the 27 segments is calculated using:

Grid Connected:

$$core\ (Si) = W_1 \times Value(C_{i1}) + W_2 \times Value(C_{i2}) + W_3 \times Value(C_{i3}) + W_4 \times Value(C_{i4}) + W_5 \times Value(C_{i5}) + W_6 \times Value(C_{i6})$$

Off-grid:

$$Score\ (Si) = W_1 \times Value(C_{i1}) + W_2 \times Value(C_{i2}) + W_3 \times Value(C_{i3}) + W_4 \times Value(C_{i4}) + W_5 \times Value(C_{i5}) + W_7 \times Value(C_{i7})$$

Finally, the ranking of 27 segments can be established and visualised on the following maps:

Figure 11 – Off-Grid Final Ranking

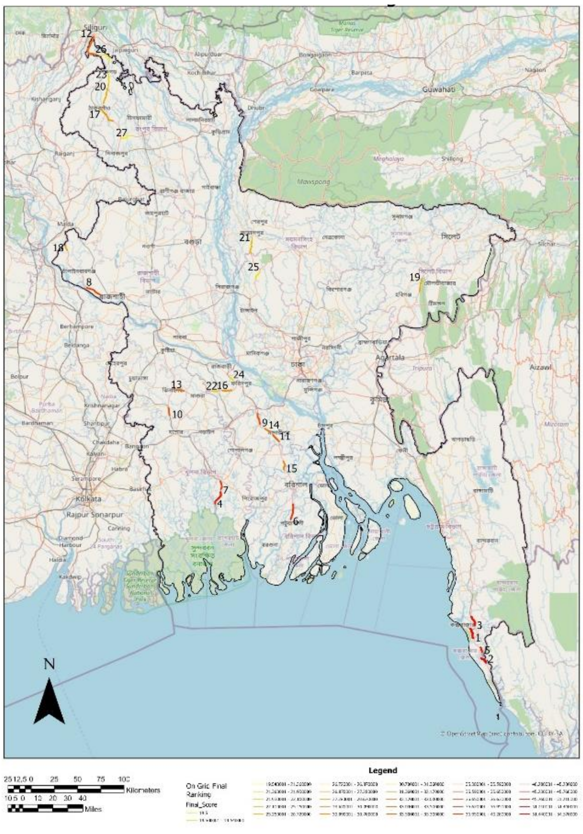

Figure 12 – Grid-Connected Final Ranking

5. Results

5.1 Priority Corridor Identification

Provided below (Table 33 & Table 34) is a summary of the site prioritisation output, showing the Top 5 ranked segments based on their Site Suitability Index for both grid-connected and off-grid calculations. The full output containing each of the 27 feasible road segments and its corresponding Site Suitability Index can be found in the Appendix; Table 47 & Table 48.

In each case, the greater the Index score, the more suitable the road segment is at meeting the solar generation site feasibility and electricity need characteristics outlined previously (per section 4. Methodology), and therefore the greater the priority placed on each road segment.

Road Segment	Segment ID	Site Suitability Index
(N1) Dhaka-Cumilla-Chattogram-Teknaf	4	54.57
(N1) Dhaka-Cumilla-Chattogram-Teknaf	6	51.44
(N1) Dhaka-Cumilla-Chattogram-Teknaf	3	51.21
(N7) Daulatdia-Faridpur- Jhenaidah-Jashore-Khulna-Mongla	16	45.76
(N1) Dhaka-Cumilla-Chattogram-Teknaf	5	45.23

Table 33 - Top 5 road segments according to Grid-Connected Site Suitability Index

Road Segment	Segment ID	Site Suitability Index
(N1) Dhaka-Cumilla-Chattogram-Teknaf	4	60.89
(N1) Dhaka-Cumilla-Chattogram-Teknaf	6	58.65
(N1) Dhaka-Cumilla-Chattogram-Teknaf	3	57.65
(N7) Daulatdia-Faridpur- Jhenaidah-Jashore-Khulna-Mongla	16	52.91
(N7) Daulatdia-Faridpur- Jhenaidah-Jashore-Khulna-Mongla	15	52.82

Table 34 - Top 5 segments according to Off-Grid Site Suitability Index

However, to ascertain the effectiveness of the identified sites in meeting the World Banks objectives, a comparison must be made between the solar potential and the national highway lighting electricity demand.

5.2 Solar Potential

To assess the total solar potential of the 27 candidate road segments identified in Section 4, the solar potential of each segment is calculated as follows:

$$Solar\ Potential(kW) = Solar\ Irradiance(kW/m^2) \times Area(m^2) \times Efficiency(\%) \times Performance\ Ratio\ (\%)$$

Whereby the efficiency depends on the solar panel technology, and therefore the supplier considered (details of which can be found in Section 2; Table 3), and the Performance Ratio, which accounts for system losses and is typically assumed to be 80% for solar panel infrastructure (PV plant in Bangladesh showed and average PR of ~ 78.6% (Ali et al., 2023)).

	Min Segment Potential (kWh/year)	Max Segment Potential (kWh/year)	Total Solar Potential (kWh/year)
Supplier 1	6,081,663	29,130,845	350,803,335
Supplier 2	5,715,950	27,379,102	329,708,257
Supplier 3	6,637,004	31,790,900	382,836,602

Table 35 - Annual Solar Generation Potential Based on the Efficiencies of the Various Solar Panel Suppliers

The full breakdown of solar generation potential for reach individual road segment and supplier can be found in the Appendix; Table 49Table 49.

5.3 Electricity Demand

Due to a lack of existing information regarding electricity usage on Bangladesh highways, this report proposes a standardised lighting layout for all national highways, to be used in calculating the total road lighting electricity requirements.

The proposed layout follows the key lighting objectives reviewed in Section 2.4, being:

i. **Safety** – Ensuring good visibility for drivers, pedestrians, and service road users.
ii. **Uniformity** – Minimising glare and shadows, maintaining consistent lighting levels.
iii. **Energy Efficiency** – Using LED or energy-saving light bulbs.
iv. **Compliance** – Following the road lighting manual, BS 5489-1:2013 and BS EN 13201 for urban road lighting.

5.3.1 National Highway Lighting Layout

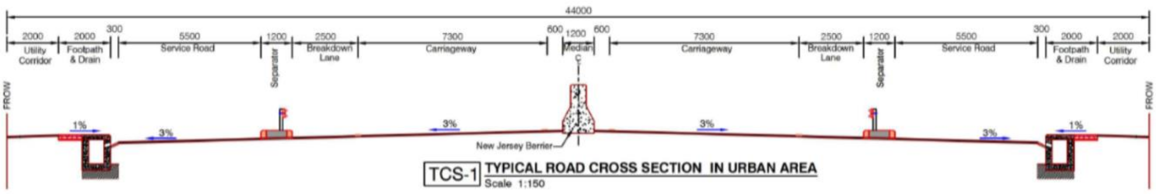

Figure 13 - Typical Urban Road Cross-Section used for WeCare Project

Following the typical urban road cross-section design proposed for the WeCare project (Figure 13 - Typical Urban Road Cross-Section used for WeCare Project)(Roads and Highways Department et al., 2018), five distinct lighting zones have been identified, see Table 36 below.

Zone	**Width (m)**	**Lighting Purpose**
Footpath & Drain	2.3	Pedestrian safety and visibility
Service Road	5.5	Local vehicle traffic
Breakdown Lane	2.5	Emergency vehicle visibility
Carriageway	7.3	Main traffic lanes for vehicles
Median & Separator	1.2 - 2.4	Optional low-level or marker lighting

Table 36 - Lighting zones based on the urban road cross-section

Each of the lighting zones has different requirements for illuminance based on its lighting purpose, with footpaths for instance, requiring more focused lighting and lower glare whilst carriageways require the highest brightness and uniformity. An outline of the assumed lighting parameters for national highways, on which the electricity demand has been calculated, can be found in Table 36 - Lighting zones based on the urban road cross-section.

Parameter	**Value / Explanation**
Lamp Type	LED Street Lighting
Pole Heights	Footpath & Service Road: 8 m, Carriageway & Breakdown Lane: 12 m
Pole Placement	Central Median: symmetrical lighting coverage for both carriageways and breakdown lanes. Footpath: footpath and service road lighting
Pole Spacing	Footpath & Service Road: 25 m, Carriageway & Breakdown Lane: 35 m (minimum typical for these heights, see Appendix; Table 50
Illuminance Levels	Footpath: 10 lux, Service Road: 15 lux, Breakdown Lane: 10 lux, Carriageway: 20 lux (See Appendix; Table 50)

Lamp Efficacy	130 lumens/watt (typical for modern LED streetlamps)
Lamp Output	Calculated from required lighting level and area coverage
Lighting Standard References	BS 5489-1:2013, Road Lighting Manual- Part 1, Section 3, BS EN 13201-2:2015 (Lighting Classes and Levels)
Operating Hours	12 hours/night (typical for Bangladesh as it is close to the equator)

Table 37 - Assumed lighting parameters based on the literature

5.3.2 Highway Lighting Electricity Usage

To obtain the electricity requirements for the proposed national highway lighting layout, the road surface area must first be calculated for each of the identified lighting zones Table 36.

Section	Width (m)	Length (m)	Area (m²)
Footpath & Drain	2.3 * 2 = 4.6	1,000	4,600
Service Road	5.5 * 2 =11.0	1,000	11,000
Breakdown Lane	2.5 * 2 = 5.0	1,000	5,000
Carriageway	7.3 * 2 = 14.6	1,000	14,600

Table 38 - Road surface area of each lighting zone

Next, the total lumens required to light each zone to an acceptable level of illuminance (Table 37) are calculated using the formula:

$$\text{Total Lumens} = \text{Illuminance (Lux)} \times \text{Area } (m^2)$$

Section	**Average Illuminance (lux)**	**Area (m²)**	**Total Lumens Needed (lm)**
Footpath & Drain	10	4,600	46,000
Service Road	15	11,000	165,000
Breakdown Lane	10	5,000	50,000
Carriageway	20	14,600	292,000

Table 39 - Total lumens needed to meet acceptable illuminance levels for each zone

Based on an assumed lamp efficiency of 130 lm/W (per Table 37), the wattage required to power each zone is calculated using the formula:

$$\text{Wattage} = \text{Lumens} / \text{Efficacy (lm/W)}$$

Section	**Total Lumens (lm)**	**Efficacy (lm/W)**	**Wattage Required (W)**
Footpath & Drain	46,000	130	354
Service Road	165,000	130	1,270
Breakdown Lane	50,000	130	384
Carriageway	292,000	130	2,246
Total			**4,254**

Table 40 - Power requirements of each zone

Subsequently, using the assumed 12-hour operating time, the total wattage required across all lighting zones and the 2,185 km length of the national highway, the **total daily** road lighting electricity requirements are **111,549.58** kWh/day and the **total annual** road lighting electricity requirements are **40,715,596.38** kWh/yr.

5.4 Site Evaluation

Having obtained the potential for solar generation and an estimate of the electricity demand for the national highways lighting, there **is sufficient solar potential along the ROW of national highways to meet the power demands.**

As Table 41 shows, placing solar panels in the ROW of only the four highest ranked road segments will produce more than the 40,715,596.38kWh required to power the national highways. This also demonstrates significant potential for supplying surplus electricity to the grid to help meet Bangladesh's growing electricity demand from other sectors.

Even given the worst-case scenario shown in Table 42, which accounts for the energy output from solar photovoltaics decreasing by up to 36% (Gopi et al., 2021) during the monsoon season (per section 2.) and a 15% efficiency reduction due to the build-up of dirt (per section 2.), the electricity demands can still be met if the number of solar generation sites is increased to either six or seven road segments, depending on the solar panel manufacturer.

Road Segment	Segment ID	Segment Solar Potential			Cumulative Solar Potential		
		Supplier 1	Supplier 2	Supplier 3	Supplier 1	Supplier 2	Supplier 3
(N1) Dhaka-Cumilla-Chattogram-Teknaf	4	14,098,088.22	13,250,318.99	15,385,441.48	14,098,088.22	13,250,318.99	15,385,441.48
(N1) Dhaka-Cumilla-Chattogram-Teknaf	6	9,012,297.18	9,835,246.37	9,835,246.37	23,110,385.40	23,085,565.36	25,220,687.85
(N1) Dhaka-Cumilla-Chattogram-Teknaf	3	13,176,801.46	12,384,432.55	14,380,028.32	36,287,186.86	35,469,997.91	39,600,716.17
(N7) Daulatdia-Faridpur-Jhenaidah-Jashore-Khulna-Mongla	16	16,651,903.61	15,650,564.19	18,172,456.06	**52,939,090.47**	**51,120,562.11**	**57,773,172.23**

*Table 41 - **Annual** segment and cumulative solar generation potential of Off-Grid ranked road segments*

Road Segment	Segment ID	Segment Solar Potential			Cumulative Solar Potential		
		Supplier 1	Supplier 2	Supplier 3	Supplier 1	Supplier 2	Supplier 3
(N1) Dhaka-Cumilla-Chattogram-Teknaf	4	21,011.95	19,748.42	22,930.63	21,011.95	19,748.42	22,930.63
(N1) Dhaka-Cumilla-Chattogram-Teknaf	6	13,432.03	14,658.56	14,658.56	34,443.97	34,406.98	37,589.19
(N1) Dhaka-Cumilla-Chattogram-Teknaf	3	19,638.85	18,457.89	21,432.15	54,082.82	52,864.87	59,021.34
(N7) Daulatdia-Faridpur-Jhenaidah-Jashore-Khulna-Mongla	16	24,818.18	23,325.77	27,084.43	78,901.00	76,190.65	86,105.77
(N7) Daulatdia-Faridpur-Jhenaidah-Jashore-Khulna-Mongla	15	13,939.47	13,101.24	15,212.34	92,840.48	89,291.89	101,318.11
(N8) Dhaka -Mawa-Bhanga-Barishal-Patuakhali	21	15,931.96	14,973.91	17,386.77	108,772.43	104,265.80	**118,704.88**
(N7) Daulatdia-Faridpur-Jhenaidah-Jashore-Khulna-Mongla	18	13,657.94	12,836.64	14,905.10	**122,430.37**	**117,102.44**	133,609.98

*Table 42 - **Daily** segment and cumulative solar generation potential of Off-Grid ranked road segments based on a worst-case scenario*

5.5 Segment Scores & Interactive Map

Figure 14 14 - QR code to interactive map

Figure 14 is a QR code linking to the interactive map created as an output of the project, displaying the 27 candidate road segments identified during the feasibility and demand assessment (per Section 4.1). Each segment is ranked from 1 to 27, with 1 representing the most suitable site for solar generation and 27 the least.

There are two separate rankings: one for an "On Grid" (Grid-Connected) scenario, where solar panels are connected to the national electrical grid, and another for an "Off Grid" scenario, where the panels supply power only to nearby batteries.

The interactive map can also be found using the following link:
https://imperialcollege.maps.arcgis.com/apps/instant/atlas/index.html?appid=b4583745aeb949bb82099ee1c5dc8469&webmap=208e20aea3e64361a074e2c1fd25ff89

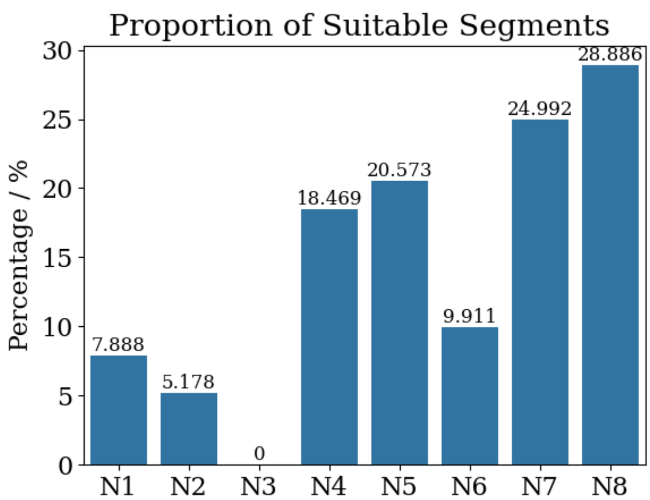

Figure 15 - Proportion of Suitable Segments

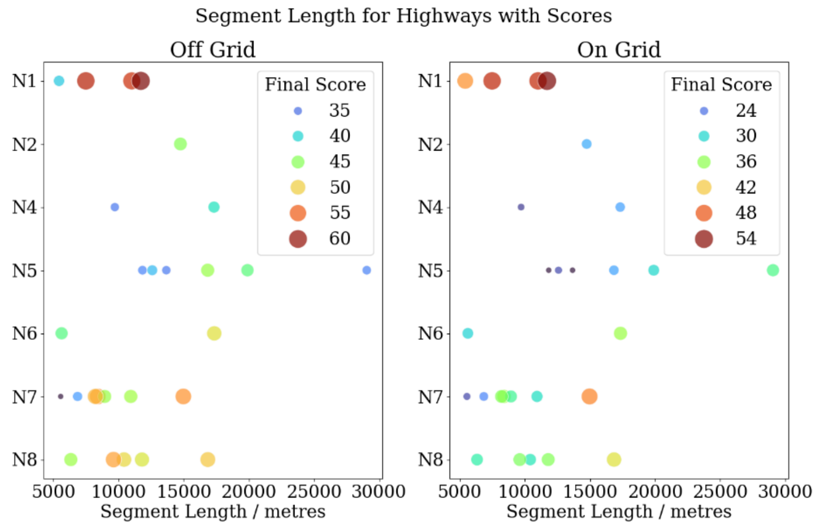

Figure 16 - Segment Scores

Figure 15 shows the percentage of road length that is covered by suitable segments with N8 possessing the highest proportion. Of the 27 suitable segments there are none on the highway N3. Figure 16 shows the length of each section by highway number with the data points colour coded by the final score.

5.6 Limitations

As with many developing countries, information procurement for Bangladesh is difficult, and often no updated records are kept. As such key assumptions have been made, as is the case in calculating the electricity demands of the highway and measuring the available ROW, which will require corroborating with further studies. Similarly, a lack of information for seasonal variation of solar irradiation, meant having to use the yearly average figure and a worst-case scenario was analysed for the monsoon season based on the literature findings.

As this report does not make a recommendation on which solar panel to purchase and therefore the dimensions of the solar panels are unknown, the solar potential has been calculated based on generation for the full width of the ROW (a minimum of 2 meters on each side are required for the solar panels, meaning that at least 3 meters of space on each side are needed for installation and maintenance. As a result, the typical urban road cross section must expand to a total width of 50 meters). The solar panels are unlikely to perfectly align to this specification, and access considerations will mean that the actual solar generation area is slightly smaller. Therefore, the estimations made in this report will likely be slightly greater than real world figures.

6. Conclusions

The report reflects the comprehensive approach taken to conduct the conceptual design to ensure readiness for implementation. The conceptual design includes:

- A detailed review of the literature, including site requirements and financing opportunities based on case study analysis and the level of current solar technology
- Sustainability considerations such as the development of skills and creation of jobs for local communities
- A robust analysis of the policy and regulatory environment in Bangladesh including an initial assessment of potential stakeholders

The group design project produced (a) framework for assessing solar power generation along government ROWs, (b) analytical tools in the form of an interactive map, and (c) preliminary list of highway segments for pre-feasibility studies, thus meeting all deliverables outlined in the project briefing.

6.1 Recommendations

6.1.1 Delineation and Quantification of Right of Way of the Highways

The delineation and quantification of highway ROW are critical, yet unresolved issues for Bangladesh's solar highway initiatives. While comprehensive GIS mapping exists for the country's road network categories, the absence of clearly defined ROW boundaries creates significant uncertainty for project planning. This data gap is particularly problematic given Bangladesh's complex land ownership patterns and the dense development along major highway corridors.

For meaningful progress, especially in attracting private sector investment, precise identification and mapping of available ROW space for solar installations is essential. Without this clarity, developers face substantial risks in project design, land acquisition negotiations, and financial modelling. The uncertainty directly impacts LCOE calculations, as unknown variables in land availability and potential relocation costs can dramatically alter project economics.

6.1.2 Initial Trial Site

Based upon the report's findings, a pilot project for solar generation is recommended along the ROW of segment 4, Dhaka-Cumilla-Chattogram-Teknaf, N1 national highway. This segment scored highest on the Site Suitability Index for both grid-connected and off-grid generation and an initial look into its feasibility shows the area to be less densely developed, with greater space available along the ROW for solar panel placement than the rest of Bangladesh, as confirmed by a visual inspection of Google Maps.

This is particularly promising as the region is already subject to planned development works including an expansion of the road network and creation of a new port.

6.1.3 Grid Connection Recommendations for Solar Highway Projects

On-Grid Connections: Bangladesh's existing transmission infrastructure along major highways presents both opportunities and challenges for grid integration. The national highways, particularly the N1-N8 corridors, typically run parallel to power distribution lines, making interconnection technically feasible. However, several considerations demand attention.

The proximity to BPDB substations becomes crucial – projects located within 5-10 km of existing substations can significantly reduce interconnection costs. In cases where there is frequent grid instability and load-shedding issues, inverters must incorporate advanced grid-support features, including voltage regulation and frequency ride-through capabilities. The recent net-metering policy allows systems up to 3 MW, but highway projects exceeding this capacity require negotiating agreements with BPDB.

Synchronisation with the national grid's variable quality requires robust power conditioning equipment. During the monsoon season, when solar generation drops but grid demand peaks for irrigation pumps, these systems can provide valuable peak-shaving support to rural feeders along highway corridors.

Off-Grid Considerations: For remote highway sections, particularly in the Chittagong Hill Tracts or char areas, off-grid solutions offer immediate implementation advantages without BPDB coordination delays. These system suit:

- Highway toll plazas requiring 24/7 operation
- Rural centres along highways lacking reliable grid access
- Emergency communication towers and highway patrol stations
- LED highway lighting systems with battery backup

The key challenge lies in battery sizing for Bangladesh’s extended monsoon periods, typically requiring 3-5 days of autonomy. The high humidity and temperature fluctuations require weatherproof enclosures and tropical-rated batteries, which increase capital costs by 20-30% compared to grid-tied systems.

Off-grid implementations can begin immediately as demonstration projects, building local acceptance while grid-connection permits are processed. However, the success of these off-grid systems hinges critically on energy storage. In the absence of grid support, battery systems must reliably bridge the gap between solar generation and consumption patterns, given the country’s extended monsoon periods and high-humidity environment, which can last for 3-4 months annually. The selection of emerging Battery as a Service (BaaS) models becomes pivotal, which has distinct implications for project economics, operational reliability, and long-term sustainability.

Battery as a Service (BaaS):
The BaaS model, successfully demonstrated in Bangladesh's telecom sector since 2018, offers a practical alternative. Pilot Battery-as-a-Service schemes have been introduced in Bangladesh’s telecom sector, with local power companies such as Rahimafrooz and Energypac marketing turnkey battery-backup solutions for BTS towers.

This operational model aligns perfectly with Bangladesh's procurement framework where RHD owns the project. Government agencies can classify BaaS as a utility service, similar to electricity bills, thereby bypassing lengthy tender processes for capital equipment. Fees typically range from $ 1/kWh/day capacity, including maintenance and replacement guarantees (Tiger New Energy, Critical Session 2 with the World Bank). In the case of PPPs, the private partner can undertake the service and reduce upfront costs, end-of-life costs and costs of battery upgrades in the case technology changes.

There are many advantages to consider BaaS instead of outrightly purchasing battery storage. BaaS providers have developed tropicalized solutions through years of local experience. Providers like Tiger New Energy offer (Tiger New Energy, 2023):

- Uptime guarantees with financial penalties, crucial for highway safety lighting and toll operations.
- Decentralized energy storage systems designed for emerging countries
- Thermal control, fire protection and waterproof (IP64)
- GPS embedded battery with anti-theft alarm, with intelligent diagnostics

By aggregating demand across projects, BaaS operators achieve economies of scale, resulting in approximately 25-30% lower per-unit costs compared to individual installations. This model has already enabled rapid deployment of renewable energy in rural health clinics and could similarly accelerate highway solar adoption.

7. References

8. Appendix

	Flood Risk	Seismic Risk	Population Density	Solar Irradiation	Land Area	Proximity Electric Grid
Flood Risk	1	2	1/2	1/6	1/3	1/2
Seismic Risk	1/2	1	1/2	1/6	1/3	1/3
Population Density	2	2	1	1/3	1/2	1/2
Solar Irradiation	6	6	3	1	2	2
Land Area	3	3	2	1/2	1	1
Proximity Electric Grid	2	3	2	1/2	1	1

Table 43 - Pairwise Matrix (Grid-Connected)

	Flood Risk	Seismic Risk	Population Density	Solar Irradiation	Land Area	Night Light Intensity
Flood Risk	1	2	1/2	1/6	1/3	1/4
Seismic Risk	1/2	1	1/2	1/6	1/3	1/5
Population Density	2	2	1	1/3	1/2	1/3
Solar Irradiation	6	6	3	1	2	2
Land Area	3	3	2	1/2	1	1/2
Night Light Intensity	4	5	3	1/2	2	1

Table 44 - Pairwise Matrix (Off-Grid)

Test of Consistency (Amin et al., 2023; Taherdoost, 2017)**:**
The evaluation of expert judgements in the comparison of criteria is based on the level of consistency of their assessments. To verify this consistency, two key indicators are used: the consistency index (CI) and the consistency ratio (CR), which are used to determine whether the pairwise comparison matrix is reliable.

The verification procedure is as follows:

First, a decision matrix E is generated by multiplying the vector of criterion weights W by the pairwise comparison matrix P.

$$E = P \times W$$

Next, the sum of the columns of this matrix *E* is divided by the corresponding weights *Wi* which gives the priority matrix *F*.

$$F_i = \frac{\sum_{j=1}^{n} E_{ij}}{W_i}$$

The principal eigenvalue λ_{max} is then calculated using the priority matrix *F* as follows:

$$\lambda = \frac{\sum_{i=1}^{n} F_i}{n}$$

The CI consistency index is then calculated as follows:

$$CI = \frac{\lambda - n}{n - 1}$$

The AHP method verifies the validity of the consistency index (CI) by comparing it to a random index (RI), whose values depend on the order of the comparison matrix (see Table). This comparison allows the consistency ration (CR) to be calculated using the following formula

$$CR = \frac{CI}{RI}$$

Matrix Order	3	4	5	6	7	8
Random Index	0.58	0.90	1.12	1.24	1.32	1.41

Table … - Random Index (ref)

A CR of less than 0.1 indicates that the pairwise comparisons are sufficiently consistent. However, if CR exceeds 0.1, this indicates inconsistency in the experts' judgements. In this case, the values in the comparison matrix must be reviewed and adjusted.

In our study, six evaluation criteria were considered, so the Random Index was RI = 1.24. The calculations yielded:

- On-grid: CR = 0.0150
- Off-grid: CR = 0.0363

In both cases, the pairwise comparison matrices are therefore considered consistent.

Segment ID	**Flood Risk** (scale 1 – 9)	**Seismic Risk** (scale 1 – 9)	**Population Density** (inhab/km²)	**Solar Irradiation** (kWh/m²/year)	**Land Area** (m²)	**Proximity Electric Grid** (km)	**Night Light** (kW/(m².sr)
1	3	6	1,116.6	1,637	35,187.70	29.05	46.1
2	6	6	987.6	1,704	63,111.73	13.24	48.6
3	0	6	1,190	1,797	40,827.76	11.10	54.8
4	0	6	1,119.1	1,808	43,416.57	8.88	54.9
5	0	6	1,277.6	1,797	20,133.31	29.47	83.5
6	0	6	1,004.1	1,801	27,862.20	38.75	53.6
7	3	3	995.4	1,685	61,954.90	3.40	55
8	3	3	1,197.4	1,681	38,216.21	18.82	35.3
9	2	4	782.1	1,564	103,707.46	19.68	81.1
10	2	4	945.2	1,570	48,811.60	10.19	46.6

Segment ID	Flood Risk (scale 1 – 9)	Seismic Risk (scale 1 – 9)	Population Density (inhab/km²)	Solar Irradiation (kWh/m²/year)	Land Area (m²)	Proximity Electric Grid (km)	Night Light (kW/(m².sr)
11	2	4	893.8	1,587	44,918.53	1.88	45.3
12	6	6	895.8	1,652	53,436.59	15.60	38.9
13	2	4	955.2	1,600	60,205.34	5.39	39
14	2.5	5	923.4	1,612	71,387.53	3.18	50.6
15	3	3	764.1	1,689	30,832.19	14.19	42.1
16	3	3	472.9	1,684	55,057.37	6.02	65
17	3	3	1,125.1	1,693	32,735.46	3.20	48
18	3	3	998.9	1,702	29,978.73	18.11	40.8
19	2	2	1,209.3	1,687	43,104.91	21.42	47.4
20	2	1	1,233.1	1,689	23,242.25	9.34	45.6
21	2	1	1,206.7	1,689	35,239.29	7.12	37.7
22	4	6	1,025.5	1,631	62,585.08	4.35	47.2
23	3	6	1,187.8	1,621	42,583.82	10.09	40.8
24	6	2	1,247.2	1,669	20,288.95	7.014	57.1
25	6	2	1,048.5	1,678	40,065.60	10.74	44
26	6	2	1,285.6	1,686	25,100.14	14.67	50
27	3	1	1,193.3	1,682	20,330.97	23.12	46

Table 45 - Raw Data

Segment ID	Score_ Flood (0 – 100)	Score_ Seismic (0 – 100)	Score_ Density (0 – 100)	Score_ Solar (0 – 100)	Score_Land _Area (0 – 100)	Score_Grid Proximity (0 – 100)	Score_Night _Light (0 – 100)
1	50	0	20.79	29.92	18.01	26.31	77.59
2	0	0	36.67	57.38	51.43	69.19	72.41
3	100	0	11.76	95.49	24.76	75	59.54
4	100	0	20.49	100	27.86	81.02	59.34
5	100	0	0.98	95.49	0	25.18	0
6	100	0	34.64	97.13	9.25	0	62.03
7	50	60	35.71	49.59	50.04	95.88	59.13
8	50	60	10.85	47.95	21.64	54.05	100
9	66.67	40	61.95	0	100	51.71	4.98
10	66.67	40	41.89	2.46	34.31	77.45	76.56
11	66.67	40	48.21	9.43	29.66	100	79.25
12	0	0	47.96	36.07	39.85	62.8	92.53
13	66.67	40	40.65	14.75	47.95	90.47	92.32
14	58.33	20	44.57	19.67	61.33	96.46	68.26
15	50	60	64.17	51.23	12.8	66.6	85.89
16	50	60	100	49.18	41.79	88.76	38.38
17	50	60	19.75	52.87	15.08	96.42	73.65
18	50	60	35.28	56.56	11.78	55.97	88.59
19	66.67	80	9.39	50.41	27.49	47	74.9
20	66.67	100	6.46	51.23	3.72	79.76	78.63
21	66.67	100	9.71	51.23	18.07	85.79	95.02
22	33.33	0	32	27.46	50.8	93.28	75.31
23	50	0	12.03	23.36	26.86	77.72	88.59
24	0	80	4.72	43.03	0.19	86.07	54.77
25	0	80	29.17	46.72	23.85	75.96	81.95
26	0	80	0	50	5.94	65.32	69.5

Segment ID	Score_ Flood (0 – 100)	Score_ Seismic (0 – 100)	Score_ Density (0 – 100)	Score_ Solar (0 – 100)	Score_Land _Area (0 – 100)	Score_Grid Proximity (0 – 100)	Score_Night _Light (0 – 100)
27	50	100	11.36	48.36	0.24	42.38	77.8

Table 46 - Normalised Data

Segment ID	Road Segment	Site Suitability Index
4	(N1) Dhaka-Cumilla-Chattogram-Teknaf	54.57
6	(N1) Dhaka-Cumilla-Chattogram-Teknaf	51.44
3	(N1) Dhaka-Cumilla-Chattogram-Teknaf	51.21
16	(N7) Daulatdia-Faridpur-Jhenaidah-Jashore-Khulna-Mongla	45.76
5	(N1) Dhaka-Cumilla-Chattogram-Teknaf	45.23
7	(N8) Dhaka -Mawa-Bhanga-Barishal-Patuakhali	40.28
15	(N7) Daulatdia-Faridpur-Jhenaidah-Jashore-Khulna-Mongla	36.95
2	(N6) Kashinathpur-Natore-Rajshahi-Nawabganj-Baliadighi	36.62
19	(N8) Dhaka -Mawa-Bhanga-Barishal-Patuakhali	35.65
18	(N7) Daulatdia-Faridpur-Jhenaidah-Jashore-Khulna-Mongla	35.59
21	(N8) Dhaka -Mawa-Bhanga-Barishal-Patuakhali	35.3
9	(N5) Dhaka (Mirpur)- Bogura-Rangpur- Banglabandha	33.5
17	(N7) Daulatdia-Faridpur-Jhenaidah-Jashore-Khulna-Mongla	33.03
20	(N8) Dhaka -Mawa-Bhanga-Barishal-Patuakhali	32.17
8	(N8) Dhaka -Mawa-Bhanga-Barishal-Patuakhali	31.36
25	(N7) Daulatdia-Faridpur-Jhenaidah-Jashore-Khulna-Mongla	30.7
14	(N5) Dhaka (Mirpur)- Bogura-Rangpur- Banglabandha	30.09
27	(N6) Kashinathpur-Natore-Rajshahi-Nawabganj-Baliadighi	29.67
12	(N2) Dhaka-Bhairab-Sylhet-Tamabil	27.28
13	(N5) Dhaka (Mirpur)- Bogura-Rangpur- Banglabandha	26.87
22	(N4) Joydebpur-Tangail-Jamalpur	26.72
26	(N7) Daulatdia-Faridpur-Jhenaidah-Jashore-Khulna-Mongla	25.25
11	(N5) Dhaka (Mirpur)- Bogura-Rangpur- Banglabandha	22.1
24	(N7) Daulatdia-Faridpur-Jhenaidah-Jashore-Khulna-Mongla	21.93
1	(N4) Joydebpur-Tangail-Jamalpur	21.36
10	(N5) Dhaka (Mirpur)- Bogura-Rangpur- Banglabandha	19.54
23	(N5) Dhaka (Mirpur)- Bogura-Rangpur- Banglabandha	19.5

Table 47 - Ranked Road Segments by Grid-Connected Site Suitability Index

Segment ID	Road Segment	Site Suitability Index
4	(N1) Dhaka-Cumilla-Chattogram-Teknaf	60.89
6	(N1) Dhaka-Cumilla-Chattogram-Teknaf	58.65
3	(N1) Dhaka-Cumilla-Chattogram-Teknaf	57.65
16	(N7) Daulatdia-Faridpur-Jhenaidah-Jashore-Khulna-Mongla	52.91
15	(N7) Daulatdia-Faridpur-Jhenaidah-Jashore-Khulna-Mongla	52.82
21	(N8) Dhaka -Mawa-Bhanga-Barishal-Patuakhali	52.27
18	(N7) Daulatdia-Faridpur-Jhenaidah-Jashore-Khulna-Mongla	51.19
7	(N8) Dhaka -Mawa-Bhanga-Barishal-Patuakhali	50.47
8	(N8) Dhaka -Mawa-Bhanga-Barishal-Patuakhali	49.34
2	(N6) Kashinathpur-Natore-Rajshahi-Nawabganj-Baliadighi	48.93
19	(N8) Dhaka -Mawa-Bhanga-Barishal-Patuakhali	48.48
25	(N7) Daulatdia-Faridpur-Jhenaidah-Jashore-Khulna-Mongla	45.88
20	(N8) Dhaka -Mawa-Bhanga-Barishal-Patuakhali	45.71
17	(N7) Daulatdia-Faridpur-Jhenaidah-Jashore-Khulna-Mongla	45.55
13	(N5) Dhaka (Mirpur)- Bogura-Rangpur- Banglabandha	45.54
12	(N2) Dhaka-Bhairab-Sylhet-Tamabil	44.99
14	(N5) Dhaka (Mirpur)- Bogura-Rangpur- Banglabandha	43.65
27	(N6) Kashinathpur-Natore-Rajshahi-Nawabganj-Baliadighi	43.36
22	(N4) Joydebpur-Tangail-Jamalpur	40.99
5	(N1) Dhaka-Cumilla-Chattogram-Teknaf	39.34
11	(N5) Dhaka (Mirpur)- Bogura-Rangpur- Banglabandha	38.49
26	(N7) Daulatdia-Faridpur-Jhenaidah-Jashore-Khulna-Mongla	37.14
23	(N5) Dhaka (Mirpur)- Bogura-Rangpur- Banglabandha	36.13
9	(N5) Dhaka (Mirpur)- Bogura-Rangpur- Banglabandha	35.95
10	(N5) Dhaka (Mirpur)- Bogura-Rangpur- Banglabandha	35.68
1	(N4) Joydebpur-Tangail-Jamalpur	35.52
24	(N7) Daulatdia-Faridpur-Jhenaidah-Jashore-Khulna-Mongla	31.29

Table 48 - Ranked Road Segments by Off-Grid Site Suitability Index

Road Segment ID	Land Area (m^2)	Segment Solar Potential (kWh)		
		Supplier 1	Supplier 2	Supplier 3
1	35,187.70	10,345,366.24	9,723,261.81	11,290,043.34
2	63,111.73	19,314,613.85	18,153,156.00	21,078,309.10
3	40,827.76	13,176,801.46	12,384,432.55	14,380,028.32
4	43,416.57	14,098,088.22	13,250,318.99	15,385,441.48
5	20,133.31	6,497,849.08	6,107,109.83	7,091,193.88

Road Segment ID	Land Area (m²)	Segment Solar Potential (kWh)		
		Supplier 1	Supplier 2	Supplier 3
6	27,862.20	9,012,297.18	8,470,355.04	9,835,246.37
7	61,954.90	18,749,163.97	17,621,708.68	20,461,225.72
8	38,216.21	11,537,765.63	10,843,957.90	12,591,325.52
9	103,707.46	29,130,845.15	27,379,101.67	31,790,900.05
10	48,811.61	13,763,506.29	12,935,856.69	15,020,307.53
11	44,918.53	12,802,913.39	12,033,027.73	13,971,999.02
12	53,436.59	15,854,592.47	14,901,198.26	17,302,339.22
13	60,205.34	17,300,606.86	16,260,258.56	18,880,395.01
14	71,387.53	20,667,775.96	19,424,947.56	22,555,033.90
15	30,832.19	9,352,772.68	8,790,356.50	10,206,812.05
16	55,057.37	16,651,903.61	15,650,564.19	18,172,456.06
17	32,735.46	9,953,634.88	9,355,086.68	10,862,541.40
18	29,978.73	9,163,874.82	8,612,817.76	10,000,665.18
19	43,104.91	13,060,150.10	12,274,795.86	14,252,725.06
20	23,242.25	7,050,406.42	6,626,439.88	7,694,207.45
21	35,239.29	10,689,640.81	10,046,833.91	11,665,755.01
22	62,585.08	18,332,897.33	17,230,473.66	20,006,948.09
23	42,583.82	12,397,495.55	11,651,989.13	13,529,560.84
24	20,288.95	6,081,662.74	5,715,950.28	6,637,003.88
25	40,065.60	12,074,522.55	11,348,437.67	13,177,095.88
26	25,100.14	7,600,462.79	7,143,419.37	8,294,491.69
27	20,330.97	6,141,725.19	5,772,400.96	6,702,550.88

Table 49 - Annual Solar Generation Potential for Each Road Segment Based on the Efficiencies of Various Solar Panel Suppliers

Road Section	Pole Height (m)	Lamp Spacing (m)	Average Illuminance (lux)	Uniformity Ratio (Min)	Surround Ratio (Min)	Notes
Footpath Drain	6–8	25–35	10–20	0.4–0.6	0.3	Pedestrian-focused lighting with low glare
Service Road	6–8	30–40	15–20	0.4–0.6	0.3–0.5	Local traffic with moderate brightness
Breakdown Lane	10–12	35–40	10–15	0.3–0.5	0.5	Emergency lane, lower brightness than carriageway
Carriageway	10–12	35–40	20–30	0.4–0.6	0.5	Main traffic lanes, higher brightness and uniformity
Median (lamp posts)	10–12	35–40	—	—	—	Supports lighting for carriageway and breakdown lane

Table 50 - Recommended Pole Height, Lamp Spacing, Average Illuminance, Uniformity Ratio (Min), and Surround Ratio (adapted from Tables 1, 2a, 2b from Road Lighting Manual)