Unlocking the Potential for Solar PV System Deployment for Sustainable Energy Transition in Bangladesh through Policy and Technology Innovation

by

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Declaration

I hereby affirm that the present work was written by me alone, using no sources or aids other than those referenced in it. All of the materials taken directly or indirectly from external sources (including electronic sources, the internet and oral communication) are marked as such, without exception and with a precise indication of the source. The core PhD thesis content has not been used previously for another thesis or work submitted in order to obtain an academic qualification. In particular, I have not received the help of a so-called “doctoral consultant” (“Promotionsberaterinnen/Promotionsberater”). Third parties have neither directly nor indirectly received money or goods with a monetary value from me in exchange for work related to the content of the herewith submitted thesis. The work has not been submitted, in its present form or a similar form, to any other examination authority, either in Germany or abroad. I have been informed of what it means to submit an affidavit in lieu of an oath, of the penal consequences of a §§156,161 StGB [German Criminal Code].

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Executive Summary

The global shift towards sustainable energy is a critical component in addressing climate change. However, it presents unique challenges for renewable energy resource-constrained and densely populated countries such as Bangladesh, Singapore, and the Maldives. This research focuses on Bangladesh as a case study to examine and address these challenges through local opportunities and innovation.

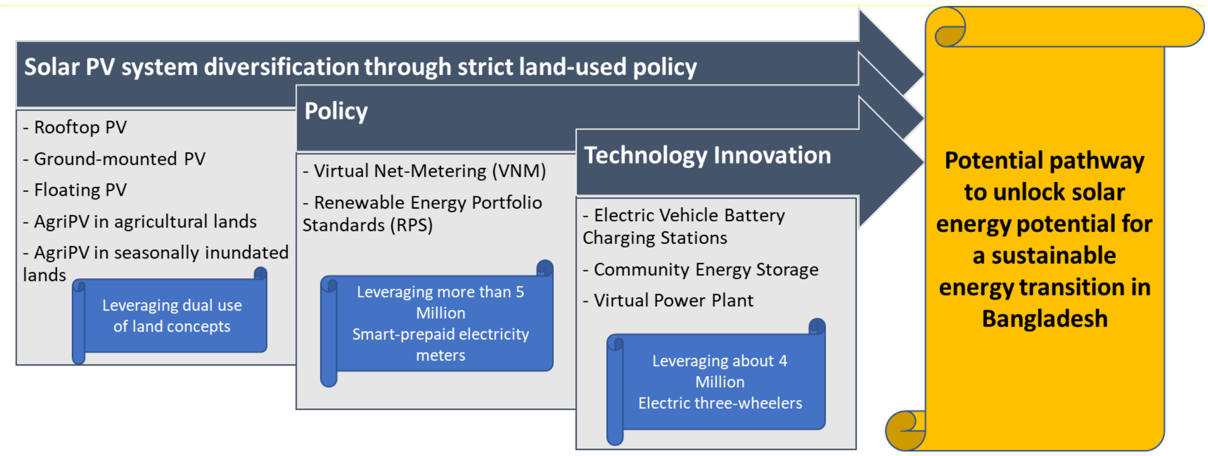
Bangladesh's energy consumption from fossil fuels has more than tripled since 2000, rising from 0.3 million Terajoule. Energy demand is projected to increase by another threefold by 2050, considering factors such as population growth, urbanisation and economic shift towards industrialisation. The country faces significant challenges in balancing growing energy demand with its sustainable energy transition targets. Despite having ambitious renewable energy development goals, Bangladesh's renewable energy share remains below 5%, while its reliance on imported fossil fuels continues to grow, raising concerns about energy security. Solar energy, abundant and widely accepted, holds substantial potential for driving this transition through solar photovoltaic (PV) technology. However, the country faces considerable barriers, including a lack of suitable land, financial constraints, and outdated grid infrastructure, which hinder the deployment of solar PV systems. While Bangladesh has achieved notable success with the Solar Home System (SHS) Programme in enhancing electricity access, the current development trajectory has eclipsed this progress. Additionally, local opportunities, such as the widespread adoption of electric rickshaws, remain underexplored as a means to increase solar PV integration. This research aims to articulate opportunities to overcome these challenges through advanced geospatial analysis, innovative policy tools, and adaptive infrastructure models, providing actionable pathways for integrating solar PV systems into Bangladesh's energy framework. The research collectively explores how Bangladesh can realise its solar energy potential by synergising land use, policy, and technological innovation with local opportunities to unlock solar energy potential for a sustainable energy transition in Bangladesh. It spans three interconnected studies, each addressing critical challenges and opportunities for solar PV adoption, and is structured to provide comprehensive insights into methodologies, findings, and implications.

The research adopts interdisciplinary and mixed-method approaches, combining geospatial modelling, economic feasibility analysis, and energy system modelling to investigate Bangladesh's renewable energy potential and implementation pathways. Building on the challenges and opportunities identified, the first study in Chapter 2 employs geospatial analysis with high-resolution spatial data to evaluate land suitability and capacity potential for various solar PV systems, integrating local environmental and socio-economic factors. The scope of the assessment of solar PV potential encompasses rooftop (RPV), ground-mounted (GPV), floating (FPV), and agrivoltaic (APV) PV systems. The second study in Chapter 3 uses economic feasibility analysis, applying the socket parity method to assess the economic viability of Virtual Net-Metering (VNM) as a policy tool to expand renewable energy investments, with feasibility indicators including net present cost (NPC) and discounted payback periods. The third study in Chapter 4 employs HOMER Pro software to simulate an energy system model, evaluating the feasibility of using electric rickshaw charging stations as distributed energy storage units. Together, these methodologies provide a comprehensive exploration of the technical, economic, and societal dimensions necessary to unlock Bangladesh's renewable energy potential and develop actionable implementation pathways for a sustainable energy transition.

The findings reveal significant untapped potential for solar PV deployment in Bangladesh. The GIS analysis in Chapter 2 identifies over 100 GW of potential solar capacity, comprising 30 GWp from RPV, 9 GWp from GPV, 5 GWp from FPV, and 81 GWp from APV. The levelised cost of energy

(LCOE) from RPV systems is identified as the most economical, ranging from 36 USD/MWh for large systems to 70 USD/MWh for smaller systems. In contrast, GPV and FPV systems are more than twice as expensive as RPV, while APV exhibits the highest LCOE due to its technology immaturity and the exclusion of dual land use benefits in the analysis. Given the lower investment costs and substantial capacity potential of RPV, along with its adaptability across diverse consumer sectors, the research focuses on the transformative potential of the Virtual Net-Metering (VNM) policy, leveraging the widespread adoption of pre-paid electricity meters. The VNM analysis highlights its potential to enable inclusive participation in renewable energy investments, particularly for multi-family residential, commercial, and industrial entities. Economic assessments indicate significant savings in electricity bills, up to 50%, and attractive payback periods of six years, demonstrating VNM's feasibility as a scalable policy to maximise RPV potential. The study also underscores VNM's role in facilitating energy community formation and laying pathways for other policies, such as Renewable Energy Portfolio Standards (RPS). Additionally, Chapter 4 explores the integration of intermittent renewable energy sources through electric rickshaw charging stations as distributed energy storage units. Simulation results reveal that these systems can facilitate the integration of local solar PV systems into the grid while effectively managing intermittencies. Additionally, the energy system demonstrates that such solutions enable communities to plan for energy independence, reduce reliance on fossil fuels, and promote a circular battery economy. Simultaneously, they address environmental concerns linked to the unsustainable recycling of electric rickshaw batteries. Furthermore, the study also showed how the centralised energy storage system could enable the implementation of virtual power plants (VPP) aggregating local generation units.

In summary, this research offers a strategic roadmap for overcoming the challenges of achieving renewable energy targets through solar PV to facilitate Bangladesh's sustainable energy transition. It demonstrates the synergy between land use, policy, and technological innovation, combined with local opportunities, can create an actionable pathway to unlock solar energy potential for a sustainable energy transition. The findings serve as a guide for policymakers and stakeholders while contributing valuable insights to the global discourse on renewable energy adoption, particularly in densely populated and resource-constrained developing nations.



Dedication

To my children Ramin & Raif and my wife Rahima

Acknowledgements

I am deeply grateful to the many individuals who provided both tangible and intangible support throughout my doctoral research journey. Without their encouragement and assistance, this research would not have been possible. Here, I would like to express my appreciation to a few of them.

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Table of Contents

List of Tables

List of Figures

Units

Energy and Power Units:

- kWp (Kilowatt-peak): Capacity rating for PV systems.
- MWp (Megawatt-peak): Larger PV system capacities.
- Wh/km (Watt-hour per kilometre): Energy consumption of e-rickshaws.
- kWh (Kilowatt-hour): Used for energy measurements such as e-rickshaw battery capacity, daily energy consumption, and energy yield from PV systems.
- GWh (Gigawatt-hour): Used in estimating potential energy generation from rooftop PV systems.
- kWh/m²/day: Solar irradiance for determining potential energy generation from solar PV systems
- %: Efficiency rates, such as PV module efficiency, round trip battery efficiency, and state of charge (SOC) in batteries.
- % DOD (Depth of Discharge): Battery discharge levels for determining available energy.
- A/Ah (Ampere per Ampere-hour): Battery maximum charge rate.
- Amp: Battery current capacity, charge, and discharge currents.
- V (Volt): Nominal voltage for batteries in e-rickshaw systems.

Currency, Economic and Financial Units:

- BDT (Bangladeshi Taka): Cost metrics for investment, wheeling, and operation in Bangladesh.
- USD: For international comparison of costs.
- %: Discount rates, inflation rates, and wheeling cost escalation.
- BDT/kWp and USD/kWp: Investment costs per kilowatt-peak for PV systems.
- BDT/kWh: Wheeling costs for energy transportation across grid networks.
- Euro/kW: Cost per kilowatt for converters in distributed energy systems.

Geospatial Units:

- m and km (meter and kilometre): Used for distance and area measurements.
- m² and km² (square meter and square kilometre): Land area for PV installations and building footprint analyses.
- EPSG 9680: Coordinate Reference System (CRS) used for Bangladesh

Abbreviation

AHP: Analytic Hierarchy Process

APV: Agrivoltaic PV

APV-SIL: Agrivoltaic PV in Seasonally Inundated Land

AUF: Area Utilization Factor

BSCS: Battery Swapping and Charging Stations

CBESS: Community Battery Energy Storage System

CRF: Capital Recovery Factor

CSP: Concentrated Solar Power

DOD: Depth of Discharge

DSM: Digital Surface Model

DTM: Digital Terrain Model

FPV: Floating PV

GCR: Ground Coverage Ratio

GHI: Global Horizontal Irradiance

GHSL: Global Human Settlement Layer

GIS: Geographic Information System

GPV: Ground-mounted PV

IEPMP: Integrated Energy and Power Master Plan

LCOE: Levelized Cost of Electricity

LER: Land Equivalent Ratio

MCDM: Multiple-Criteria Decision-Making

PV: Photovoltaic

RCR: Roof Coverage Ratio

RPV: Rooftop PV

SCR: Surface Coverage Ratio

SOC: State of Charge

TPES: Total Primary Energy Supply

VNM: Virtual Net Metering

WCR: Water Coverage Ratio

Abstract

The global shift towards sustainable energy presents unique challenges for densely populated, resource-constrained countries like Bangladesh to make a suitable balance between sustainable energy and development. As Bangladesh's energy demand is anticipated to triple by 2050, driven by population growth, economic development and industrialisation, the country remains heavily dependent on indigenous and imported fossil fuels while renewable sources contribute less than 5% of its energy mix for electricity production. Although the widespread adoption of solar home systems (SHS) has significantly improved energy access, Bangladesh has fallen short of achieving several key milestones of its renewable energy targets. Among its renewable energy resources, solar energy, particularly solar photovoltaic (PV) systems, emerges as a more practical solution to achieve its RE target due to availability. However, challenges such as land scarcity, financial constraints, and inadequate grid infrastructure hinder widespread adoption. Hence, to find pathways to unlock the potential for solar PV deployment for the sustainable energy transition in Bangladesh, this dissertation performs three interconnected research studies focusing on resource assessment, policy and technology innovation using local opportunities as catalysts. The studies employ a multidisciplinary approach integrating geospatial analysis, economic feasibility studies, and energy system modelling. The resource reassessment study identifies over 100 GW of solar PV potential, with rooftop PV (RPV) systems offering the most economical solution (36–70 USD/MWh). It showed Bangladesh can meet solar PV installation targets by implementing RPV systems and recommends keeping the provision of dual use of lands while developing ground-based solar PV systems. The policy study highlights the potential of Virtual Net-Metering (VNM) as a scalable policy tool to enhance the widespread adoption of grid-connected solar PV, especially to materialise RPV potential and replicate the success of the SHS programme. It also shows the potential of VNM to reduce electricity costs by up to 50% and offers more inclusive participation in renewable energy investment. Additionally, the technology innovation research shows the utilisation of electric rickshaw charging stations as distributed energy storage units to integrate intermittent RE generators and open avenues for several other opportunities, such as virtual power plants in rural areas. In summary, collectively, this dissertation provides actionable pathways for deploying solar PV systems in Bangladesh, emphasising the synergy between land use, innovative policies, and technological innovations. It offers solutions that are based on locally developed opportunities to policymakers and stakeholders and contributes to the global discourse on renewable energy adoption in resource-constrained, densely populated nations facing similar challenges.

Eine deutsche Übersetzung mit Hilfe von KI Tools ist am Ende der Arbeit angefügt.

Abstract (বাংলা)

২০৫০ সালের মধ্যে বাংলাদেশে জনসংখ্যা বৃদ্ধি, অর্থনৈতিক উন্নয়ন এবং শিল্পায়নের কারণে জ্বালানির চাহিদা তিনগুণ বৃদ্ধি পাওয়ার প্রত্যাশা করা হচ্ছে। ভবিষ্যতের এই বিশাল চাহিদা মেটানোর জন্য দেশটির পরিকল্পনায় রয়েছে আমদানি করা জীবাশ্ম ও (স্থানীয়) নবায়নযোগ্য জ্বালানি। কিন্তু বর্তমানে নবায়নযোগ্য উৎসগুলি বিদ্যুৎ উৎপাদনের ক্ষেত্রে এর জ্বালানি মিশ্রণের ৫%-এরও কম অবদান রাখে। যদিও সোলার হোম সিস্টেমের (SHS) ব্যাপক বিতরণ ও গ্রহণ উল্লেখযোগ্যভাবে বিদ্যুতায়নের হার উন্নতি করেছে, তবে বাংলাদেশ নবায়নযোগ্য জ্বালানির লক্ষ্যমাত্রার অনেক গুরুত্বপূর্ণ মাইলফলক অর্জনে ব্যর্থ হয়েছে। বিভিন্ন গবেষণায় বাংলাদেশে সৌর শক্তি, বিশেষত সোলার ফটোভোলটাইক (PV) সিস্টেম, দেশের নবায়নযোগ্য জ্বালানির লক্ষ্যমাত্রা অর্জনের জন্য সবচেয়ে কার্যকর সমাধান হিসেবে উঠে এসেছে। তবে পর্যাপ্ত ও উপযুক্ত ভূমির অভাব, আর্থিক সীমাবদ্ধতা, এবং অপর্যাপ্ত গ্রিড অবকাঠামোর মতো চ্যালেঞ্জসমূহ এর ব্যাপক গ্রহণযোগ্যতাকে বাধাগ্রস্ত করছে। এই চ্যালেঞ্জগুলো মোকাবিলায় এবং বাংলাদেশে টেকসই জ্বালানী ব্যবস্থার জন্য সৌর PV সিস্টেমের সম্ভাবনা উন্মোচনের পথ খুঁজতে, এই গবেষণা প্রতিবেদনটি তিনটি আন্তঃসম্পর্কিত গবেষণাপত্র প্রকাশ করেছে। এই গবেষণাগুলো স্থানীয়ভাবে বিকশিত সুযোগগুলোকে (যেমনঃ বৈদ্যুতিক রিকশার ব্যাপক ব্যবহার) মূলমন্ত্র হিসেবে কাজে লাগিয়ে সোলার সিস্টেমভিত্তিক সৌর বিদ্যুতের সম্ভাব্যতা পুনর্মূল্যায়ন, নীতি এবং প্রযুক্তিগত উদ্ভাবনের উপর বিশেষ গুরুত্ব দেয়া হয়েছে। গবেষণাগুলো ভৌগলিক তথ্য (GIS) বিশ্লেষণ, সম্ভাব্যতা নিরীক্ষণ এবং জ্বালানি ব্যবস্থার মডেলিং সমন্বিত একটি বহুমুখী পদ্ধতি গ্রহণ করেছে। সোলার সিস্টেমভিত্তিক সৌর বিদ্যুতের সম্ভাব্যতা পুনর্মূল্যায়ন গবেষণার মাধ্যমে ১০০ GW এর বেশি সৌর PV সম্ভাবনা চিহ্নিত করা হয়েছে, যেখানে রুফটপ PV (RPV) ব্যবস্থা অর্থনৈতিকভাবে সবচেয়ে সাশ্রয়ী সমাধান হিসেবে প্রাক্কলিত হয়েছে (৩৬–৭০ USD/MWh)। এটি দেখিয়েছে যে বাংলাদেশ RPV ব্যবস্থার বাস্তবায়নের মাধ্যমে সোলার সিস্টেম স্থাপনার লক্ষ্যমাত্রা অর্জন করতে পারে। ভূমির সংকট মোকাবেলায় এই গবেষণায় ভূমি-ভিত্তিক সোলার সিস্টেম স্থাপনের ক্ষেত্রে দ্বৈত ভূমি ব্যবহারের সুযোগ রাখার সুপারিশ করেছে, যেমন কৃশি বা এগ্রি সোলার। নীতি গবেষণায় ভার্চুয়াল নেট-মিটারিং (VNM) কে গ্রিড-সংযুক্ত সৌর PV এর ব্যাপক গ্রহণযোগ্যতা ও স্থাপন বৃদ্ধির একটি নীতিগত সরঞ্জাম হিসেবে দেখান হয়েছে। গবেষণাটি দেখিয়েছে যে VNM বিদ্যুতের খরচ ৫০% পর্যন্ত কমাতে সক্ষম এবং নবায়নযোগ্য জ্বালানিতে বিনিয়োগে আরও অন্তর্ভুক্তিমূলক অংশগ্রহণের সুযোগ প্রদান করে। এটি বিশেষত RPV সম্ভাবনা বাস্তবায়ন এবং SHS প্রোগ্রামের সাফল্য পুনরাবৃত্তির জন্য ভূমিকা রাখতে পারবে বলে আশা করা যায়। এছাড়াও, প্রযুক্তিগত উদ্ভাবন গবেষণায় দেখানো হয়েছে যে ইলেকট্রিক রিকশা চার্জিং স্টেশনগুলোকে ডিস্ট্রিবিউটেড বিদ্যুৎ সঞ্চয় ইউনিট হিসেবে ব্যবহার করে সোলার সিস্টেম কর্তৃক উৎপাদিত বিদ্যুতের অস্থিতিশীলতা মোকাবিলা করা যেতে পারে এবং গ্রামীণ এলাকায় কাল্পনিক বিদ্যুৎকেন্দ্র বা ভার্চুয়াল পাওয়ার প্ল্যান্ট গঠনের মতো একাধিক সুযোগ উন্মোচিত হতে পারে। পরিশেষে, এই গবেষণা প্রতিবেদনটি ভূমি ব্যবহার, উদ্ভাবনী নীতি এবং প্রযুক্তিগত উদ্ভাবনের মধ্যে সমন্বয়ে জোর দিয়ে বাংলাদেশে সোলার সিস্টেম স্থাপনার জন্য কার্যকর পথনির্দেশনা প্রদান করে। এটি স্থানীয়ভাবে বিকশিত সুযোগের উপর ভিত্তি করে নীতিনির্ধারক এবং অংশীদারদের জন্য একটি বাস্তবসম্মত সমাধান প্রস্তাব করে এবং সারা বিশ্বের অন্যান্য জনবহুল, সম্পদ-সীমাবদ্ধ দেশগুলোর জন্য নবায়নযোগ্য জ্বালানি গ্রহণ বিষয়ে বৈশ্বিক আলোচনায় অবদান রাখে।

Chapter 1 Introduction

1.1 Research motivation

1.1.1 Local Motivation: Adoption of solar PV and electric mobility in Bangladesh

Figure 1.1 Solar Home Systems (SHS) in Bangladesh

Photo: Author
Top Left: SHS installed on the roof of a low-income household. Top Right: SHS installed on the roof of a higher-income household.

In the early 2000s, Bangladesh's access to electricity, in binary metric, was about 30% (The World Bank 2023). Mostly, the rural people of Bangladesh were deprived of access to electricity (Sharif and Mithila 2013). The lack of access to energy was not just an inconvenience; it was a major barrier to development, health, and opportunity (Mondal and Klein 2011).

However, instead of extending the national grid to reach the off-grid rural communities, Bangladesh and its development partners introduced an innovative solution- the Solar Home System (SHS) Programme. The programme was launched in 2003 by the Infrastructure Development Company Limited (IDCOL). After its inception, this program sought to revolutionise the way rural Bangladesh accessed electricity. The goal was ambitious: bring clean, sustainable power to millions of households far from the reach of traditional infrastructure.

The SHS programme was more than just providing solar panels and batteries; it empowered communities to take control of their own energy needs. It provided access to modern life from rich to poor in rural areas, as shown in Figure 1.1, minimising the social gap for basic energy access. Furthermore, through a public-private partnership model, it brought together several stakeholders, such as non-governmental organisations (NGOs), private entrepreneurs, and microfinance institutions. Families could purchase solar systems through affordable loans via microfinance institutions (MFIs), enabling even the poorest households to access clean energy. Hence, this model was about more than providing a product; it was about creating a sustainable ecosystem that would allow the solar PV system market to grow and thrive (Sharif and Mithila 2013; Newcombe and Ackom 2017).

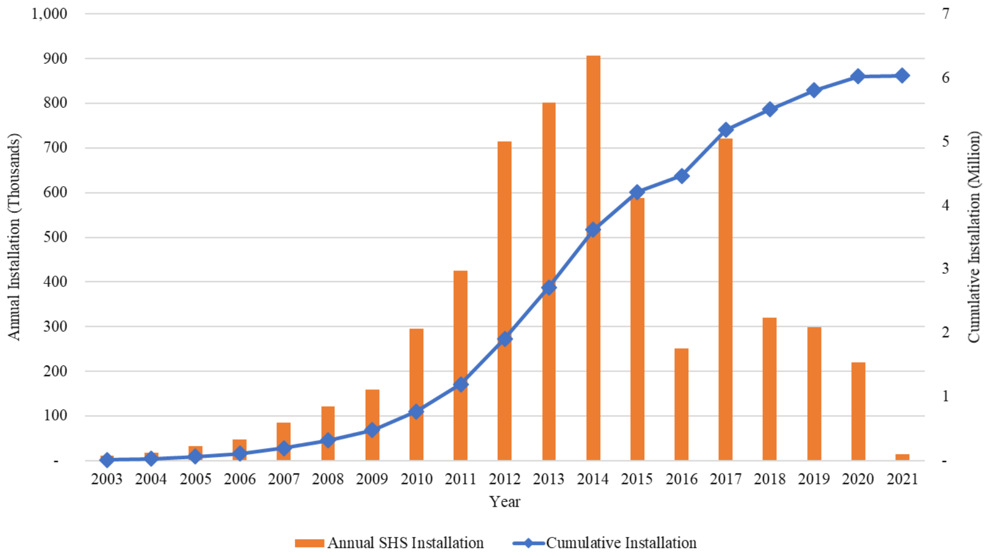


Figure 1.2 Development of Bangladesh Solar Home System Programme

Annual (left axis) and cumulative (right axis) distribution of Solar Home Systems between 2009-2021 in Bangladesh
Data source: (Hossain et al. 2023b)

As summarised by Mondal and Klein (2011), Hossain et al. (2023a) & Cabraal et al. (2021), over the past two decades, the impact has been staggering. By 2020, more than 6 million (Figure 1.2) solar home systems had been installed, benefiting more than 20 million people. The programme not only improved household lighting, but also transformed education, health, and livelihoods. Children could study after dark, entrepreneurs could extend business hours, and families no longer had to breathe in toxic fumes from kerosene lamps. The social and economic impact was profound. Furthermore, SHSs were also adopted in the grid-connected area to deal with the unreliability and unavailability issues of the grid.

This SHS programme went beyond achieving energy access, it was a utilisation of human potential. The SHS programme created over 100,000 direct and indirect jobs by training local technicians, entrepreneurs, and service providers (IRENA 2020). It fostered a local solar industry, proving that renewable energy can be a driver of economic development. Most importantly, it demonstrated that with the right mix of vision, innovation, and partnership, even the most daunting challenges could be overcome.

However, this programme has also started seeing its fall after 15 years of its inception due to various reasons such as grid expansion and lifting subsidies (Hellqvist and Heubaum 2023). The further challenges were managing old systems, dealing with growing energy demand, and keeping the program sustainable in the face of rapid economic development (Hossain et al. 2023a). But, the programme has played a significant role and paved the way for universal access to electricity. It is also undeniable that the acceptance and adoption of the technology by the people of Bangladesh were pivotal.

On the other hand, over the past decade, a quiet revolution has been unfolding on the streets of Bangladesh. Once dominated by noisy, polluting vehicles, the roads are now increasingly shared by electric rickshaws, symbolising the growing public acceptance of electric mobility. Unlike the SHS programme, the proliferation of electric rickshaws and the shift towards electric mobility emerged organically without subsidies and without waiting for government intervention to address transport needs. These three-wheeled electric vehicles, commonly referred to as “Electric Rickshaws” and “Easy

Bikes," are transforming both urban and rural transport by offering a cleaner, more affordable, and more efficient alternative to traditional petrol-powered rickshaws. In addition to providing emission-free journeys, electric rickshaws are contributing to the creation of employment opportunities for millions of people across Bangladesh (Nurunnahar et al. 2022). Although official statistics are unavailable, some sources suggest that the number of electric three-wheelers in the country exceeds more than 4 million to date (Hassan et al. 2024; The Financial Express 4/2/2024).

This present research is inspired by the active engagement of Bangladesh's population in the SHS Programme, which has played a pivotal role in expanding energy access. Additionally, the growing public embrace of electric mobility, which has informally yet effectively addressed increasing transport demands in both urban and rural areas, reinforces the motivation for this study. With this motivation, the author seeks to explore the nexus between the country's solar energy potential and opportunities to support its energy transition journey.

1.1.2 Global Motivation: The role of solar energy in global energy transition

Transition to sustainable energy is identified as one of the key preconditions of fighting climate change through decarbonisation (Yu et al. 2024). Hence, sustainable energy transition is a global movement now. As the world is embracing the harsh reality of climate change, countries around the globe pledge to set climate-friendly goals and adopt technologies to achieve them (IEA 2023). To foster the sustainable energy transition, transitioning away from fossil fuel is also given strong emphasis at the Conference of the Parties (COP 28) of the UNFCCC held in Dubai in 2023 (UNFCCC 2023). However, to end the fossil fuel era, it is essential to identify sustainable alternatives for each country individually. As renewable energy (RE) resources, such as solar, wind, geothermal, biomass, and ocean energy, are not equally distributed around the world, replacing fossil fuel with sustainable alternatives will be very challenging for resource-disadvantaged regions or countries.

Solar energy, especially Solar PV technology, has a significant role in the energy transition considering that it has the highest spatial availability around the globe. The flexibility and scalability of solar PV make it the suitable solution for diverse applications in both off and on-grid domains. Solar PV technology has been featured in a number of energy system models around the globe. Breyer et al. (2017) presented an exhaustive list of global energy models until 2017 that show the role of solar PV in the global energy transition. Breyer et al. (2017) also estimated that solar PV can have the potential to meet about 41% of electricity demand in integrated energy systems with 12,000 GWp by 2030 to achieve 100% renewable energy share around the world. IRENA (2019), estimates 8,500 GW of solar capacity by 2050 in electricity systems, representing 42% of the total installed capacity. IEA (2021) also revealed a net-zero scenario by 2050 in 2021, estimating about 14,000 GW of Solar PV capacity covering more than 35% of electricity demand. With rapidly falling costs and technological improvements, solar PV has become a cornerstone of decarbonising the energy sector. Until 2023, global solar PV installed capacity reached over 1,600 GW, contributing more than 4% of the world's electricity demand (Statista 2024). However, to meet the Net Zero goal aligning with the Paris Agreement, the world needs to scale up this capacity significantly. To meet IEA's Net Zero target by 2050, the solar PV capacity needs to increase 11 times more capacity than today, meaning more than 600 GW of solar PV capacity addition per year until 2050 (IEA 2021). However, as can be seen in Figure 1.3, the annual net solar energy capacity addition has never reached this annual target.

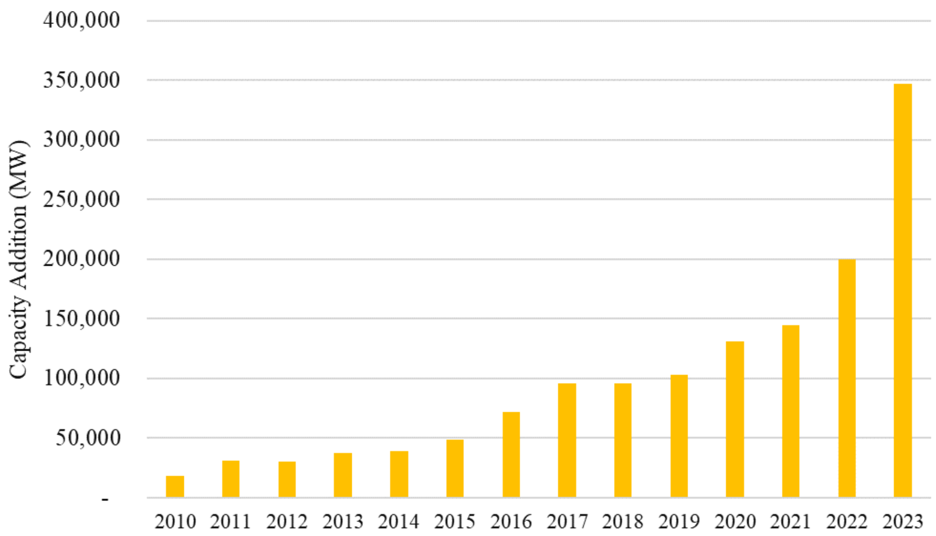


Figure 1.3 Annual net solar energy capacity addition for electricity generation globally

Data Source: (IRENA 2024)

Nevertheless, although the annual capacity goals have never been achieved, renewable energy technologies have experienced significant deployment around the globe over the past decade, especially solar PV, as shown in Figure 1.3 (IRENA 2024). PV technologies have also experienced an unprecedented improvement in efficiency and capacities for commercial application (Fraunhofer ISE 2024; GWEC 2024). Fraunhofer ISE (2024) reported 22% efficiency and 700 W PV modules for PV modules, making them more space efficient. Continuous improvements in these technologies call for suitable deployment of the technologies considering land use and environmental considerations.

However, although solar resources are available almost everywhere on the Earth's surface, harnessing solar resources requires more space compared to traditional energy technologies. This is particularly challenging for smaller countries and countries with high population density due to area competition. Therefore, innovative policies and applications in both supply and demand are essential for replacing fossil fuels with sustainable energy technologies. In addition, it is also essential to consider local innovations in energy production and use for faster adoption of technology (Goggins et al. 2022).

1.2 Bangladesh

Bangladesh is a small South Asian country of 147,000 km^2, bordered by India, Myanmar, and the Bay of Bengal (see Figure 1.4, left). The country consists of 8 administrative divisions and 64 districts. As shown in Figure 1.4 (right), the country is characterised by its vast river systems, including the Ganges, Brahmaputra, and Meghna, making it a fertile delta but prone to seasonal floods. With over 170 million people, it is one of the world's most densely populated countries. More than 60% of the population is categorised as “persons of working age”. The modern economy of Bangladesh is driven by its industry, commercial activities, agriculture, and remittances, as shown in Figure 1.6. Population growth and economic shifts have significantly driven the expansion of built settlements in Bangladesh, leading to unsustainable land use changes (see Figure 1.5). Furthermore, despite socio-economic improvements in recent decades, such as reducing poverty and improving living standards, challenges like lack of good governance, rapid urbanisation, and the effect of climate change persist.

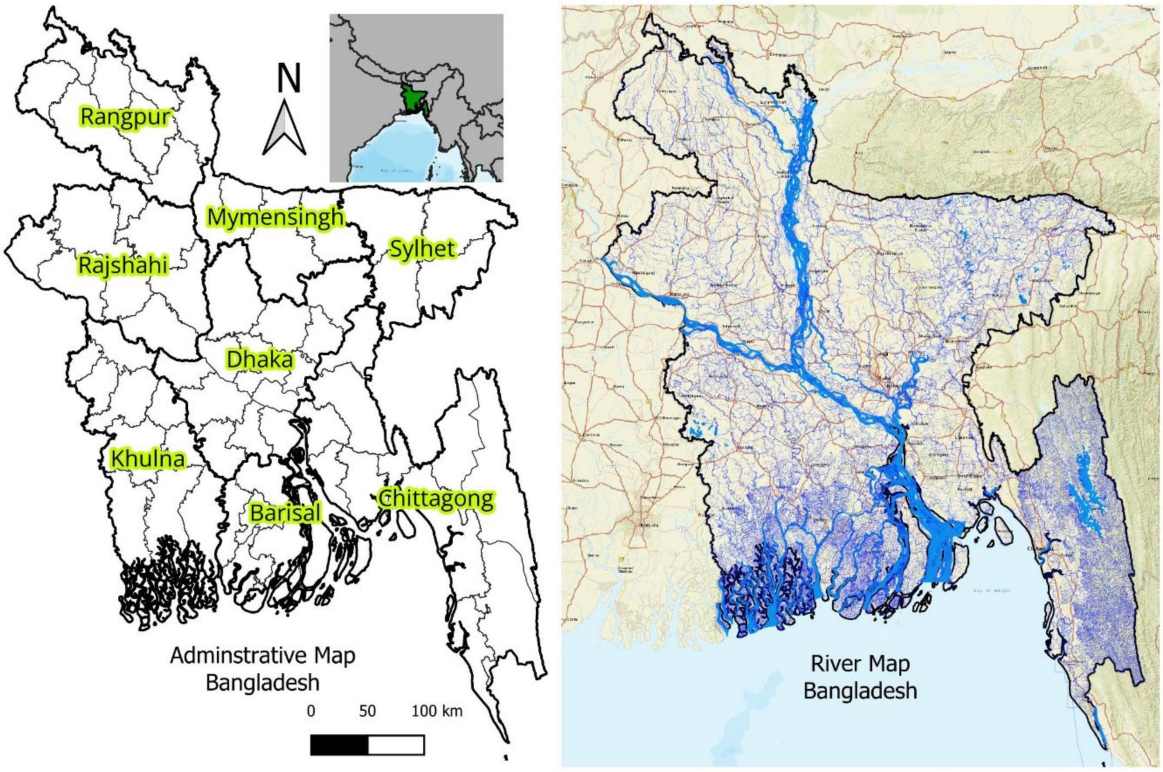


Figure 1.4 Bangladesh administrative (left) and river maps (right)

Data Source: (OCHA 2024)

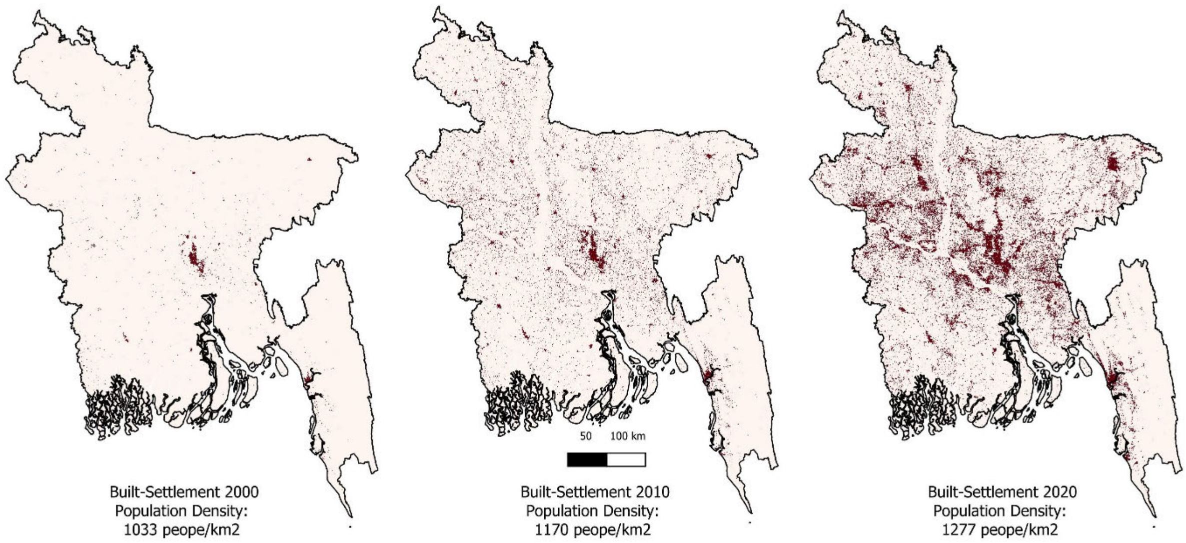


Figure 1.5 Bangladesh built settlement growth from 2000 to 2020

Data source: (WorldPop 2018)

1.3 Bangladesh's economic growth and energy infrastructure

Bangladesh's economy has experienced significant growth and development over the past decade. According to the data, the country has consistently maintained annual gross domestic product (GDP) growth well above 5% annually (The World Bank 2023). As depicted in Figure 1.6, Bangladesh's economy is undergoing a transition from agriculture to industry, accompanied by rapid urbanisation, resulting in notable changes in land use.

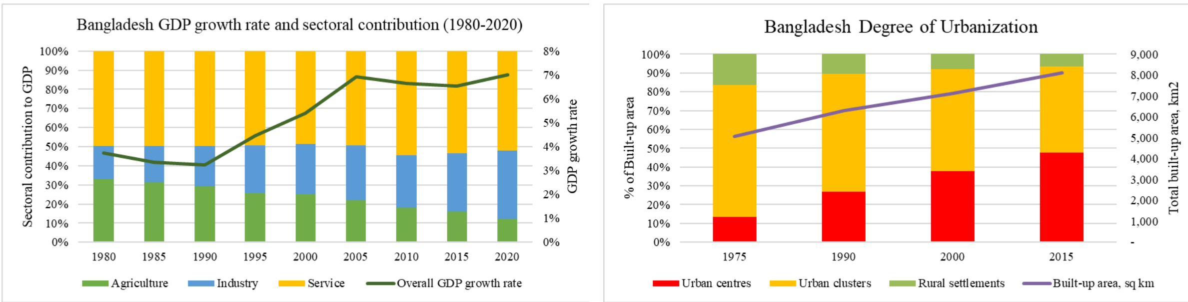


Figure 1.6. Bangladesh's historical GDP (Left) and Urbanisation growth rate (right).

Data source: (Finance Division 2023; GHSL-Global Human Settlement Layer 2018)

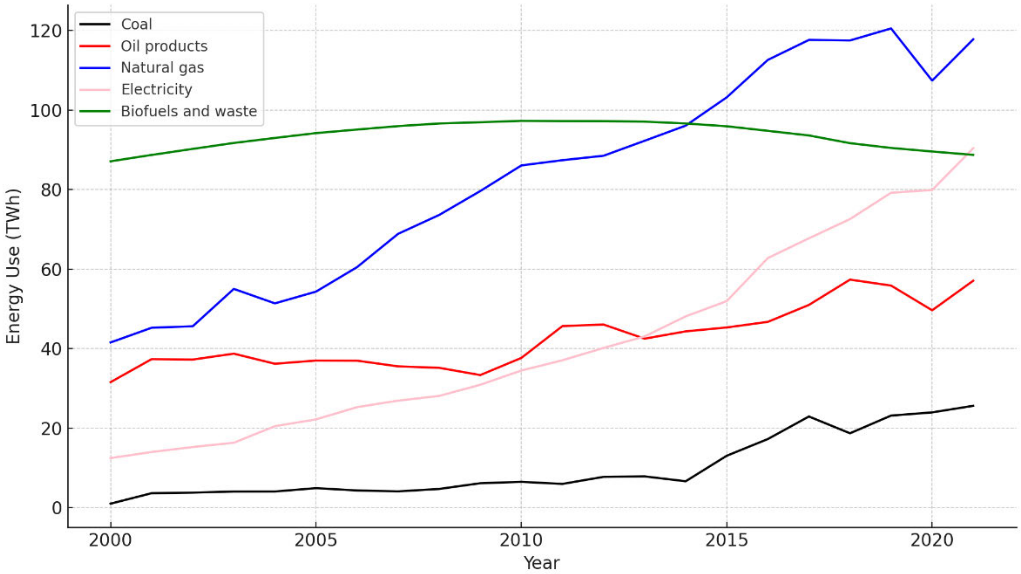


Figure 1.7 Evolution of total final consumption in Bangladesh

Data source: (IEA 2024b)

As can be seen in Figure 1.7, domestic natural gas has played a crucial role as the primary driver of the energy sector, contributing to over 50% of the energy supply and supporting the country's economic advancement with relatively lower carbon dioxide (CO2) emission intensity (IEA 2024b). In addition to indigenous natural gas, Bangladesh heavily relies on imported fossil fuels to address its increasing energy demand, presenting challenges to the country's energy security and environmental sustainability.

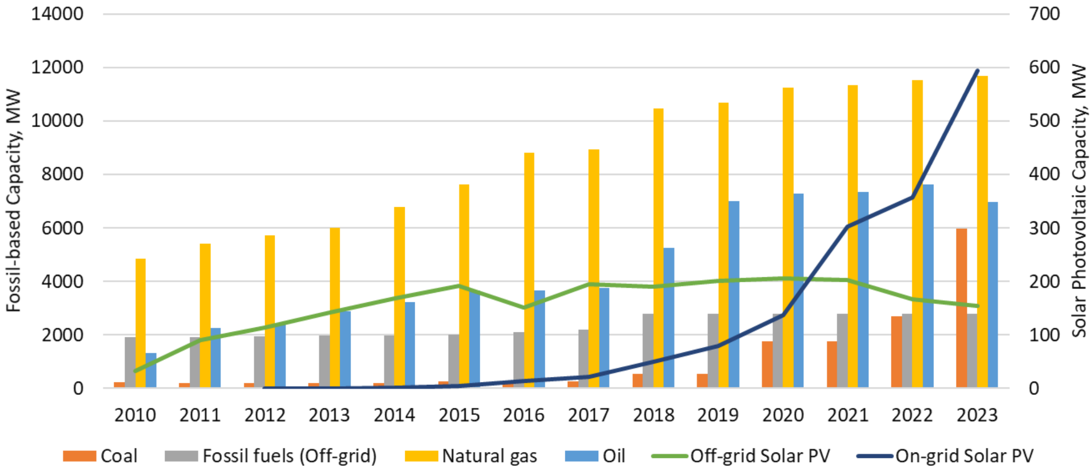
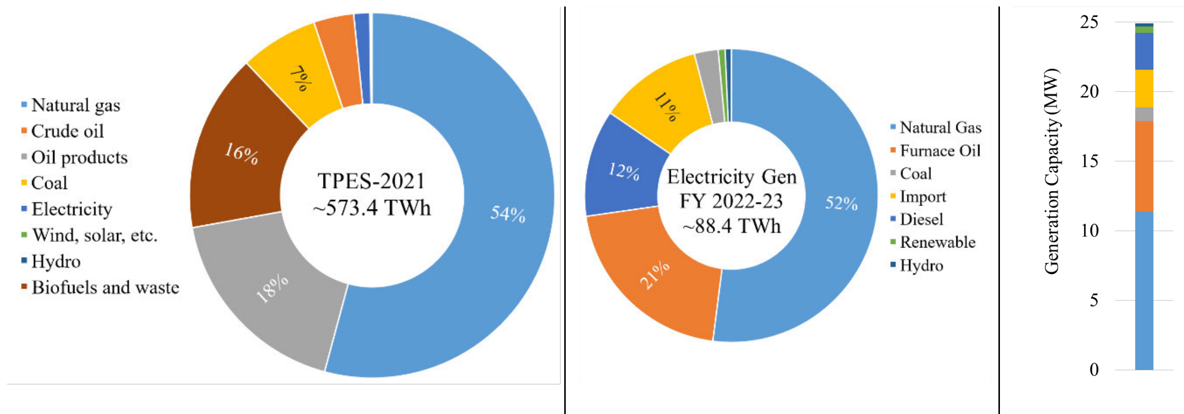


Figure 1.8 Development of Bangladesh's fossil and solar photovoltaic capacity since 2010

Data Source: (IRENA 2024)

Figure 1.8 illustrates the development of Bangladesh's electricity generation capacity since 2010, revealing that oil- and gas-based generation more than doubled, becoming the primary contributors to the power sector. Hydropower capacity remained constant at 230 MW, while biomass- and wind-based renewable generation stayed minimal, below 50 MW and 2 MW, respectively (IRENA 2024). Off-grid solar PV, primarily driven by solar home systems (SHS), and on-grid solar PV increased significantly, making them the leading renewable source of electricity in Bangladesh. However, as Figure 1.9 highlights Bangladesh's primary energy supply and the composition of the 2022 electricity generation system, the dominance of fossil fuels and dependence on fossil fuel imports remain evident.



Total Primary Energy Supply (TEPS) 2021

Electricity Generation installed generation capacity as of FY 2022-23

Figure 1.9. Fuel composition in Bangladesh's energy sector.

Left: TPES 2021 (IEA 2024b). Middle: Electricity generation in the financial year 2022-23 and Right (bar chart): Grid-connected installed capacity for power generation (BPDB 2024). The legend with energy generation is also valid for the generation capacity bar graph.

With aspirations to achieve high-income status by 2041, Bangladesh anticipates 2-3 fold (about 1200-1500 TWh in 2050) growth of energy demand compared to current levels (about 600 TWh in 2023) (MPEMR 2023). However, although demand growth is noticeable, the forecast contradicts the recent energy consumption data from the Bangladesh Power Development Board (BPDB) (Shafiqul 2024).

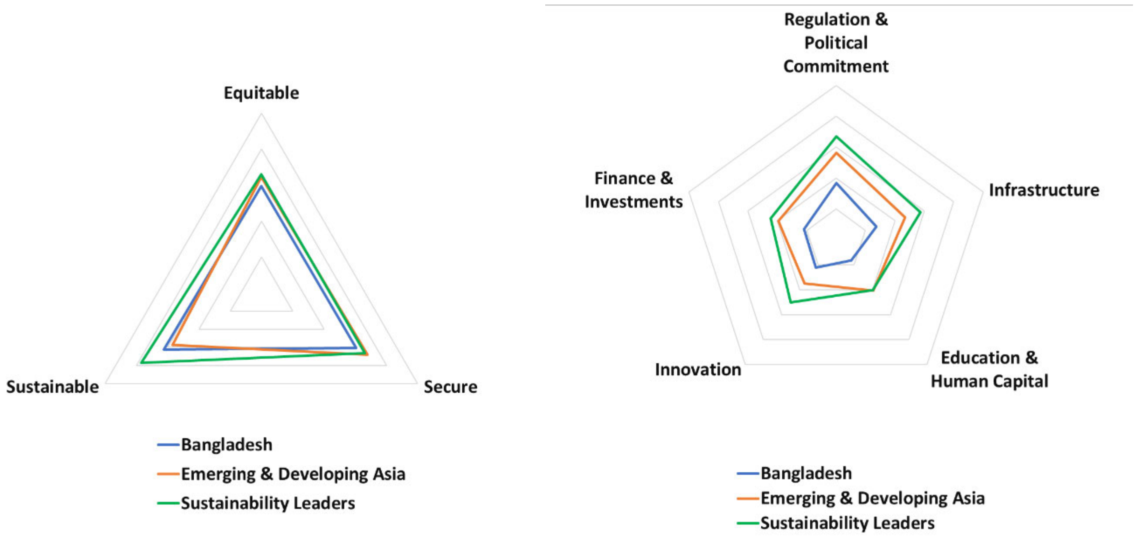
To address rising energy demand and promote sustainability, Bangladesh introduced the Integrated Energy and Power Master Plan (IEPMP) in 2023, targeting a Net-Zero Scenario (NZS) by 2070 (MPEMR 2023; Debnath and Mourshed 2024). The plan includes ambitious goals to expand solar and wind capacities to 28 GW and 55 GW, respectively, by 2050, but lacks strategies for the grid infrastructure needed to support this growth.

In contrast to this ambitious plan, the recent data indicates that the share of renewable power capacity and energy generation remains below 5% of the total installed capacity and power generation, as illustrated in Figure 1.9 (BPDB 2024). As of September 2024, Bangladesh's solar PV capacity stood at about 1000 MWp, including over 35% being off-grid solar PV capacity, comprising more than 6 million solar home systems and additional off-grid installations such as mini-grids and solar irrigation (SREDA 2024; Kirchhoff and Strunz 2024; Hossain et al. 2023b). Although Bangladesh has made significant progress in ensuring basic electricity access through solar home systems and nationwide grid expansion, challenges persist in addressing the multidimensional aspects, such as availability and reliability, of energy access (Alam and Bhattacharyya 2017; Debnath and Mourshed 2024).

1.4 Status of Bangladesh's energy transition

The Global Energy Transition Index (ETI) published by the World Economic Forum (WEF), Bangladesh ranks 109th out of 120 countries around the world, making it one of the lowest-scoring countries globally and within its region, as shown in Figure 1.10 (WEF 2024). The country's overall ETI score is 46.8, with a system performance score of 60.8 and an energy transition readiness score of 25.6. While Bangladesh's current system performance is somewhat comparable with that of neighbouring developing nations and global sustainability leaders, the country's transition readiness index needs significant improvement.

Over the past 15 years, the government of Bangladesh has implemented short-sighted and temporary measures to boost electricity generation capacity and expand grid coverage. This approach has led to a costly and unsustainable energy system, drawing significant criticism (Debnath and Mourshed 2024; Shafiqul 2024). The unsustainability is evident in the low transition readiness score, reflecting a focus on meeting immediate energy demand with temporary solutions. Key areas for energy transition, such as infrastructure, human capital, innovation, finance and investment, and regulatory and political commitment, were largely overlooked.



A: System performance (Scale of 100) B: Transition readiness (Scale of 100)

Figure 1.10 Energy Transition Index of Bangladesh, Emerging & Developing Asia and Sustainability Leaders

Data source: (WEF 2024)

1.5 Literature review on Bangladesh's energy transition

Mondal et al. (2014); Buckley et al. (2016); Das et al. (2018); Teske et al. (2019); Gulagi et al. (2020) & Das et al. (2020), to name a few, have researched Bangladesh's energy systems with renewable energy resources to promote energy transition. From these studies, Table 1.1 summarises the role of local variable renewable energy (VRE), especially solar energy. Although the studies presented high penetration of RE in the energy systems in their models, they lack little initiative to create implementation pathways. Teske et al. (2019) provided a comprehensive analysis of Bangladesh's energy transition under 100% renewable energy (RE) scenarios. The authors estimated an energy demand of about 970 TWh, including 380 TWh for electricity, by 2050 for a 100% RE scenario. To cater for this demand with 100% RE, the study estimated a need for around 200 GW of local renewable energy capacity in the electricity generation capacity, predominantly from solar PV and wind energy technology, by 2050. While the authors assessed Bangladesh's solar PV potential to be around 190 GW, using spatial data, they emphasised the need for further research on the breakdown of the potential to evaluate PV potential based on specific system types, including ground-mounted, agrivoltaics and floating PV.

Table 1.1 Renewable energy and solar PV capacities in different scenarios for Bangladesh

Study	Model	Model year	Scenario	System Capacity (GW)	VRE Share	Solar PV (Share, Capacity)
(Mondal et al. 2014)	MARKAL	2035	Null Coal Import	100	~45 %	41 GW 41%
(Das et al. 2018)	TIMES	2045	High RE	78	~15 %	10 GW 13%
(Teske et al. 2019)	[R]E24/7	2050	RE 1.5° C	198	~87 %	127 GW 64%
			RE 2.0° C	150	~85 %	96 GW 64%
(MPEMR 2023)	Unknown	2050	ATS PP 2041	138	~20 %	6 GW 4%
		2050	Net Zero	Not Available	Not Available	28 GW -

Debnath and Mourshed (2024) reviewed Bangladesh's Integrated Energy and Power Master Plan (IEPMP) 2023 and evaluated six scenarios to estimate the cost of decarbonising the electricity sector. Their analysis revealed that, under current policies and practices, the average cost of decarbonisation in Bangladesh is significantly higher than the global average across all scenarios. Additionally, they highlighted that planned investments in fossil fuel power plants rely heavily on loans, particularly from India and China, potentially placing the country in a "debt-fossil fuel production trap." To address these issues, they recommended measures such as controlling corruption, deregulating or privatising the energy market, and enhancing transparency to lower the cost of capital for renewable energy deployment.

The existing studies have largely focused on broad overviews of Bangladesh's energy system, paying limited attention to detailed, actionable steps necessary to achieve ambitious goals like net zero and 100% RE.

1.6 Challenges towards sustainable energy transition in Bangladesh

As shown in Figure 1.10 B, Bangladesh faces several challenges to achieve sustainable energy transition, such as infrastructure, innovation, finance and investment, human capital and Regulation & Political Commitment, according to global indicators. These challenges hinder the shift from a fossil-fuel-dominated energy system to one that integrates renewable energy resources effectively. The following discussion also identifies some other specific challenges.

1.6.1 High dependency on fossil fuels and import

Bangladesh's energy mix heavily relies on fossil fuels, particularly natural gas, which has historically been the country's primary energy resource. However, depleting reserves and growing energy demand are increasing the dependency on imported fossil fuels, raising significant energy security concerns. According to Hassan Shetol et al. (2019), "the country would be able to fulfil the growing demand for natural gas for the next 10–12 years with the remaining gas reserve." The country began importing liquefied natural gas in 2018 to meet the demand for natural gas-based energy. This shift reduced self-sufficiency significantly, dropping from 75% in 2018 to 60% in 2022, see Figure 1.11 (IEA 2024a). Additionally, over the past decade, the government has developed several large-scale fossil fuel power plants, especially coal-based ones, which have skyrocketed Bangladesh's coal import portfolio. The indigenous coal can meet only about 10% of the coal demand of those power plants. However, the country's coal reserve is very limited and lacks suitable mining strategies (Sajjad and Rasul 2015). The reserves of other resources are negligible. A significant use of bioenergy can be noticed in Bangladesh's energy mix, especially for cooking. However, due to a lack of sustainable forest management and economic shift, bioenergy is also slowly facing the sustainability issue in the country. Bangladesh is also exploring offshore fossil fuel resources but their existence has yet to be determined. Overall, the reliance on fossil fuels makes the country vulnerable to global market fluctuations and supply chain disruptions.

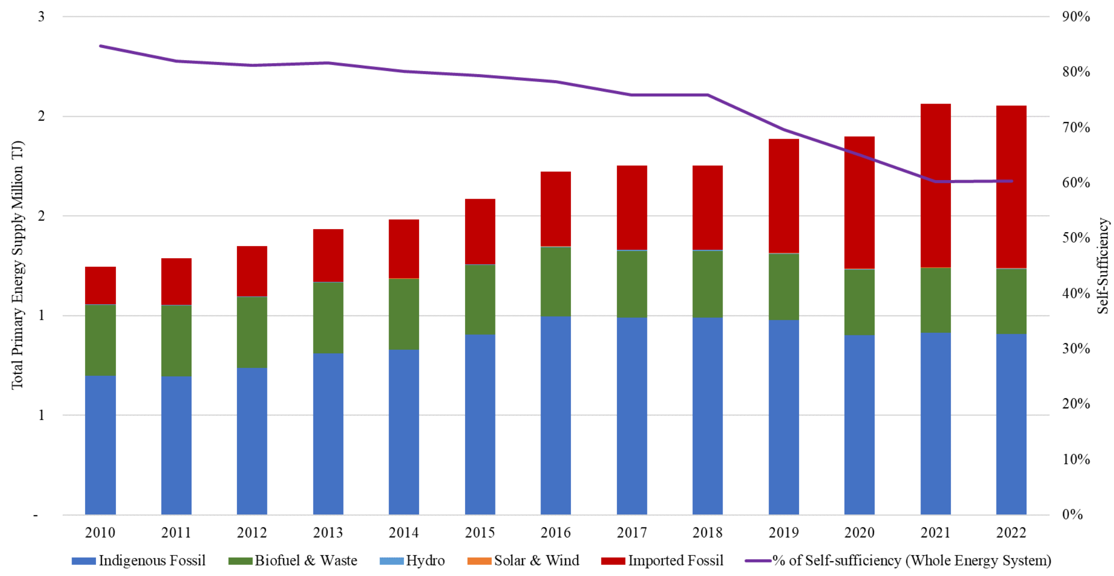


Figure 1.11 Trend of depleting indigenous resources and decreasing self-sufficiency in energy supply

Data source: (IEA 2024a)

1.6.2 Renewable energy resources and competing land use challenge for its development

Several studies, including those by Islam and Islam (2005); Mondal and Denich (2010); Nandi et al. (2013); Shiraishi et al. (2019); NREL-USAID (2018) & Ahmed et al. (2024), have assessed the renewable energy potential in Bangladesh. According to these studies, solar, wind, biomass, and hydro are the recognised renewable resources in Bangladesh. However, their full potential remains undetermined due to factors such as population density, land use, technological options, and associated costs. Among the resources, solar energy has been identified as having the highest potential to support the country's energy transition. On the other hand, research, including Teske et al. (2019), highlights a significant wind energy potential, particularly in offshore areas. However, frequent tropical storms pose substantial challenges, increasing the costs associated with risk mitigation. Ahmed et al. (2024) estimate a promising biomass potential through the use of agricultural residues, animal dung, and municipal solid waste. Despite this potential, biomass use in Bangladesh has largely been limited to cooking, with minimal efforts directed toward producing biogas for domestic use or electricity generation. Bangladesh has limited hydropower potential due to geographic constraints, making it a marginal contributor to the energy mix.

Land scarcity is a significant obstacle to scaling up renewable energy projects. High population density and competing demands for agricultural and urban development make it difficult to allocate suitable land for large-scale solar installations. To address this issue, innovative solutions such as floating solar, agrivoltaics, and rooftop systems have been proposed by researchers like Shiraishi et al. (2019) & Hossain et al. (2023b), as well as government policy documents, such as IEPMP 2023. However, the adoption of these solutions has been slow due to factors like insufficient resource assessments, high implementation costs, and a lack of investment and investors.

1.6.3 Financial and investment barriers to sustainable energy

The renewable energy sector in Bangladesh faces challenges due to a lack of investment in research and development, combined with inadequate funding for renewable energy projects (Hossain et al. 2023b). Additionally, high investment risks stemming from market volatility discourage both private sector participation and foreign investment. On the other hand, over the past decade, the government of

Bangladesh has shown a preference for fossil fuel-based power plants over renewable energy projects. This preference has made many investors more inclined to invest in traditional energy systems, despite their vulnerability to supply disruptions (Debnath and Mourshed 2024; Shafiqul 2024). Furthermore, government policies have done little to encourage residential and commercial sectors to invest in renewable energy initiatives. Hence, investment in RE is highly dependent on large-scale investors and the potential of small-scale but large in quantity, similar to the SHS programme, has been undermined.

1.6.4 Policy gaps and institutional challenges

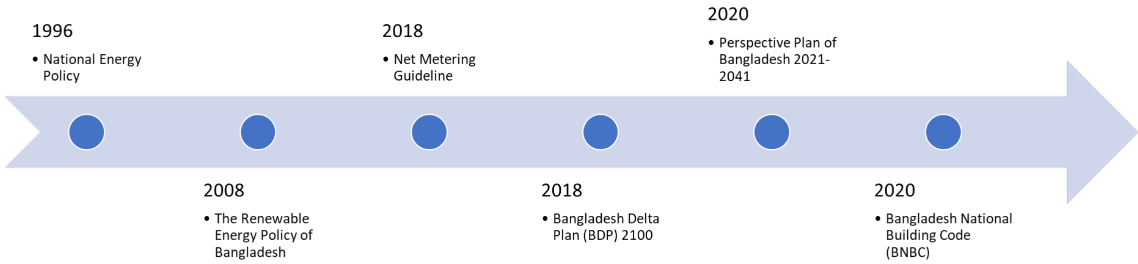


Figure 1.12 Policies to promote renewable energy in Bangladesh

Since 1996, several policy documents in Bangladesh have directly or indirectly addressed the development of renewable energy in the country, as shown in Figure 1.12. Although these policies aim to promote renewable energy development in the country, they lack suitable policy instruments, such as renewable portfolio standards, tax incentives, feed-in-tariff (FIT), grants and subsidies, financing, etc. (Moazzem et al. 2022). In 2018, Bangladesh introduced a net-metering (NEM) policy to encourage rooftop solar installations. By September 2024, the policy had facilitated the integration of approximately 2,500 systems, equivalent to 112 MWp, into the grid (SREDA 2024). According to SREDA (2024), the majority of these systems are operated by commercial entities. Due to power system stability concerns, the NEM policy restricts installations to 3-phase consumers, effectively limiting participation to those with both roof space and a 3-phase connection. In parallel, utility-scale solar power plants are implemented under power purchase agreements (PPAs), but high investment costs and limited availability of suitable land have constrained their development. By September 2024, only 12 utility-scale solar power plants, with a cumulative capacity of 540 MWp, had been developed in the country. Additionally, in 2014, Bangladesh established the Sustainable and Renewable Energy Development Authority (SREDA) to strengthen institutional capacity for promoting renewable energy and energy efficiency. However, despite its broad mandate, SREDA has achieved limited success in advancing renewable energy development and has made little progress in developing business models and a supply chain ecosystem similar to the successful Solar Home Systems (SHS) program in Bangladesh.

1.6.5 Inadequate grid to host variable renewable energy

Like many countries worldwide, Bangladesh's electric grid infrastructure was designed with centralised generation, particularly fossil fuel plants, in mind. This design presents significant limitations in accommodating distributed renewable energy generation. Despite substantial growth in generation capacity, the energy sector continues to face blackouts, voltage fluctuations, and frequency instability, reflecting weaknesses in the grid and unsynchronised planning (IESD 2023). Moreover, the grid lacks modern transmission and distribution systems capable of stabilising fluctuations caused by renewable energy inputs. Challenges such as grid congestion, poor maintenance, and frequent outages further complicate the integration of distributed generation (Power Division 2016). Additionally, outdated infrastructure and limited investment in smart grid technologies hinder the efficient incorporation of decentralised renewable energy, such as solar PV plants, into the national grid. While these issues are evident, energy demand is growing steadily and putting more strain on the grid. Recognising the demand growth, the Government of Bangladesh introduced the Power System Master Plan in 2016 and the Integrated Energy and Power Master Plan (IEPMP) in 2023. These plans propose diverse energy sources, including a significant share of variable renewable energy (VRE). However, while efforts to expand renewable energy such as solar and wind are evident, detailed planning and action plans for upgrading grid infrastructure remain underdeveloped (Hossain et al. 2023b). Furthermore, although electric vehicles, particularly electric three-wheelers, are growing in popularity, little effort has been made to leverage concepts like grid-to-vehicle (G2V) and vehicle-to-grid (V2G) to facilitate VRE integration.

1.7 Research problem and hypothesis

The aforementioned challenges lead to the following research problem: While Bangladesh faces resource constraints in driving its sustainable energy transition, the utilisation of its key renewable energy resource, solar energy, is hindered by competing land use challenges arising from high population density, inadequate policies, and grid integration constraints. Moreover, the absence of comprehensive resource data and spatial assessments addressing land-use concerns further complicates the development of solar PV projects. Conversely, Bangladesh presents several opportunities, such as the widespread adoption of smart energy meters and electric mobility, including electric three-wheelers, which remain largely untapped in tackling these challenges. In response to this problem, the research proposes the following hypothesis:

"Synergising land use, policy, and technological innovation with local opportunities can create a pathway to unlock the potential for solar PV for a sustainable energy transition in Bangladesh"

1.8 Research objectives and questions

The primary objective is to explore how the country can realise its solar energy potential by addressing key implementation challenges and capitalising on local opportunities. To achieve this objective, the study employs a comprehensive solar PV potential assessment approach to determine implementable capacity, utilising the best available spatial data. Additionally, it leverages local opportunities, such as the widespread adoption of smart prepaid electricity meters and electric three-wheelers, to inform the development of policy and technology-related pathways.

The following research questions guide in attaining the objective and focus on developing a nexus to substantiate the hypothesis:

I. What is the implementable solar PV potential in Bangladesh according to different types of solar PV systems that can address the competing land use challenge?

II. What policy can help increase participation in adopting and investing in solar PV to implement the potential and address the land or space availability constraints by leveraging the widespread adoption of smart electric meters?

III. How can Bangladesh address the VRE integration challenge by leveraging the growing adaptation of electric mobility, such as electric three-wheelers?

1.9 Research scope

As this research focuses on using existing opportunities and practices in the country, the scope of this research is also narrowed down accordingly. However, while the objective statements define the scope of this research, it considers the following boundaries:

- The solar PV resource assessment only assesses the potential for emerging systems according to installation practices with silicon-based solar PV modules.
- Since Bangladesh has introduced a net metering policy, the scope of this research focuses on this policy and its modification.
- This research focuses on electric 3-wheelers as electric vehicles for integrating solar PV into the grid.

The lifecycle assessment of solar PV systems and other systems concepts introduced in this research is out of the scope.

1.10 Methodological approach

This thesis adopts various methodological approaches, including geospatial assessment and simulation techniques, using data from diverse sources. These approaches were chosen to address the research questions and achieve the study's objectives.

1.10.1 Data sources and collection

This research used spatial and non-spatial data to perform spatial, economic and technical assessments. The data used were sourced from various national and international sources such as the Bangladesh Bureau of Statistics (BBS), Bangladesh Agricultural Research Council (BARC), Bangladesh Sustainable and Renewable Energy Authority (SREDA), the European Space Agency (ESA), Japan Aerospace Exploration Agency (JAXA) etc. Satellite images and site information from The OpenStreetMap (OSM), Google Map, Bing Map and Esri World Imagery Wayback have also played a significant role in modelling and validation in this study. In addition, some primary data, especially related to solar PV system cost, were directly gathered from different stakeholders. Furthermore, grey literature, such as country-specific reports and newspaper articles, was used to collect data, and research topics such as Virtual Net Metering and Electric Rickshaws were highly underexplored and novel in the Bangladesh context.

1.10.2 Geospatial modelling

The geospatial assessment was conducted using the Geographic Information Systems (GIS) platform QGIS to analyse spatial patterns and relationships between different types of land use and the potential for different types of solar PV systems. Vector and raster-based analyses were performed, and several GIS models were built to assess resource potentials for different types of solar PV systems.

1.10.3 Non-spatial modelling and simulation

HOMER Pro software was used to simulate a small-scale energy system that connects an electric rickshaw charging station with a distributed energy system. The software's optimisation feature was employed to identify the most suitable systems, focusing on finding the least-cost solution.

In addition to simulation, Microsoft Excel-based modelling was used to develop policy concepts, applying financial metrics such as Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period.

1.11 Research structure and published articles

This doctoral research is presented as a publication-based dissertation using published peer-reviewed articles in recognised journals. Table 1.2 provides the list of the articles and their position in this dissertation.

Table 1.2: Published peer-reviewed articles by the author

Research Article	**Published in (Journal)**	**Chapter**
Hasan, A. S. M. Mominul; Kesapabutr, Prin; Möller, Bernd (2024): Bangladesh's pathways to net-zero transition: Reassessing country's solar PV potential with high-resolution GIS data. In Energy for Sustainable Development 81, p. 101511. DOI: 10.1016/j.esd.2024.101511.	Energy for Sustainable Development, Elsevier	2
Hasan, A. S. M. Mominul (2022): Virtual Net-Metering Option for Bangladesh: An Opportunity for Another Solar Boom like Solar Home System Program. In Energies 15 (13), p. 4616. DOI: 10.3390/en15134616.	Energies, Multidisciplinary Digital Publishing Institute (MDPI)	3
Hasan, A.S.M. Mominul (2020): Electric Rickshaw Charging Stations as Distributed Energy Storages for Integrating Intermittent Renewable Energy Sources: A Case of Bangladesh. In Energies 13 (22), p. 6119. DOI: 10.3390/en13226119.	Energies, Multidisciplinary Digital Publishing Institute (MDPI)	4

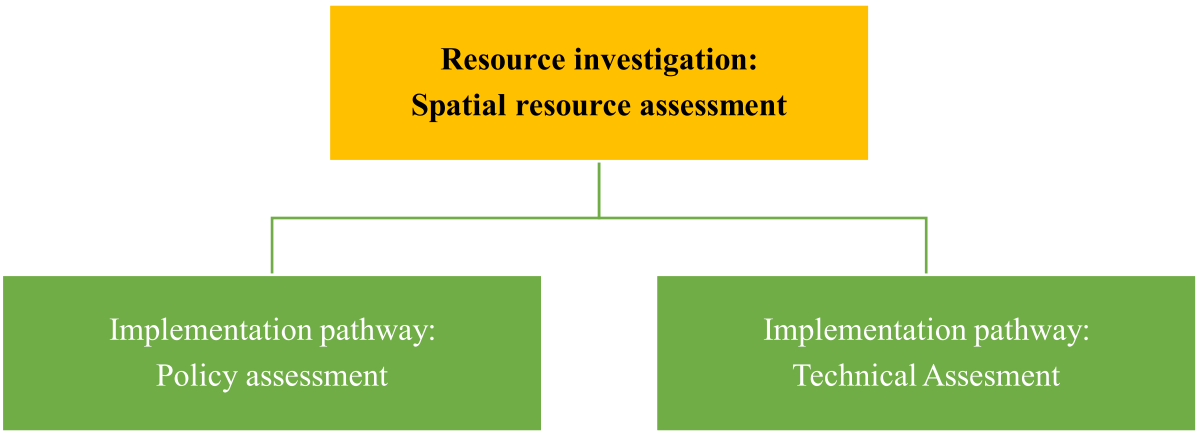


Figure 1.13: Methodological framework overview

The chapters are organised according to the order of the research objectives, as shown in Figure 1.13. Firstly, in Chapter 2: "Bangladesh's pathways to net-zero transition: Reassessing country's solar PV potential with high-resolution GIS data, this research", Bangladesh's solar PV potential has been estimated, considering different types of solar PV systems, using high-resolution GIS data such as a 10-m land cover layer from ESA and about 20 million most recent building footprint vector data from OSM. To avoid land use conflict, initially, 4 types of solar PV systems, such as Rooftop PV (RPV), Ground-mounted PV (GPV), Floating PV (FPV) and Agrivoltaics (APV) were considered by defining strict land use criteria for each system types. In addition to a literature review, existing design practices from 10 solar power plants in Bangladesh were reviewed to develop methodologies for selecting suitable lands for GPV, FPV and APV systems. This analysis provided comprehensive solar PV potential in Bangladesh, estimating about 30 GWp for RPV, 9 GWp for GPV, 5 GWp for FPV, and 81 GWp for APV applications. The result also showed that Bangladesh should emphasise implementing rooftop systems considering land scarcity, growing urbanisation and low-cost implementation. It also recommends implementing systems that offer dual use of land to avoid land use conflict and high cost of land.

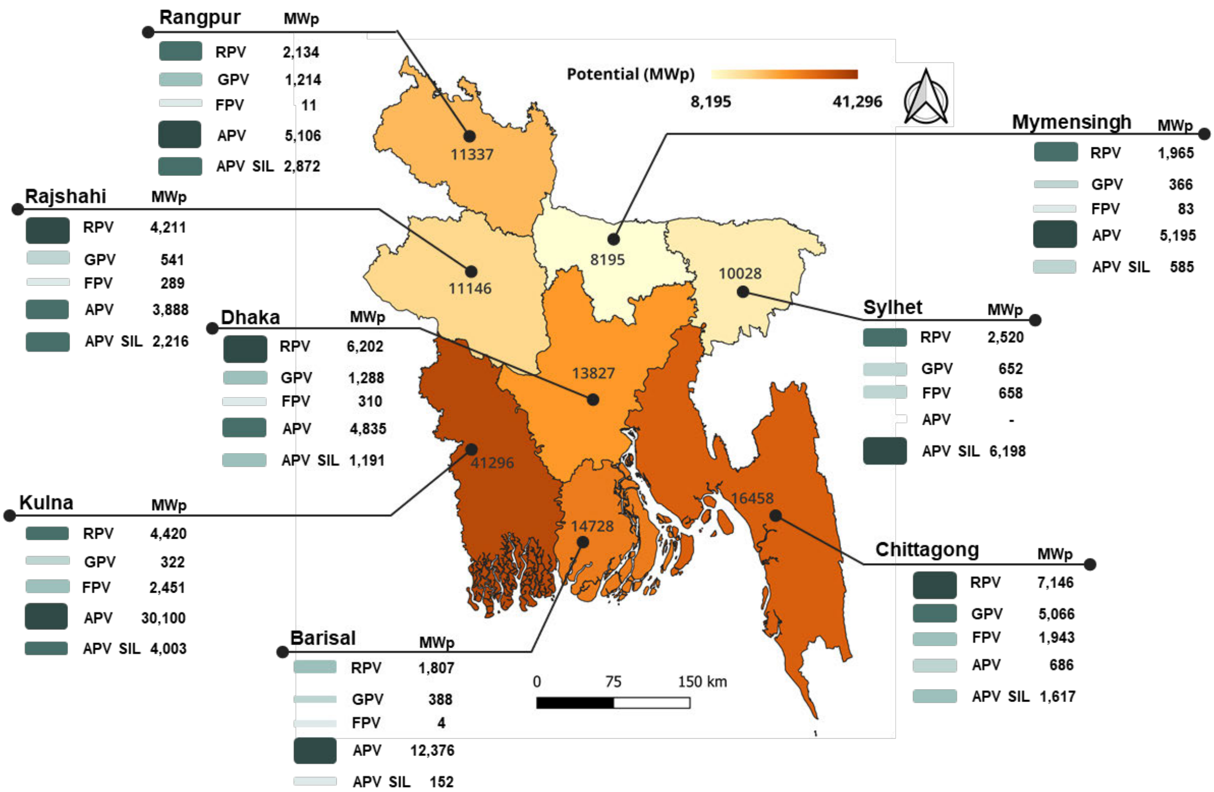
Secondly, Chapters 3 and 4 focus on the implementation of the identified potential, considering policy and technical aspects.

Considering the widespread potential of rooftop PV systems, it is essential to identify suitable policies and policy instruments to enable widespread consumer groups such as residential, commercial, industrial and others. Therefore, Chapter 3: "Virtual Net-Metering Option for Bangladesh: An Opportunity for Another Solar Boom like Solar Home System Program", explored the virtual net-metering (VNM) option for enabling widespread investment opportunities in renewable energy for self-consumption in Bangladesh. It focused on consumers, such as households and businesses in multi-family and multi-story buildings, who cannot participate in traditional net-metering policy due to technical and space constraints. The study adopted the classical socket parity method to identify suitable consumers for VNM. It determined the consumer benefits of using VNM by calculating the net present cost (NPC) and discounted payback period. The results revealed that several consumer categories can significantly save on electricity costs through VNM. For example, commercial consumers can save more than 50% of their electricity bills by investing in a VNM-enabled remote solar power plant with a discounted payback period of fewer than six years. The discussion articulated more comprehensive benefits of VNM. It addressed challenges for investment in renewable energy development by identifying local opportunities, such as the widespread adoption of smart prepaid electricity meters. This research provided materials to initiate policy dialogues and create momentum for citizen investments in the energy transition.

Since the widespread adoption of PV can cause integration challenges, Chapter 4: "Electric Rickshaw Charging Stations as Distributed Energy Storages for Integrating Intermittent Renewable Energy Sources: A Case of Bangladesh", explored how to increase solar PV share in Bangladesh by using electric rickshaws. It proposed a grid-connected local energy system considering a battery swapping and charging station (BSCS) for e-rickshaws as a community battery energy storage (CBESS). This system was simulated using the HOMER Pro software. The simulation results show that such systems can help communities significantly reduce their dependency on the national grid by integrating solar PV locally. The research also discussed how the proposed concept be used for battery-swapping electric boats. In addition, it showed that BSCS is also an opportunity for battery demand reduction and circular battery management for electric rickshaws.

Finally, chapter 5 synthesises the findings and discusses the limitations and outlooks of the research.

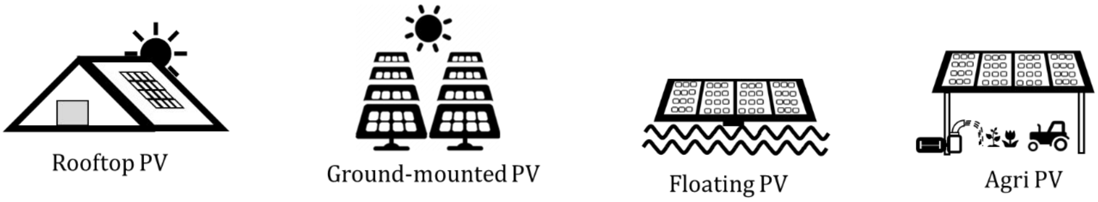
Chapter 2 Bangladesh's Solar Photovoltaic Potential



The content of the chapter was published in Energy for Energy for Sustainable Development journal in July 2024. The materials have been reused in this dissertation with the consent of the co-authors.

Article: Hasan, A.S.M. Mominul; Kesapabutr, Prin; Möller, Bernd (2024): Bangladesh's pathways to net-zero transition: Reassessing country's solar PV potential with high-resolution GIS data. In Energy for Sustainable Development 81, p. 101511. DOI: 10.1016/j.esd.2024.101511.

2.1 Chapter highlights



- System-specific Solar PV potential assessment of Bangladesh
- Analysis of existing 10 solar PV plants reveals design practices in Bangladesh
- The estimate uses the latest 10-metre land cover and 20 million building footprints
- The country has more Rooftop PV potential than ground-mounted systems
- Dual-use PV systems can address land scarcity concerns for sustainable energy transition

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Bangladesh's pathways to net-zero transition: Reassessing country's solar PV potential with high-resolution GIS data

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A R T I C L E I N F O

Keywords:
Net-zero transition
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Agrivoltaics
Geospatial modelling
Solar energy

A B S T R A C T

Solar photovoltaic (PV) technology stands out as a cornerstone in Bangladesh's journey towards achieving net-zero emissions, representing a crucial building block in the country's sustainable energy transition plan. However, rapid land use change and the lack of suitable land for developing PV pose significant barriers to achieving Bangladesh's renewable energy targets and decarbonisation goals towards a net-zero transition. Our analysis of the predevelopment land use state of ten existing solar PV plants in Bangladesh reveals a substantial use of scarce agricultural land for their establishment. Therefore, to identify pathways for overcoming the challenges, this study reassesses Bangladesh's geographic and technical potential for solar PV using geospatial modelling by considering local contexts. Our investigation encompasses Rooftop PV (RPV), Ground-mounted PV (GPV), Floating PV (FPV), and Agrivoltaic (APV) systems. To identify suitable areas and quantify potential, we employ a comprehensive exclusion model and system-specific suitability models using the QGIS platform. Utilising the latest spatial datasets, including footprint data comprising approximately 20 million buildings, a 10 metre (m) resolution land cover map, and bathymetry data, our study provides a robust analysis. The results of our models present a holistic view of Bangladesh's solar PV potential, estimating about 30 GWp for RPV, 9 GWp for GPV, 5 GWp for FPV, and 81 GWp for APV applications. Given the escalating urbanisation in Bangladesh, our findings recommend diversifying solar PV deployment with a focus on RPV and other PV systems that offer dual use of land to facilitate a smoother energy transition towards sustainable development.

Nomenclature

PV	Photovoltaic
APV	Agri PV
AC or ac	Alternating Current
AHP	Analytic Hierarchy Process
APV SIL	APV in Seasonally Inundated Land
AUF	Area Utilisation Factor
BARC	Bangladesh Agricultural Research Council
CO2	Carbon Dioxide
CRF	Capital Recovery Factor
CSP	Concentrated Solar Power
DC or dc	Direct Current
DSM	Digital Surface Model
DTM	Digital Terrain Model
EPSG	European Petroleum Survey Group Geodesy
FPV	Floating PV
GCR	Ground Coverage Ratio
GDP	Gross Domestic Products
GHI	Global Horizontal Irradiance
GHSL	Global Human Settlement Layer
GIS	Geographic Information System
GPV	Ground-mounted PV
GTI	Global Tilted Irradiance
IEPMP	Integrated Energy and Power Master Plan
kWh	kilo Watt-hour
LC	Land cover
LCOE	Levellized Cost of Electricity
LER	Land Equivalent Ratio
LiDAR	Light Detection and Ranging
MapRE	Multicriteria Analysis for Planning Renewable Energy
MCDM	Multiple-criteria decision-making
ML	Machine Learning
MUSD	Million USD
NREL	National Renewable Energy Laboratory
NZS	Net Zero Scenario

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POA	Project Opportunity Area
PR	Performance Ratio
RCR	Roof coverage Ratio
RPV	Rooftop PV
SCR	Surface Coverage Ratio
SS	Substation
STC	Standard Testing Condition
TPES	Total Primary Energy Supply
USD	United States Doller
VNM	Virtual Net Metering
WCR	Water Coverage Ratio
W	Watt
Wp	Watt-peak
Wh	Watt-hour
MW	Mega Watt
MWh	Mega Watt-hour

Introduction

Background

Bangladesh's economy has experienced significant growth and development, positioning the country as a shining example of progress over the past decade. Despite global economic turmoil, the country has consistently maintained annual gross domestic product (GDP) growth well above 5 % annually (The World Bank, 2023). As depicted in Fig. 1, Bangladesh's economy is undergoing a transition from agriculture to industry, accompanied by rapid urbanisation, resulting in notable changes in land use. Domestic natural gas has played a crucial role as the primary driver of the energy sector, contributing to over 50 % of the energy supply and supporting the country's economic advancement with relatively lower carbon dioxide (CO_2) emission intensity (IEA, 2024). In addition to indigenous natural gas, Bangladesh heavily relies on imported fossil fuels to address its increasing energy demand, presenting challenges to the country's energy security and environmental sustainability (see Fig. 2). With aspirations to achieve high-income status by 2041, Bangladesh anticipates a doubling of energy demand compared to current levels (MPEMR, 2023). However, this surge in demand also presents an opportunity to transition towards sustainable energy solutions for sustainable development.

Considering both sustainability and development, Bangladesh has unveiled its Integrated Energy and Power Master Plan (IEPMP) in 2023, embracing a Net-Zero Scenario (NZS) to be accomplished by 2070 (MPEMR, 2023; Debnath & Mourshed, 2024). Within this framework, the country aims to augment its solar and wind power capacities by 28 GW and 55 GW, respectively, by 2050. However, recent data indicates that the share of renewable power capacity and energy generation remains below 5 % of the total installed capacity and power generation, as illustrated in Fig. 2 (BPDB, 2024). As of January this year, Bangladesh's solar PV capacity stood at 970 MWp, including over 35 % being off-grid solar capacity, comprising >6 million solar home systems and additional off-grid installations such as mini-grids and solar irrigation (Hossain et al., 2023; Kirchhoff & Strunz, 2024; SREDA, 2024). Despite Bangladesh's remarkable progress in ensuring energy access through solar home systems and extensive nationwide grid expansion, consumers still face challenges with the availability and reliability of the grid (Alam & Bhattacharyya, 2017; Debnath & Mourshed, 2024).

The challenge of land scarcity has been underscored as a significant obstacle to achieving renewable energy targets (Shiraishi et al., 2019; Hossain et al., 2023). Some press articles by (Syful Islam 5/21/, 2021) and (Md. Tamid, 2022) have also confirmed this issue. To address this challenge, literature and the IEPMP 2023 advocate for the diversification of PV systems, considering various types such as rooftop PV, floating PV, and agrivoltaic systems to attain the capacity target for the net-zero scenario. Table 1 provides a summary of the previously estimated solar PV potential of the country. However, to support Bangladesh's net-zero aspirations and the diversification of PV systems, it is imperative to quantify spatial PV potential according to emerging PV system types.

Mondal and Denich (2010), Nandi et al. (2013) and Halder et al. (2015) conducted non-spatial assessments of renewable energy resources in Bangladesh. Their studies evaluated solar, wind, biomass, and hydro resources, highlighting solar energy, especially for Solar PV applications, as the most abundant renewable resource in the country. A limited number of scientific studies have explored the spatial dimensions of renewable energy resources in Bangladesh as found out based on a literature search using Google Scholar and Science Direct among others. For instance, Shiraishi et al. (2019) acknowledged this limitation and investigated the solar and wind potential in Bangladesh utilising the Multicriteria Analysis for Planning Renewable Energy (MapRE) model developed by (Wu et al., 2017). The researchers applied a land-use discount factor to identify Project Opportunity Areas (POAs) and tailor the model for Bangladesh, estimating installable capacities for solar and wind technologies. The study estimated 53 GW of low-cost solar PV capacity at 91 USD/MWh and 53 GW of concentrating solar power (CSP) without storage, employing a 10 % land-use discount factor in POAs primarily situated in cropland. RPV potential was also estimated at 2 GW, utilising 10 % of the area in urban and built-up areas. Since MapRE was developed, higher-resolution (~10 m) land use data and built-up characteristics have become available, which allow for a continuous spatial modelling approach of settlements and their immediate surroundings. Islam et al. (2022) and Islam et al. (2024) employed a Geographic Information System (GIS) and Analytical Hierarchy Process (AHP) methodologies to identify areas suitable for wind farms and solar power plants in Bangladesh. The researchers assert that over 10,000 km^2 of land is highly suitable for developing wind farms, and >60,000 km^2 of areas are suitable for solar power plants. Also, this study does not include a spatial representation of built-up areas and their neighbourhood that is sufficient for a technology-sharp assessment of potential locations of various types of PV.

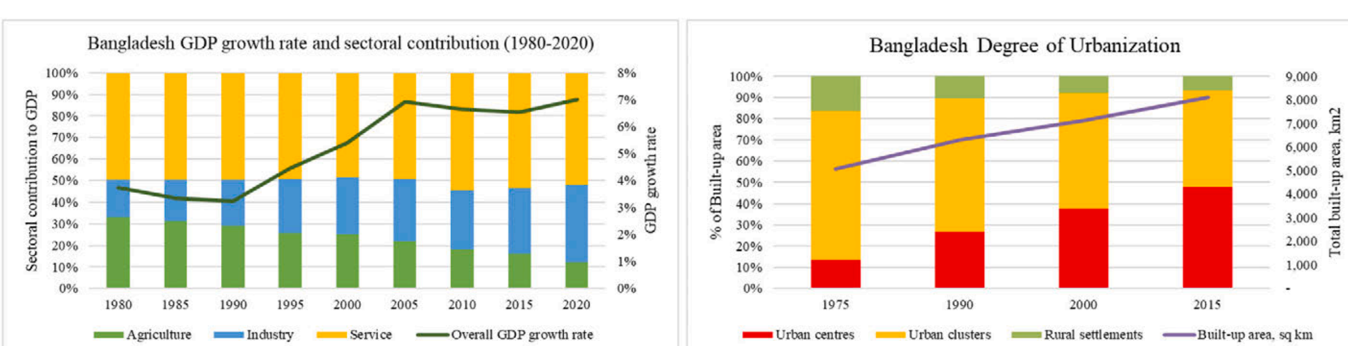


Fig. 1. Bangladesh's historical GDP (Left) and Urbanisation growth rate (right). Data: (GHSL-Global Human Settlement Layer, 2018; Finance Division, 2023).

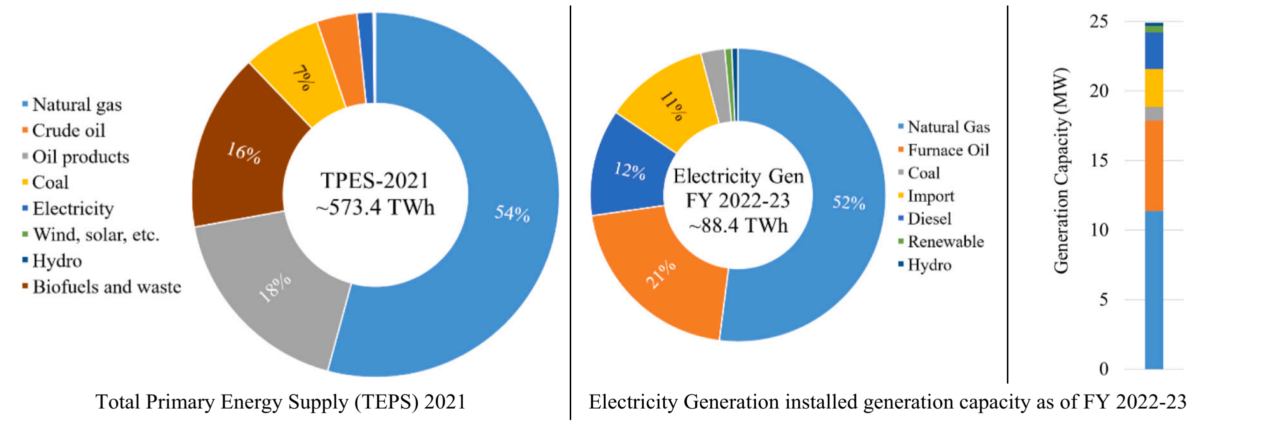


Fig. 2. Fuel composition in Bangladesh's energy sector. Left: TPES 2021 (IEA, 2024). Middle: Electricity generation in the financial year 2022–23 and Right (bar chart): Grid-connected installed capacity for power generation (BPDB, 2024). The legend with energy generation is also valid for the generation capacity bar graph.

Table 1
Bangladesh's solar PV development target for net-zero scenario and potential estimates by some previous studies.

Reference	Capacity (GWp)	PV System type	Comment
MPEMR (2023)	16	Solar Parks	Capacity target for net-zero scenario in 2050 with land use restrictions
	12	Rooftops	Capacity target for net-zero scenario in 2050
Chowdhury (2020)	12	Solar power hubs (mixed)	Proposed capacity for 12 specific locations in the country where the government predominantly owns lands.
Shiraishi et al. (2019)	5.3/42/84	Ground-mounted	Using 1 %/6 %/10 % of the project opportunity area that is primarily cropland
	0.2/1/2	Rooftop	Using 1 %/5 %/10 % of urban and built-up area
Mondal and Islam (2011)	50	Unspecified	Assuming 1.7 % of the total land area

Table 2
PV systems and their definition and acronym used in this research.

Sl.	System type	Definition used in this study	Acronym
1	Rooftop PV	A solar PV system mounted on the roofs of buildings for electricity generation.	RPV
2	Ground-mounted PV	A solar PV system mounted on open ground or land dedicated to electricity generation (also known as a typical ground-mounted PV system).	GPV
3	Agrivoltaic	An elevated solar PV system mounted on open agricultural land for simultaneous crop and electricity production.	APV
4	Agrivoltaic	An elevated solar PV system mounted on open ground or land that is seasonally inundated and used for agricultural production during dry seasons. We propose this novel system type for electricity and fish production during the wet season and crop and electricity production during the dry season.	APV-SIL
5	Floating PV	A solar PV system mounted on a floating structure on a permanent water body within the land boundary of a country for simultaneous fish and electricity production.	FPV

In general, despite laying the groundwork for a spatial assessment of renewable energy resources in Bangladesh, the studies fall short of providing system-specific potentials for PV installations such as GPV, FPV, and APV systems. We also identify further research leads arising from these studies, suggesting a reassessment of GPV potential excluding croplands and RPV potential using building footprint data instead of built-up areas. Hossain et al. (2023) also confirm this gap as one of the potential challenges for sustainable energy transition in Bangladesh.

Research objective, scope, and contribution

This study seeks to support Bangladesh's solar PV capacity target for the net-zero scenario by addressing land availability constraints. It aims to identify suitable locations (geographic potential) for various types of PV systems and estimate their capacity and energy generation (technical potential) using binary overlay methods within a GIS modelling platform. As a secondary objective, we intend to analyse existing utility-scale PV plants. Furthermore, we aim to assess the geographic and technical potential in terms of costs, land use, and proximity to grid substations to suggest system and site prioritisation strategies. Table 2 represents the technical scope of this study on different types of PV systems.

Our study presents several unique value propositions and contributions:

- To the best of our knowledge, this is the first study that conducts PV system-specific geospatial analysis to estimate potentials for five types of PV systems.
- Our data and model are based on high-resolution (10 m, 30 m, & 100 m) spatial and state-of-the-art data, ensuring the best possible results.
- The study is highly customised for Bangladesh, considering its existing PV system implementation practices.

Furthermore, this research endeavours to support Bangladesh's commitment to a sustainable energy transition by identifying suitable locations for solar PV installations across settlement roofs, lands, and water bodies.

Literature review

Over the past decades, solar PV systems have evolved significantly, addressing land use conflicts and enabling dual-use of surfaces with innovations like RPV, FPV, and APV concepts. Recognising the advantages of diversified systems for tailoring a renewable energy development plan, identifying suitable areas for system-specific solar PV applications has become an emerging topic of scientific research. This is particularly significant for countries with high population densities and limited renewable resources. For instance, countries like Bangladesh, Singapore, Bahrain, and the Maldives face space constraints for implementing solar PV systems despite having higher solar resource potentials (IRENA, 2023).

Including some examples in Table 3, numerous studies have used GIS to identify suitability, techno-economic characteristics and area conflict of renewable energy sources. Most prominent is the use of suitability modelling using Multiple-criteria decision-making (MCDM) and AHP in the raster domain, using either continuous or discrete data or derivatives such as distance, density or flow modelling as input (Ruiz et al., 2020; Raza et al., 2023; Rekik & El Alimi, 2023). Models of available theoretical, technical, economic and social or environmental potentials use a combination of potentials, costs and constraints (Sun et al., 2013; Mentis et al., 2017; Isihak et al., 2022; Benalcazar et al., 2024). In an early paper, Ramachandra and Shruthi (2007) have used a vector-based, district-wise assessment of available renewable energy sources in India. Later studies have fully embraced the concept of raster-based data to map potentials for solar, wind and biomass energy continuously, and realised that the raster format is best suited for the continuous mapping of potentials as well as constraining factors (Peters et al., 2020). The quality and focus of recent research are driven by better available data, the use of machine learning/artificial intelligence, and open data and open research (Varriale et al., 2024).

Table 3 presents a summary of relevant literature concerning the utilisation of various geospatial methods for renewable energy resource assessment across different geographic regions. Our analysis reveals that existing literature predominantly concentrates on spatial evaluations of solar energy potential, particularly for GPV and RPV systems. However, limited attention has been given to FPV and APV systems. Furthermore, comprehensive assessments specific to different PV systems, encompassing all prevalent and emerging technologies, are scarce both in Bangladesh and globally.

Materials and methods

Review of ground-mounted PV power plant design practices in Bangladesh

To comprehend the spatial planning and implementation practices of solar PV power plants and the associated costs, we studied ten utility-scale GPV plants in Bangladesh, as outlined in Table 4. Plant data were compiled from diverse sources, including news agencies, government databases (SREDA, 2024), and aerial observations employing

Table 3
Review of relevant literature on GIS-based renewable energy resource potential assessment.

Reference	Geographic scope	RE Technology scope	Study focus and methods
Sebastian et al. (2014)	African continent	Solar PV, CSP, Wind, Biomass	This study estimates the technical potential of multiple renewable (RE) resources in the African continent. The authors developed a straightforward binary GIS model, which initially excludes constrained areas and then integrates them with resources to estimate the energy in gigawatt-hours (GWh).
Wu et al. (2017)	African continent	Solar PV, CSP, Wind	This advanced spatial model identifies suitable sites for technology and estimates capacity (in MW) and energy (in MWh) by applying a multicriteria analysis framework. It also calculates the levelized cost of electricity (LCOE) based on site criteria to compare the cost of supply among zones. Additionally, this research project provides a tool for model replication, which is accessible at https://mapre.es.ucsb.edu/gis-tools/. Subsequently, the World Bank developed a tool named REZoning, inspired by this model. REZoning (https://rezoning.energydata.info/) covers almost all countries in the world for solar PV, onshore, and offshore wind technologies.
Bao et al. (2022)	Germany	Ground-mounted PV	The authors claim that the models in this study adopt a bottom-up approach, combining geoinformation with solar PV yield simulation in hourly resolution. They utilise a 5 m resolution terrain surface point cloud derived from the digital terrain model (DTM) of Germany.
Asare-Addo (2022)	Ghana	Ground-mounted PV	This study employs a geospatial AHP multi-criteria approach to estimate the capacity, energy generation potential, and levelized cost of energy for solar PV and concentrating solar power (CSP) systems on a regional scale in Ghana.
Kim et al. (2019)	South Korea	Floating PV	This study analysed the potentiality of the reservoirs in South Korea to determine the suitable reservoirs for FPV installation. The authors set the constraint on water depth to be >5 m, and the maintaining water depth should be at least 1 m to scope down the number of reservoirs for the study. The power generation was estimated on 1134 from 3401 reservoirs using TMY to calculate solar irradiance and the geospatial analysis to estimate the surface area of each reservoir, then using the assumption for the ratio of water coverage as 10 % satisfying their study conditions.
Nebey et al. (2020)	Ethiopia	Floating PV	This literature is an example of Geo AHP, which aims to identify potential areas for FPV in Ethiopia. However, the scope of the study is limited to three irrigation dams only.
Laub et al. (2022)	Germany	Agrovoltaics	The researchers establish a relationship between the reduction in solar irradiance and crop yield for various crops. According to their findings, the yield of berries, fruits, and fruity vegetable crops increases under reduced light conditions.
Willockx et al. (2022)	Europe	Agrovoltaics	This research concentrates explicitly on the geospatial analysis of elevated APV systems at the EU level, with a resolution of 25 km, considering shade-loving, shade-tolerant, and shade-intolerant crops. The authors investigate the relationship between Ground Coverage Ratio (GCR in %) for APV systems, Daily Light Integral (DLI in mol/m^2/day) for crops, LCOE, and Land Equivalent Ratio (LER). They identify that the lower the DLI requirement by the crops, the higher the energy production, resulting in a lower LCOE and higher LER.
Gagnon et al. (2018)	United States (USA)	Rooftop PV	This research utilises Light Detection and Ranging (LiDAR) data to assess and identify suitable space on rooftops, thereby quantifying the potential for the entire USA. The estimated potential for RPV in this study surpasses previous estimates from the National Renewable Energy Laboratory (NREL). One of the contributing factors to the higher estimation, as mentioned in the article, is the increased number of building footprint identifications achieved through LiDAR data and statistical data.
Bódis et al. (2019)	Europe	Rooftop PV	This 100 m resolution geospatial assessment estimates RPV potential and generation cost for Europe using a combination of satellite and statistical data. The researchers also employ machine learning techniques to calculate technical potential. The study concludes that RPV can meet approximately 24 % of today's current electricity consumption in Europe.
(Joshi et al., 2021)	World	Rooftop PV	This research employs big data, machine learning, and spatial analysis to estimate the global RPV potential. The researchers analysed the world by dividing it into 10 km^2 fishnet grid cells, with each grid cell examining 100 m of land cover data. They develop a relationship between building footprints and built-up areas. The results identify a rooftop area of 0.2 million km^2 with an annual energy potential of 27 PWh.

Table 4
Data of 10 utility-scale solar power plants in Bangladesh. Basic plant data was collected from various sources, such as OpenStreetMap (OpenStreetMap 05/23/, 2023), PV Magazine (Magazine, 2023), Bangladesh's daily newspapers, and the Bangladesh government's renewable energy project database (SREDA, 2024). Elevation and distance to the nearest grid substation data were derived using a digital surface model and Bangladesh grid substation (SS) location data.

Plant #	Location (Lattitude, Longitude)	Date of Comm.	Capacity (MWdc)	DC to AC Ratio	Approximate Investment Cost (MUSD/MW)	Approximate PPA Rate (USD/kWh)	Approximate Specific Area (ha/MWp)	Elevation from sea level (Majority) Metre	Distance to Grid SS (Kilometre)
1	24.77, 89.84	July 2017	3.38	1.13	1.48	0.19	0.96	17	20
2	20.98, 92.25	Sep. 2018	28	1.4	1.25	0.13	1.68	3	55
3	26.48, 88.41	May 2019	10.31	1.29	–	0.128	1.48	90	20
4	22.49, 92.23	May 2019	7.4	1.12	1.89	0.065	1.26	19	1
5	24.70, 90.46	Nov. 2020	73.7	1.47	1.29	0	0.96	15	4
6	23.78, 89.83	Mar. 2021	44	1.17	1.25	0.13	1.29	8	21
7	24.39, 89.75	Mar. 2021	7.6	1.24	2.11	–	1.26	13	0
8	22.57, 89.57	Dec. 2021	134.3	1.34	1.46	0.138	1.05	2	6
9	26.00, 89.15	Aug. 2022	40	1.33	1.38	0.16	1.11	42	16
10	25.64, 89.54	Jan. 2023	280	1.4	1.07	0.15	0.87	25	19

freely available maps and satellite images, such as Google Maps and OpenStreetMaps. In addition to post-development data, we utilised Bangladesh's land cover (LC) data in 2015 obtained from Copernicus (Buchhorn et al., 2020a) to delineate the pre-development LC classes at each site. This land cover data offers 100 m resolution with a minimum accuracy of 77 % in Asia. Fig. 3 shows maps of pre-development land cover and post-development satellite images of these PV plants. According to the land cover data, 6 out of 10 PV plants were established on lands where the predominant LC classes were croplands, indicating a substantial sacrifice of croplands for solar PV plant development. However, we needed more data to ascertain the productivity of the lands, which was beyond our scope. Plant 1 was spotted in the backyards of households in the middle of rural settlements, while Plants 4 and 7 use the backyards of a thermal power plant and hydropower dam. Additionally, Plant 7 was installed on a seasonally inundated land with relatively higher mounting height (see Fig. 7). Plant 3, on the other hand, combines the use of a rooftop of a farm shade and uses surrounding agricultural areas. We also gathered planning parameters such as proximity to the nearest grid substation and elevation. The analysis reveals diverse geographical settings, including low-altitude lands and varying distances to substations, ranging from 0 to 55 km. General trends for the location, design, and cost could not be recognised from the available data.

Research strategy and assumptions

Considering Bangladesh's socio-economic development, demographic and land-use changes, and existing development practices, we adopt the following research strategies:

- No exclusion based on solar resources as Bangladesh benefits from ample solar resources, with the global horizontal irradiation (GHI) ranging from 4.33 to 4.95 kWh/m^2 (Solargis, 2023) across its territory, making it highly suitable for solar PV applications.
- RPV systems can be installed virtually anywhere as long as there is a suitable roof available
- To protect agricultural lands, we have opted not to install typical GPV systems in these areas, except for implementing APV, which allows for dual land use without compromising agricultural productivity.
- Due to the high river currents during the monsoon season, we have decided against implementing FPV systems in rivers to ensure the safety and integrity of the installations.
- We have adopted a nationwide single cost estimation approach for each system category based on size, considering the country's relatively small geographic size and ensuring consistency in cost assessments.
- Since the Bangladesh government has extended the grid to almost everywhere, we use grid availability as a criterion for site prioritisation rather than site identification.
- To avoid the risk of overestimation, we have employed a conservative estimation approach

Overview of the methods

The scope of this study encompasses five categories of PV systems based on installation practices. We consider the intrinsic properties of space to identify suitable locations according to the technical considerations of each system category. The geographic scope covers Bangladesh's onshore areas, including land, water bodies, and building rooftops. Fig. 4 illustrates the general methodology applied to determine the geographic potential for all types of PV systems. Fig. 5 and Fig. 6 below showcase examples of geoprocessing, while a comprehensive set of detailed block diagrams illustrating the modelling process are provided in the supplementary material. Section 2.4–2.4.5 elaborates methods for each system category. All the geo data was reprojected to coordinate system EPSG:9680, which replaces Gulshan 303/TM 90 NE CRS code 3106 for Bangladesh (EPSG.io, 2021), to perform GIS modelling. The analysis and modelling were performed on QGIS Version 3.28 LTR and its graphical modeller (QGIS.org 12/30/, 2023).

As depicted in Table 5, the data used in this study can be categorised as base data and supporting data. Base data include building footprint polygons, high-resolution land cover, and water body polygons with bathymetry. Supporting data encompass elevation, protected areas, settlements, infrastructures, etc. The exclusion and suitability criteria values are informed by existing design practices in Bangladesh (section 2.1), scientific literature cited in the literature review (section 1.3), and estimates based on the authors' local and international experiences. Once geographically suitable areas are determined, we calculate the technical potential using solar irradiation data from the Global Solar

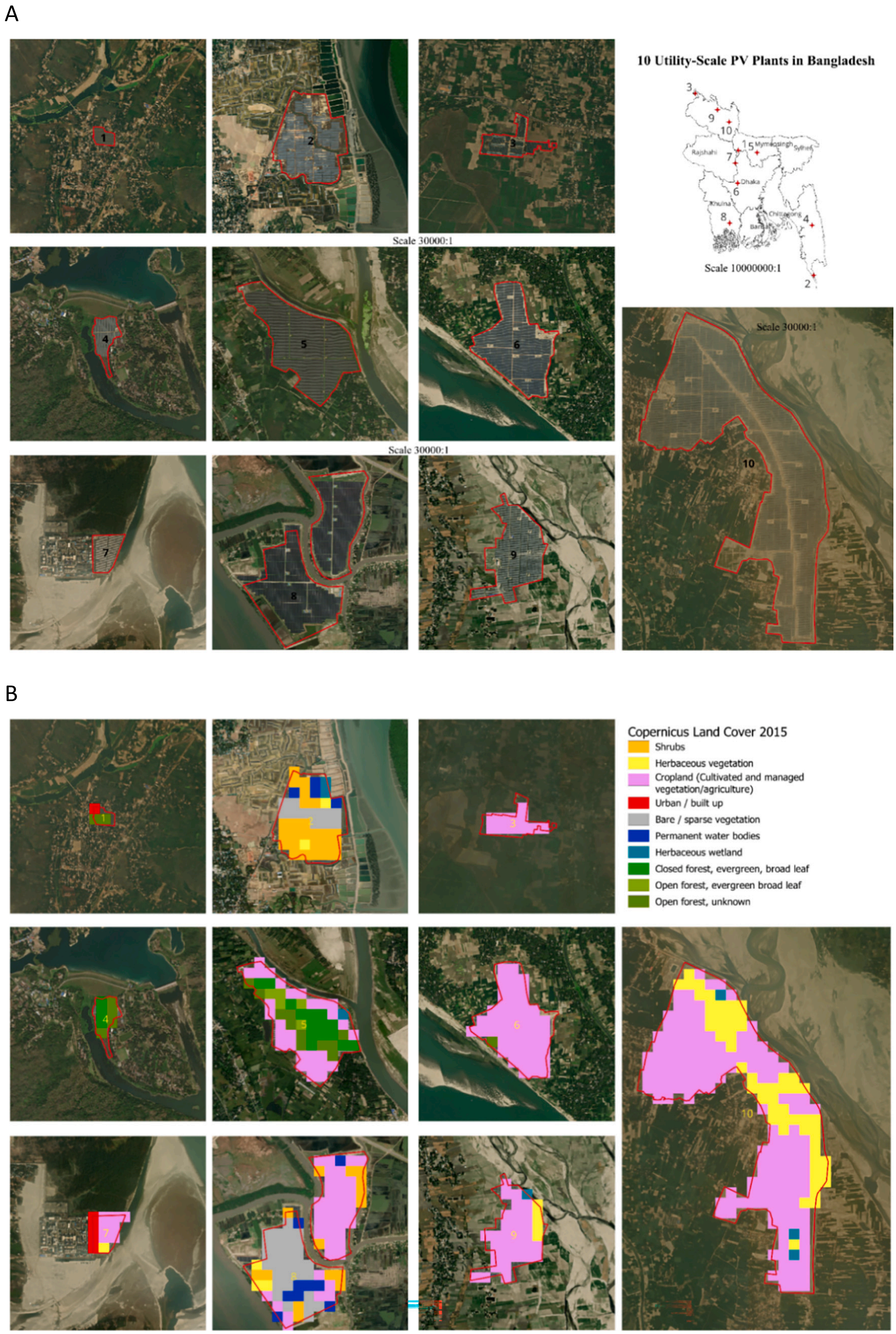
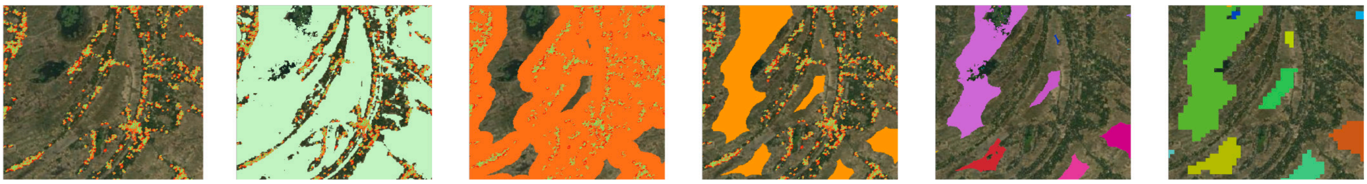


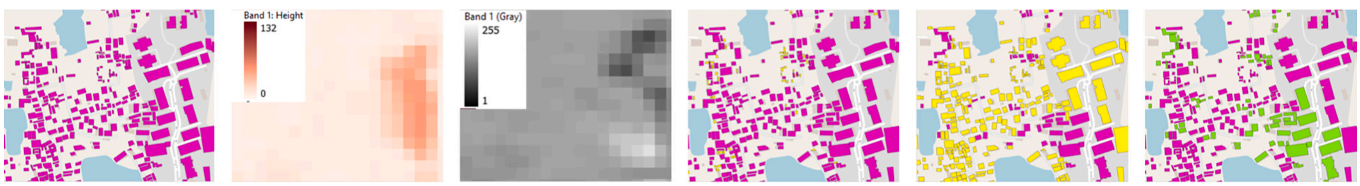
Fig. 3. Geographic footprints of 10 utility-scale solar power plants in Bangladesh. A: post-development satellite images of these PV plants; satellite image source: (Esri, 2023). B: pre-development land cover (Buchhorn et al., 2020). Pink colour represents croplands on the land cover map.

Fig. 4. Modelling process overview.



1: Small-scale settlement structures from the GHS Builtup Characteristics layer, 10m | 2: Cropland ESA Worldcover, 10m | 3: Areas within 300m of small-scale settlement structures | 4: Areas outside 300m of small-scale settlement structures | 5: Clumped areas outside settlements on cropland | 6: Morphed areas within 300m of small-scale settlement structures, resampled to 100m

Fig. 5. Example of geoprocessing for APV model. Similar processing is also used for GPV and FPV models. (1–6) to identify suitable areas for APV using QGIS. Steps 1 and 2: input data, Step 3: buffer, Step 4: raster calculation, Step 5–6: morphing.



1: Building footprint data | 2: Digital surface model (DSM) data | 3: Hillshade layer derived from DSM | 4: Exclusion of building footprint with area <50m^2 (yellow polygons) | 5: Exclusion of building footprint Hillshade <166 (yellow polygons) | 6: Suitable roofs after all filters applied (green)

Fig. 6. Example of geo-processing for RPV potential. Steps 1–6 show the major steps.

Atlas (Solargis, 2023), as mentioned in section 2.5.

For the analysis, it was assumed that the highest possible resolution of raster data yields the lowest error in representing spatial phenomena. Therefore, suitable areas were identified at the highest possible raster resolution, and subsequently aggregated to an operational cell size suitable for country-wide assessment of solar resources and costs. Because using combinations of aggregated grids obeys the rules of standard error propagation Pogson and Smith (2015), the induced error hereby is assumed to be lower than by aggregating grids prior to the suitability analysis, or by interpolating lower resolution raster data for the analysis.

Geographic potential estimation methods

Rooftop PV systems

In a quest to gather a maximum number of building footprints in Bangladesh, we rely on human and machine-generated building polygon data from OpenStreetMap through Geofabrik (OpenStreetMap Contributors, 2023a) and Microsoft Global ML Building Footprint (GlobalMLBuildingFootprints, 2023) platforms. Both datasets are incomplete, and we identify overlaps of polygons. Therefore, we combined these two building footprint data sets to maximise the features across the country using exclusive-OR logic and found about 20 million mutually unique building footprint polygons. Then, with the help of 30 m DSM data from (OpenTopography, 2016), we create two raster layers, hillshade and sky view factor, and add this data to the building footprint layer using zonal statistics. Hillshade and sky view factors data help identify roofs with relatively lower shadows and higher sky visibility for RPV applications. Gagnon et al. (2018) and Bódis et al. (2019) recommended LiDAR data to identify building footprints for estimating RPV potential. Since LiDAR data is unavailable for Bangladesh, we produced only one hillshade layer by consulting the sun path diagram of a central location in Bangladesh using 30 m DSM data. To conservatively produce this hillshade, we opted for a 45° sun elevation angle with an azimuth angle of 180°, corresponding to the midday sun position in winter (University of Oregon, 2023). This selection enables the identification of rooftops unaffected by shading from southern objects throughout the year. In our investigation, we utilise QGIS's hillshade value scale, which ranges from 1 to 255. A value of 1 represents complete obstruction, while 255 indicates no obstruction. We focus on rooftops with a minimum of 65 % clearance from obstruction, corresponding to a hillshade value of 166 or greater (ESMAP, 2021).

Ground-mounted PV systems

For the assessment of typical GPV system potential, we leverage high-resolution (10 m) land cover data sourced from the European Space Agency (Zanaga et al., 2022). Utilising this data as the foundational layer, we reclassify areas categorised as bare and sparse vegetation, grassland, and shrublands, designating them as suitable for GPV installation. Subsequently, we apply both general exclusion criteria and GPV-specific exclusions. The GPV-specific exclusion model eliminates permanent and seasonal water bodies, building and industrial footprints, and areas characterised by unsuitable topography.

Agri PV systems on agricultural land

Similar to the GPV model, our approach for assessing APV potential relies on utilising the same land cover data. Specifically, we reclassify only croplands from the land cover data suitable for APV installation.

Table 5
Overview of the GIS models and data for five systems. All the global datasets were cropped using Bangladesh's administrative boundary level 0 and reprojected to EPSG 9680.

Modelling process	GPV	APV	APV SIL	FPV	RPV
Base data (Main input)	Land cover classes(Zanaga et al., 2022) ▪ Grassland ▪ Shrubland ▪ Bare/sparse vegetation	Land cover class ▪ Cropland	Land cover class ▪ Cropland Seasonal water	Inland water bodies with bathymetry (Khazaei et al., 2022)	Building footprints ▪ OSM building footprints (OpenStreetMap Contributors, 2023a) ▪ Microsoft building footprint (GlobalMLBuildingFootprints, 2023)
General exclusion	Protected area (UNEP-WCMC and IUCN, 2023) (with 1000 m buffer) Mangrove (Bunting et al., 2022) (with 1000 m buffer) Military zone (OpenStreetMap Contributors, 2023b) (with 500 m buffer) Airport (OpenStreetMap 05/23/, 2023) (with 1000 m buffer) Railway tracks(OpenStreetMap 05/23/, 2023) (with 200 m buffer) Settlement (built-up areas) (Zanaga et al., 2022) (with 300 m buffer) Building footprint (GlobalMLBuildingFootprints, 2023; OpenStreetMap Contributors, 2023a) (100 m distance cut off) Industrial land use (OpenStreetMap 05/23/, 2023) Chimneys (with 100 m buffer) Power plants, including existing solar PV plants (OpenStreetMap 05/23/, 2023)				▪ Overlapped building polygons ▪ Shaded buildings from the South (identified using a Hillshade simulation from 45° altitude at 180° of Azimuth. Excluded values: ≤ 166/ 65 % ▪ Building lacking open sky (Sky View Factor (SVF < 90 %) (identified by generating an SVF layer using DSM layer). ▪ Roof area < 50 m^2
System-specific exclusion	Permanent water (Buchhorn et al., 2020) (with 500 m buffer) Seasonal water (Buchhorn et al., 2020) (with 500 m buffer)				
System-specific suitability criteria	o Digital surface model products (OpenTopography, 2016) ▪ Altitude > 1 m and < 800 m ▪ Slope (≤20°) ▪ Aspect (90–270°) o Area > 12,000 m^2 (for a minimum capacity of 1 MWp)	Crops (only suitable areas for the following crops by (BARC, 2022) ▪ Potato ▪ Onion/Garlic ▪ Chili ▪ Lentil ▪ Gram ▪ Mustard ▪ Ground nut Very severe and severe drought-affected areas in all seasons: Pre-Kharif, Kharif, and Rabi, by BARC (BARC, 2022)	Crops (all except Boro Rice Paddy)	▪ Reservoirs bathymetry (Deeper than 3 m) ▪ Surface reservoir area (> 1 km^2) ▪ Percent water occurrence (> 50 %) ▪ Potential flooding areas (Avoid flooding)	
Geographic potential	Suitable areas for GPV	Suitable areas for APV	Suitable areas for APV-SIL	Suitable water surfaces for FPV	Suitable Roofs for RPV

Following this, we apply the general and APV-specific exclusion models to pinpoint areas conducive to APV implementation and quantify their potential. Rice is the most dominant crop in Bangladesh. According to Nasim et al. (2017), 54 % of the net cropped area, or 4.6 million hectares, is exclusively used for rice paddy plantation. Since reduced sunshine may reduce rice productivity (Anas et al., 2023), we exclude

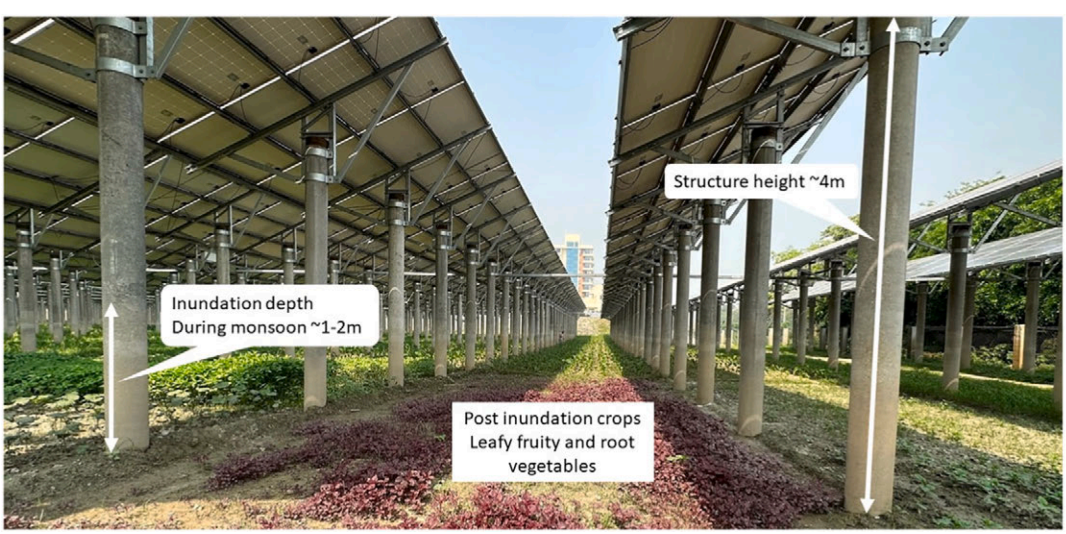


Fig. 7. An example (Plant #7 in Table 4) of APV-SIL implemented in Bangladesh. The colour difference on the concrete structure (pole) shows signs of inundation. Inundation causes sedimentation on land, which makes the land fertile for crop production.

exclusive rice lands from suitable areas. Given the experimental nature of the APV concept, we employ a suitability model primarily focusing on potato, onion and garlic, lentil, gram, mustard, and ground nut. The crop suitability zone data, integral to this model, were sourced from the Bangladesh Agricultural Research Council (BARC) (BARC, 2022).

Agri PV systems on seasonally inundated lands

Bangladesh's low-lying topography and high rainfall seasonality make it highly susceptible to flooding Dewan et al. (2022). The monsoon season, spanning from June to September, results in extensive land inundation for several months annually, exacerbating the challenges posed by the nation's permanent water features like rivers, lakes, ponds, and reservoirs. Notably, these flooded areas serve dual purposes—supporting fishing activities during monsoons and cropping endeavours in dry seasons. Recognising the distinct characteristics of these areas, we treat them separately within the agrivoltaic systems domain, designating them as Agrivoltaics on Seasonally Inundated Lands (APV-SIL). Fig. 7 illustrates an example of a GPV system in Bangladesh that aligns with the APV-SIL classification.

To identify seasonally inundated areas, we utilise five years (2015–2019) of seasonal inland water cover fraction data from (Buchhorn et al., 2020). A notable distinction in the APV-SIL model is the classification of seasonally inundated areas as 1, facilitating logical AND operations. At the same time, this value was set to 0 for the standard APV model. Subsequently, akin to the GPV and APV models, we implement general exclusion criteria and technology-specific exclusions to ascertain the potential of APV-SIL systems.

Photo courtesy: Mr. Shahriar Ahmed Chowdhury, CER, United International University.

Floating PV systems

According to the ESA land cover data, over 10 % of Bangladesh's land is covered by permanent water bodies, including rivers, lakes, ponds, and reservoirs, presenting a significant opportunity for the implementation of FPV systems to address land availability constraints. However, we excluded rivers from FPV estimation due to technical challenges and economic infeasibility arising from high monsoon river currents. Since the land cover map does not offer details about the water bodies, we utilise bathymetry data from the global lakes dataset (Khazaei et al., 2022), identifying 1175 inland water bodies in Bangladesh. The percentage of water occurrence in the study area was included in the model to find a suitable area for FPV in Bangladesh by assuming a percentage >50 % (Pekel et al., 2016). Applying general exclusion and FPV suitability criteria, with a minimum water depth of 3 m and a minimum surface area of 1000 m^2 as recommended by Nebey et al. (2020), we identify suitable water bodies for FPV development. A water occurrence of 50 % indicates that water was observed for 50 % of the data collection period at a specific location, while a value of 100 % denotes a permanent water body. Since lake size shrinks significantly during the dry season, we opted for a 50 % threshold to maintain consistency with the global lake dataset and accurately represent water body sizes.

Technical potential estimation

PV system capacity calculation

Upon identifying geographically suitable surfaces and determining the areas, we calculate the installable capacity of PV systems using Equation (1). In this equation, the Area Utilisation Factor (AUF) and the Surface Coverage Ratio (SCR) are significant factors determining the installable power capacity in a suitable area. AUF indicates how much of the identified geographic area can be utilised for a PV plant, while SCR tells how much of the utilised area is covered by PV modules within the utilised area.

As depicted in Table 6, the value of AUF varies based on system types and land use. A higher AUF value (75 %) was applied to GPV systems, reflecting the predominantly single-use nature of lands designated for GPVs. Conversely, for APV and APV-SIL systems, a lower AUF value (50 %) was selected compared to GPV, acknowledging the potential for dual land use (Fraunhofer ISE, 2022). On the other hand, we chose a very low value of AUF (10 %) conservatively as (Haas et al., 2020) indicate that an FPV to water reservoir area ratio of <40 % has little to no effect on microalgal growth. Another reason for choosing a lower value is the area differences between wet and dry seasons, as we observed in (Pekel et al., 2016) and (Buchhorn et al., 2020) data sets. For RPV, we consider only 50 % of the roof can be utilised for PV, taking into account various other applications for rooftops, such as positioning water tanks and rooftop gardening (Datta et al., 2020). In addition to flat roofs on buildings, the 50 % assumption also conservatively considers only half of the roof area covered by pitched, gable (Dochala), and hipped (Chochola) roofs, which are predominant roofing characteristics in rural Bangladesh.

Table 6
System type-wise values for area utilisation factor, roof/ground/water coverage ratio, active module area, and module efficiency.

System Types	AUF	RCR/GCR/WCR	Active Solar PV area (% of total area)	Module Efficiency
RPV	50 %	60 %	30.0 %	20 %
GPV	75 %	55 %	41.3 %	22 %
APV & APV-SIL	50 %	35 %	17.5 %	22 %
FPV	10 %	65 %	06.5 %	22 %

The value of SCR can vary for different types of PV systems and geographic locations. The average capacity footprint of existing solar power plants in Bangladesh was calculated to be about 1.2 ha per MW, which roughly results in a SCR of 58 % at a module efficiency of 15 %. Since data regarding the efficiency of the PV modules used in those power plants are openly unavailable, we could not calculate the SCR. However, for the existing PV plants in Bangladesh, a 15 % module efficiency provides an average SCR of 58 %, while it provides 44 % of SCR at 20 % module efficiency.

Since this research investigates multiple types of PV systems, distinct SCRs were employed for each system type. For GPV systems, based on existing PV plants, we considered SCR as Ground Coverage Ratio (GCR) with a value of 55 %. For APV and APV-SIL systems, a lower GCR of 35 % was considered, accounting for increased light exposure to the crops beneath (Willockx et al., 2022). For FPV systems, SCR is used as the Water Coverage Ratio (WCR). The WCR of 65 % is inspired by Haas et al. (2020) and (ADB, 2020a). This value is higher as a relatively lower module tilt angle (e.g., 15°) is used in FPV installation practices. Furthermore, a high Roof Coverage Ratio (RCR) value of 60 % was maintained, accounting for the lower tilt angle compared to GPV systems and the non-homogeneous nature of roofs such as flat and hip roofs.

Considering implementation practices, we considered two levels of efficiency for PV systems for RPV (20 %) and other systems (22 %) (Fraunhofer ISE, 2023; Ramdas et al., 2019). As Bangladesh is a small country by geographic extent, we used these values to estimate power capacities for the whole of Bangladesh for simplicity. Furthermore, to maintain methodological simplicity, we adopted the same values for SCR and GCR, as shown in Table 6, for all further capacity categorisations mentioned in the section below.

$$PV\ System\ Cpacity\ (Wp) = A \times AUF \times SCR \times \eta_{PV} \times STC\ Irradiance \quad (1)$$

Where, A represents the suitable area in m^2, coming from geographic potential. AUF is the area usability factor, which means the usable portion of the identified shape area A. SCR stands for surface coverage ratio, η_{pv} is module efficiency, and STC irradiance is the solar irradiance at the standard testing condition, which is 1000 W/m^2. Values used with this equation are provided in Table 6.

Table 7
Solar irradiation data type and performance ratio for different types of PV Systems.

System Types	Global Solar Atlas Irradiance Component	PR
RPV	GHI	75 %
GPV	GTI	75 %
APV & APV-SIL	GHI	80 %
FPV-IW	GHI	80 %

Table 8
PV system categories by capacity tiers.

System size category	RPV	GPV and FPV	APV
Very Large	kWp > 500	MWp > 100	MWp > 50
Large	100 ≤ kWp <500	50 ≤ MWp <100	15 ≤ MWp < 50
Medium	30 ≤ kWp < 100	20 ≤ MWp < 50	5 ≤ MWp < 15
Small	10 ≤ kWp < 30	5 ≤ MWp < 20	1 ≤ MWp < 5
Very Small	3 ≤ kWp < 10	1 ≤ MWp < 5	0.1 ≤ MWp < 1

PV system energy generation calculation

Equation (Eq.2) determines the energy generation potential at each site, employing site-specific solar insolation data from the Global Solar Atlas (Solargis, 2023). We utilised global horizontal irradiation (GHI) for APV, APV-SIL, and FPV systems, as these systems are installed with lower inclination angles to reduce wind load. For GPV and RPV, considering low structure height and optimum tilt angle, we used the global tilted irradiance at the optimum angle (GTIopta).

In addition, accounting for air pollution and limited rainfall during dry seasons, we set the performance ratio (a ratio between the actual and theoretical output of PV plants) to 75 % for the entire country for RPV and GPV, while 80 % was considered for APV and FPV systems, see Table 7.

$$PV\ System\ Energy\ (Wh) = Wp \times G_{site\ average} \times PR \tag{2}$$

Where Wp = PV capacity, G is annual solar insolation in kWh/m^2/year, and PR stands for performance ratio.

Energy generation cost

To leverage economies of scale, we categorise each PV type into five capacity categories or tiers (as shown in Table 8), considering unique implementation practices and spatial constraints before calculating their energy generation cost. RPV categories are based on Bangladesh's RPV system market prices collected via personal communication (Hossain, 2023). We assigned similar categorisations and costs for GPV and FPV, considering existing PV parks and FPV feasibility studies in Bangladesh (ADB, 2020a, 2020b, 2021). APV categories are derived from the GIZ report on APV in India (Kelsey et al., 2020; Subrahmanyam et al., 2023).

To estimate the LCOE, we utilise the simplified (s)LCOE method provided by NREL, as outlined below in Eq. 3 (NREL, 2024). This approach necessitates minimal data requirements, facilitating its practical application for the purpose of this study.

$$sLCOE = \frac{overnight\ capital\ cost * capital\ recovery\ factor\ (CRF) + fixed\ O\&M\ cost}{8760 * capacity\ factor} \tag{3}$$

Where overnight capital cost is measured in dollars per installed kilowatt ($/kWp), capital recovery factor is a fraction calculated as described below in Eq. 4. Fixed Operation and Maintenance (O&M) costs in dollars per kilowatt-year ($/kW-yr). The capacity factor was calculated spatially.

$$CRF = \frac{i*(1+i)^n}{(1+i)^n - 1} \tag{4}$$

Where i represents interest rate and n is the number of annuities received. We used the lifetime of PV systems as n with a value of 25 years.

Results and Analysis

In this section, we present the results and analysis of our research based on the methodologies presented above.

Geographic potential for developing PV systems in Bangladesh

Table 9 summarises the geographic potential for developing PV systems in Bangladesh, while the map (Fig. 8) pinpoints the locations for GPV, FPV, and APV systems. We identify about 1600 km^2 of area, including rooftops, open land, and water surface, are suitable for developing different types of PV systems, accounting for 1.08 % of the total onshore area of Bangladesh. Chittagong and Khulna divisions offer the highest geographic potential, notably for FPVs. Mymensingh division, on the other hand, scores the lowest.

Technical potential

Rooftop PV potential

Out of the 19.6 million identified building footprints, our analysis designates 21.2 % as suitable for installing solar PV systems, collectively offering an aggregated capacity potential of 30.4 GWp. Fig. 9 illustrates a detailed breakdown of the potential across administrative divisions and system size categories, presenting data in both installable capacity (MWp) and expected energy generation (GWh). The analysis reveals that the most prevalent system size categories, in terms of count, capacity, and energy generation potential, are "Very Small" (3 to 10 kWp) and "Small" (10–30 kWp). Remarkably, these two categories account for >98 % of the identified systems, offering over 85 % of the total installable RPV capacity. If this potential is realised, Bangladesh could generate approximately 40 TWh of energy from RPV systems, constituting nearly half of the nation's current total annual energy generation from all sources. This finding surpasses all prior estimates of RPV potential in Bangladesh. The difference can be explained by the high volume of building footprint data used in this study. Despite our estimate exceeding all prior assessments for the entire country, it remains conservative. For instance, our estimate suggests a potential of 6.1 GWp for

Table 9
Summary of the PV potential and respective land requirement from different land cover classes according to the 10 m resolution ESA WorldCover V2 2021. The "land use for solar PV systems" column shows how RPV, FPV and APV systems can be installed without changing the existing purposes of the land.

Land cover class	Area (km^2)	% of the total land	Suitable solar PV system	Estimated suitable area for PV (km^2)	% of Land in land cover class	% of the total land	Land use for PV systems	PV Capacity Potential (GWp)
Built-up	2233	1.51 %	RPV	410	18.36 %	0.28 %	Secondary or tertiary	30.41
Shrubland	8	0.01 %	GPV	108	3.26 %	0.07 %	Traditionally primary	9.84
Grassland	2307	1.56 %						
Bare/Sparse vegetation	1008	0.68 %						
Permanent water bodies	15,206	10.30 %	FPV	416	2.74 %	0.28 %	Secondary	5.75
Cropland	67,185	45.51 %	APV & APV SIL	667	0.99 %	0.45 %	Secondary	81.02
Tree Cover	53,257	36.08 %	Excluded					
Herbaceous wetland	2040	1.38 %						
Mangroves	4367	2.96 %						
Total	147,611	100.00 %	–	1601		1.08 %		127

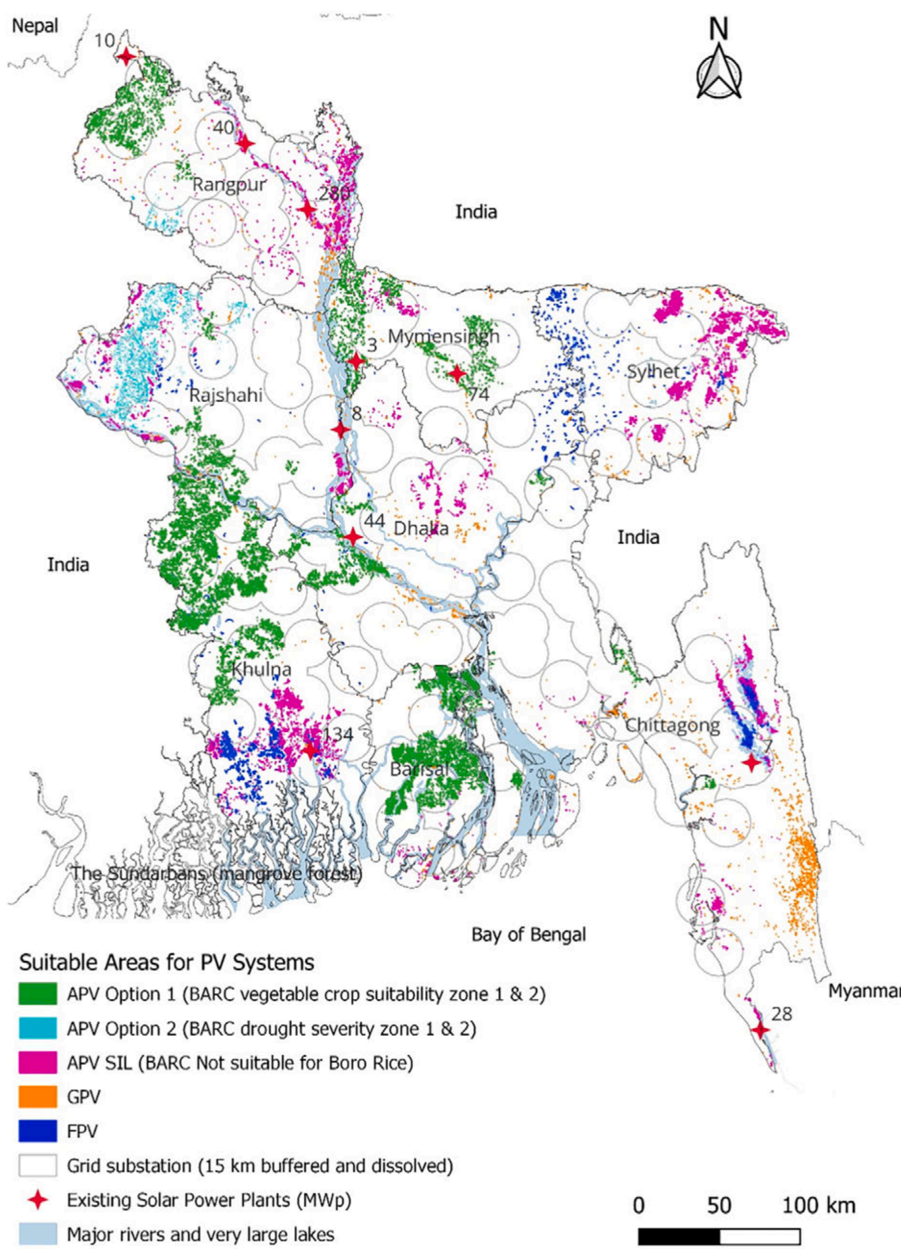


Fig. 8. Potential area for developing different types of PV systems (GPV, FPV and APV) in Bangladesh. The map also shows 15 km proximity circles of grid substation and 10 existing PV plants, as discussed in section 2.1. Substation data source: (PGCB, 2023).

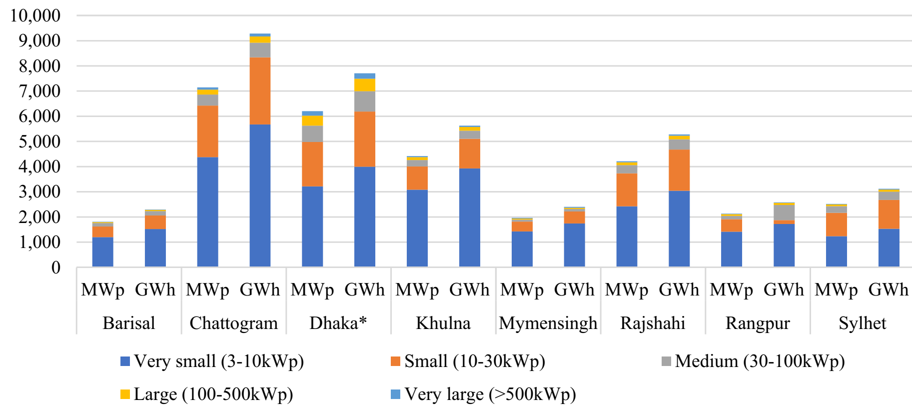


Fig. 9. Install capacity (MWp) and energy generation potential (GWh) of RPV systems in 8 administrative divisions in Bangladesh. The aggregated potential is 30.4 GWp. The segmented bars represent capacity potential according to system category by size. Numbers in the Y axis are neutral. *Both the datasets for building footprints lack building footprints for a large part of the Dhaka Division.

Table 10
Comparison between the ESMAP, 2021 estimate for Dhaka city and our results for the same geographic extent for RPV potential.

Parameters and unit	Value, ESMAP, 2021 Estimate	Value, Our Estimate
Total no. of building footprint	417,707	466,954
Total no. of suitable building footprint	411,637	156,644
% building footprint with roof area < 50 m^2	22.4 %	26.2 %
Roof suitability (% of total no. of roof)	98.55 %	33.55 %
Total cumulative roof area (m^2)	64,271,108	62,666,138
Suitable total cumulative roof area (m^2)	35,272,795	13,618,779
Suitability (% of total cumulative roof area)	54.9 %	21.7 %
Total PV Capacity (kWp)	6,842,934	1,634,267
Specific PV Area m^2/kWp	5.15	8.33
Energy Potential GWh	8446	2016
Specific PV Yield kWh/kWp	1234.24	1233.45

the entire Dhaka division. Conversely, a recent satellite image-based estimate by (ESMAP, 2021) estimated 6.8 GWp solely for Dhaka city, representing only 1.5 % of the division's total area. The study used a similar method, such as hillshade, to estimate the potential by determining building footprints directly from satellite images. Table 10 provides a quantitative comparison between ESMAP's assessment and our own. The variances stem from our conservative criteria for identifying suitable roofs. For example, unlike ESMAP, we exclude rooftops with an area less than 50m^2, deeming them too small for grid-connected rooftop PV installations.

Ground-mounted PV potential

Our analysis reveals a substantial GPV potential in Bangladesh, estimating approximately 10 GWp distributed across over 10 thousand locations, offering >13 TWh of energy annually, as shown in Fig. 10. Notably, the riverine landscape emerges as a critical focal point for GPV potential. The majority of the identified locations are situated along rivers, particularly on the banks and islands (known as Char). Simultaneously, areas with low population density and extensive grasslands, such as the Chittagong Hill Tracts, exhibit higher potential for GPV installation. Shiraishi et al. (2019) estimated a GPV potential of 5.3 GWp considering 1 % of agricultural lands in Bangladesh, while our result shows higher potential without considering any croplands from the land cover layer. The difference can be explained by the high-resolution latest land cover data with >82 % accuracy for Asia that we used in our analysis (Zanaga et al., 2022).

Floating PV potential

The FPV model identifies 763 suitable waterbodies across Bangladesh, revealing a substantial capacity potential of 5.7 GWp, as

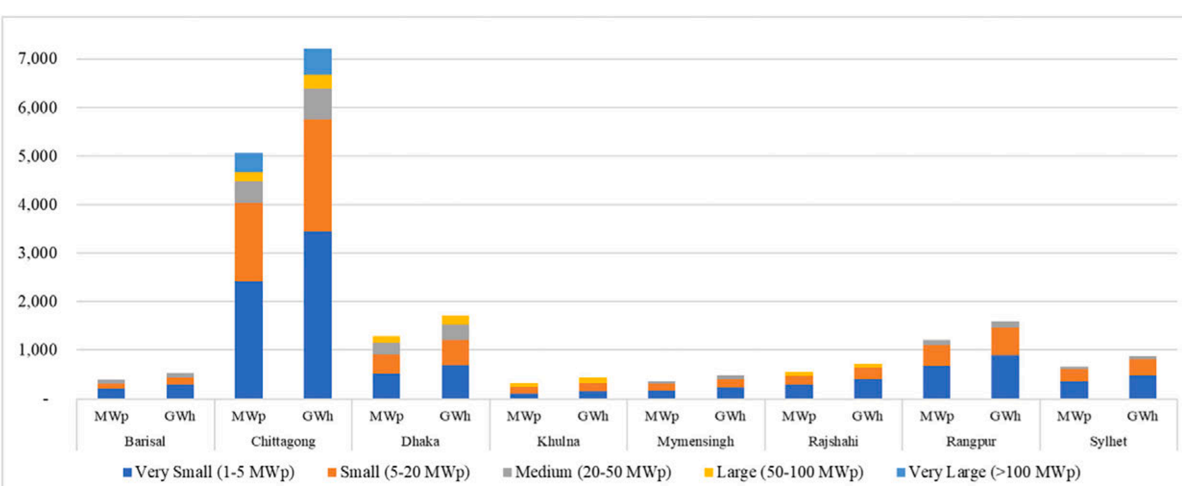


Fig. 10. Installed capacity (in MWp) and energy generation potential (in GWh) of GPV systems in 8 administrative divisions in Bangladesh. The aggregated potential is 9.8 GWp. The segmented bars represent capacity potential according to system category by size.

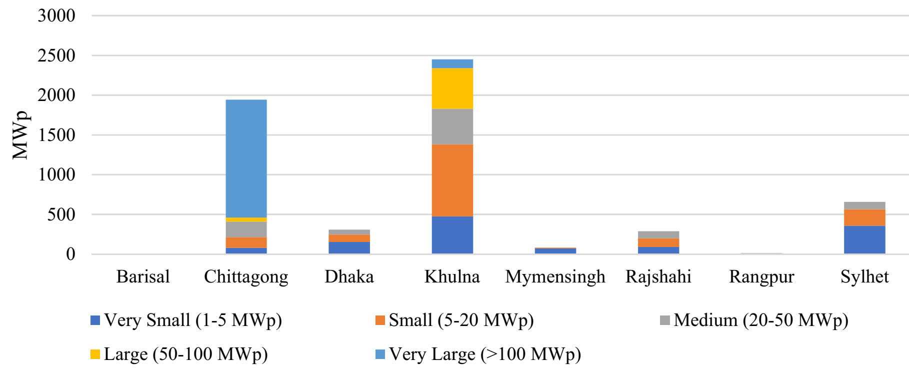


Fig. 11. FPV potential across 8 administrative divisions in Bangladesh according to system size category from very small (1 MWp) to very large (>100 MWp).

Table 11
APV potential, in MWp, in different APV-friendly crop zones across 8 administrative divisions in Bangladesh. Numbers show the potential in individual crop types, which cannot be summed for the whole country due to double-count error. Similar figures show that these zones are mutually suitable for both crops.

Suitable Zone (MWp)	Barisal	Chittagong	Dhaka	Khulna	Mymensingh	Rajshahi	Rangpur	Sylhet	Bangladesh
Potato	13,462	686	10,227	37,701	10,944	6445	14,046	–	93,511
Onion/Garlic	13,462	893	6863	43,178	8097	6292	48	–	78,832
Chili	13,462	893	8173	15	11,600	170	1	–	34,314
Lentil	14,074	649	6632	41,407	4712	16,306	5105	–	88,885
Gram	14,641	1327	16,670	44,721	9268	8591	5320	–	100,539
Mustard	16,223	6987	13,269	37,431	13,128	22,245	33,138	602	143,022
Ground nut	6914	5382	3805	17,932	2186	700	30,300	602	67,820

shown in Fig. 11. Notably, Khulna and Chittagong divisions emerge as key hubs, hosting 2.4 GW and 1.9 GW of capacity, respectively. The largest site, boasting a significant 1.4 GW installation potential, is located in Kaptai Lake in the Chittagong division. Conversely, Barisal, Rangpur, and Mymensingh exhibit minimal potential. Contrary to our result, the International Finance Corporation (IFC) estimates about 11 GWp potential of FPV in Bangladesh, which is almost twice what we identified (TBS Report 10/31/, 2023). However, the difference may be explained by comparing the data and methodology of the IFC study, which was not publicly available during this research.

Agri PV potential on agricultural lands

Our model identifies 1.4 million hectares across 93 thousand sites of agricultural land throughout the country for further exploration regarding APV applications. Subsequently, we refined these sites using crop zone information, emphasising the identification of lands with high potential for APV installations based on suitable crops outlined in the existing literature.

The Bangladesh Agricultural Research Council offers data on 15 crop zones categorised as suitable, moderately suitable, less suitable, or unsuitable at the upazila level. For APV applications, we specifically consider zones conducive to cultivating crops such as potato, onion/garlic, chili, lentil, gram, mustard, and groundnut. Table 11 details the APV potential in MWp for each of these individual zones, while Table 12 presents the capacity potential in areas mutually suitable and moderately suitable across the country.

In Bangladesh, crops often face challenges associated with drought, leading to significant production reductions in various regions (Alamgir et al., 2019; Aziz et al., 2022). Drawing on insights from Fraunhofer ISE (2022); Barron-Gafford et al. (2019), APV systems are recognised for safeguarding crops from hail, frost, and drought. Leveraging this advantage, we utilise BARC drought maps to pinpoint areas with severe and very severe drought occurrences during the Rabi (October–March), pre-kharif (March–July), and kharif (July–October) crop seasons. The potential in these identified areas is summarised in Table 13. The highest potential is observed in the Rajshahi division, known for its pronounced susceptibility to drought, followed closely by the Rangpur division.

Agri PV potential on seasonally inundated lands

Similarly to the APV results, our model pinpoints 0.42 million hectares of lands suitable for APV-SIL that are prone to seasonal inundation. A significant portion (31 %) of these areas is concentrated in the Sylhet division, locally known as Haor (seasonal wetland). Additionally, low-lying areas surrounding river basins in all other divisions contribute to the remainder. Notably, nearly half (44 %) of the identified areas are categorised as suitable or moderately suitable for Boro rice crops, which we deliberately excluded from consideration for APV-SIL applications. Though Sojib Ahmed et al. (2022) claim that rice fields can also be highly beneficial for APV applications, considering the local climate. However, this needs further research with pilot projects. Nevertheless, our analysis reveals a substantial potential of 18.83 GW for APV systems in the remaining areas, as shown in Table 14.

Table 12
APV potential in mutually suitable crop zones, mentioned in Table 11, in MWp. Categorised according to system size category for APV.

MWp	Barisal	Chittagong	Dhaka	Khulna	Mymensingh	Rajshahi	Rangpur	Sylhet	Bangladesh
Very small (0.1–1 MWp)	2953	144	663	1766	1442	517	863	–	8347
Small (1-5MWp)	4954	197	1107	3968	2189	985	1623	–	15,023
Medium (5-15MWp)	3033	281	1140	5340	1182	892	1546	–	13,415
Large (15–50 MWp)	1177	63	671	5678	228	574	521	–	8914
Very Large (>50)	259	–	1255	13,348	154	919	553	–	16,489
Total	12,376	686	4835	30,100	5195	3888	5106	–	62,188

Table 13
APV Potential in drought-prone areas, in MWp. Figures are based on two drought classes: very severe and severe.

Drought prone Area (MWp)	Barisal	Chittagong	Dhaka	Khulna	Mymensingh	Rajshahi	Rangpur	Sylhet	Bangladesh
Very small (0.1–1 MWp)	–	–	–	14	–	1010	86	–	1110
Small (1-5MWp)	–	–	–	6	–	2245	269	–	2520
Medium (5-15MWp)	–	–	–	–	–	2983	372	–	3355
Large (15–50 MWp)	–	–	–	–	–	2466	314	–	2780
Very Large (>50)	–	–	–	–	–	8450	299	–	8749
Total	–	–	–	20	–	17,154	1340	–	18,514

Table 14
Potential (MWp) for APV-SIL in areas where Boro Rice Paddy is less and not suitable.

MWp	Barisal	Chittagong	Dhaka	Khulna	Mymensingh	Rajshahi	Rangpur	Sylhet	Bangladesh
Very small (0.1–1 MWp)	30	24	98	318	50	193	279	379	1571
Small (1-5MWp)	97	527	280	840	122	450	776	1235	4327
Medium (5-15MWp)	6	252	125	728	131	290	920	1248	3701
Large (15–50 MWp)	19	190	432	755	159	284	646	1484	3968
Very Large (>50)		424	256	1362	122	999	251	1853	5268
Total	152	1617	1191	4003	585	2216	2872	6198	18,834

Discussion

The results section above presented our findings categorised according to different system types. As depicted in the results, by disaggregating the overall potential based on installation practices, we have identified a significant potential for solar PV development in Bangladesh. This potential aligns with the country's ambitious solar PV capacity target towards achieving net-zero emissions, despite the constraints posed by land availability. However, effective planning and implementation of this identified potential necessitate consideration of various factors, including land use dynamics, energy generation costs, and proximity to grid infrastructure. These factors carry significant importance in the process of diversification and deployment of solar PV systems. In this section, we further elaborate on our analysis of these critical aspects to provide essential insights required for the diversification prioritisation of PV systems. This discussion can also be considered for developing a realistic implementation pathway.

Implication of land cover and land use change in PV potential

According to our results, RPV systems emerge as the most promising avenue in Bangladesh, constituting 66 % of the total potential, excluding APVs (see Fig. 12). This potential is distributed significantly across all administrative divisions. Moreover, the RPV potential is anticipated to grow with the country's increasing population and expanding economy. A case study in the Mymensingh division by Seyam et al. (2023) reveals significant land use change over the past 20 years, identifying more than three times higher built-up areas in 2022 compared to 2002. Similarly, historical and forecasted data provided by Pesaresi (2022) and Schiavina et al. (2022) demonstrate a significant increase in Bangladesh's built-up area since 1975, as depicted in Fig. 13. This data reveals that the built-up surface has doubled over the past two decades, indicating a higher level of urbanisation and infrastructure development, which has resulted in an increase in available rooftop areas.

Contrastingly, after setting strict criteria for GPV, which excludes agricultural lands, we identify lands suitable for typical GPV systems that are mainly located along the river or on char areas, which are the results of the dynamic characteristics of rivers in Bangladesh. However, these areas are geologically challenging for developing PV plants, resulting in higher investment costs. On the other hand, as the population increases, the PV potential on the ground may decrease over time due to higher demand for land for various purposes. Given the rapid change in land use patterns in Bangladesh, finding suitable land for GPV systems might become exceptionally challenging in the future. Some news agencies (Md. Tamid, 2022; Syful Islam 5/21/, 2021) have also reported on land availability issues for solar PV development in Bangladesh and its impact on PV system development costs. In Section 2.1, we outlined the pre-development land cover status of 10 utility-scale PV power plants in Bangladesh, uncovering a significant utilisation of cropland for these installations. This situation reveals that avoiding agricultural land to develop a sizeable PV plant is challenging.

Considering the dynamic interplay between population and economic growth shaping land cover and land use, conventional GPV systems may face reduced economic viability due to the single use of land and social issues like land affordability in proximity to villages. Therefore, Bangladesh should consider prioritising the development of the

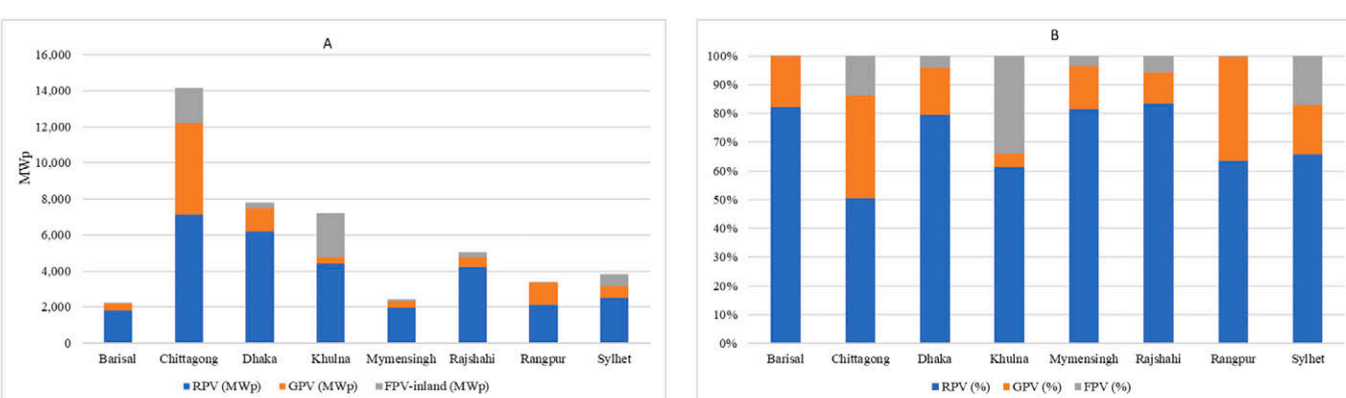


Fig. 12. Capacity potential (fig. A: in MWp and figure: B in % of capacity by system type) for RPV, GPV, and FPV systems in all the divisions.

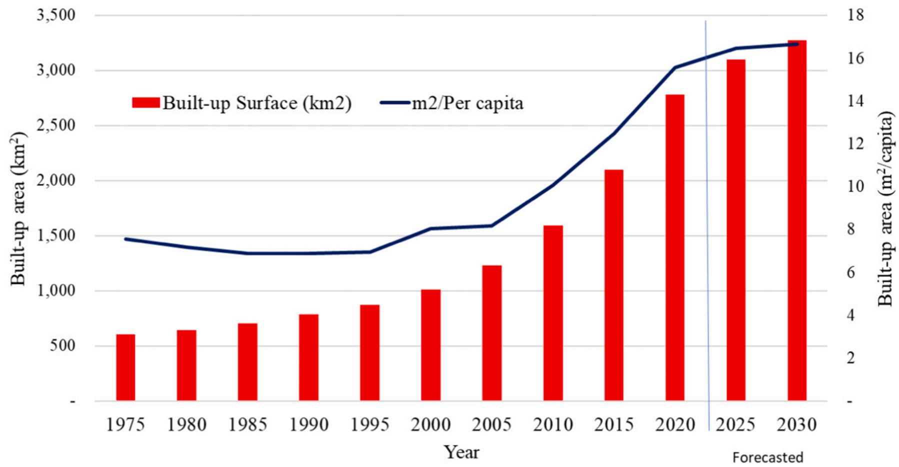


Fig. 13. The trend of built-up surface growth in Bangladesh. The red bar shows the built-up area in km^2, and the line shows the built-up area per capita. The values for 2025 and 2030 are forecasted. Data source: (Pesaresi, 2022).

RPV market and other PV systems that offer dual use of land and water surfaces, such as APVs and FPVs.

Implication for PV system development prioritisation

Prioritisation by energy generation cost

Collecting cost data from several sources, we produced average LCOE for energy generation from different PV systems according to their capacity categories.

As depicted in the charts in Fig. 14, RPV systems exhibit significant potential to offer the most cost-effective energy compared to other systems. The lower cost can be explained by the absence of the land cost or the lower lease cost of the roof. Estimated energy generation costs of RPV systems are notably lower than the retail electricity prices for commercial, industrial, and some residential consumers in Bangladesh, offering financial benefits. Furthermore, the LCOE for RPV may experience further reductions with increased adoption across various sectors, including residential, commercial, industrial, social, and governmental. However, a critical review of existing policies is imperative to encourage a broader spectrum of investors (Hasan, 2022).

In contrast, the energy generation cost for typical GPV systems is considerably higher in the country, and it is expected to rise further due to the scarcity of suitable land. On the other hand, as FPVs and APVs gain prominence globally, their costs are anticipated to decrease with the scale of implementation and ongoing innovation. However, assessing FPV and APV with LCOE is inappropriate and challenging as it fails to account for the secondary benefits of these systems.

For GPV, FPV, and APV systems, the final investment costs heavily rely on land acquisition and grid interconnection costs, which are contingent on the distance to the nearest feasible feeding point. According to the Asian Development Bank's FPV feasibility study reports (ADB, 2020a, 2020b, 2021), the grid interconnection cost for connecting a 5 MWac PV plant (including the transformer with PV inverter) to a 33 kV substation at a distance of 12 km is approximately 1.4 million USD, contributing to an increase in the project cost by over 17 %. Considering the higher costs associated with connecting PV plants, prioritising the realisation of RPV systems is essential for development. Additionally, GPV, FPV, and APV sites closer to existing grid infrastructure should be prioritised.

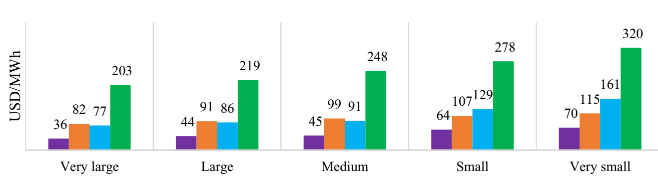


Fig. 14. LCOE of different systems based on their capacity categories. LCOEs were calculated using the Capital Recovery Factor (CRF) based equation, which considers a 6 % discount rate for RPV systems and 8 % for other systems.

Prioritisation within system types

Rooftop PV systems

Fig. 15 presents the distribution of RPV systems based on settlement typology. The data indicates that approximately 95 % (or 29 GWp) of the potential is concentrated in urban domains, notably the urban centre area (13.5 GWp). The capacity potential in the urban centre alone can significantly contribute to achieving the target. Urban centres in Bangladesh also have better electricity infrastructure and higher energy demand compared to rural areas, creating a favourable situation for realising RPV potential. Therefore, to prioritise RPV development, systems in urban centres can be given higher priority by implementing favourable policies.

Encouraging the development of larger RPV systems in public areas like rail stations, ferry terminals, academic buildings, and commercial and industrial rooftops can significantly lower costs. RPV systems also hold promise in meeting additional energy demand generated by Bangladesh's 2 million electric three-wheelers. Research by (Hasan, 2020) suggests that integrating local solar PV systems, especially RPV, with charging stations for electric three-wheelers could be beneficial. However, policy considerations are crucial for implementation.

The Bangladesh Government introduced a Net-metering policy in 2018. Recently, the government imposed solar PV system installation under the Net-metering policy as a prerequisite to obtaining a grid connection in new buildings with roofs larger than 92 m^2 (Islam, 2023). However, Hasan (2022) argues that the current net-metering policy is unable to attract a broader spectrum of investors from residential and commercial sectors due to single-phase connection limitations and roof ownership issues in Bangladesh. The same author proposes virtual net-metering (VNM) as one of the solutions to these issues. As noted by Hasan (2022) "VNM allows remote energy generation and virtual consumption via the grid to receive credits in electricity bills." The author also mentioned that VNM enables electricity to be generated in 3-phase on any rooftop or space and consumed virtually using 1-phase utility connections anywhere, with electricity wheeling charges paid to the utility. A variant of the VNM policy, known as Tenant Electricity, introduced in Europe, permits building owners to install PV on rooftops and sell the generated electricity to their tenants (Moser et al., 2021). Introducing a similar policy in Bangladesh could utilise RPV potential

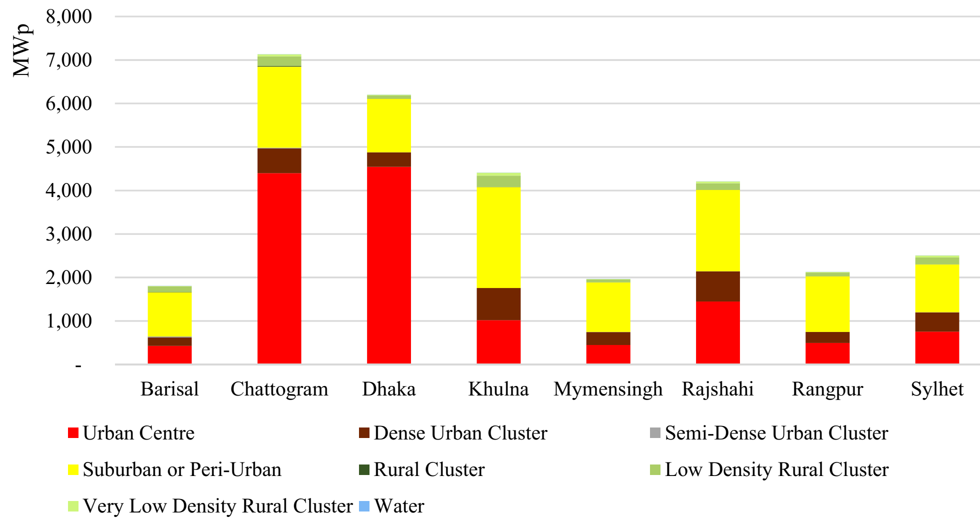


Fig. 15. Installed capacity potential by settlement typology. The source (Schiavina et al., 2022) provides the details of the typology. The colour of this graph follows the colour scheme of classification.

and address ownership issues, enhancing the net-metering system's effectiveness.

GPV, FPV, APV systems

Given that the cost of investing in grid lines significantly amplifies the cost of energy generation, prioritising identified sites for GPV, FPV, and APV systems based solely on their proximity to grid substations could be advantageous. As illustrated in Table 15, a small fraction of the technical potential is located very close to the vicinity of grid substations. However, a substantial capacity potential is also situated within a 5 km radius of the grid substation. Within this proximity, GPV potential alone offers >1 GWp, exceeding the current installed capacity. Therefore, prioritising this capacity for fast-track implementation through individual site feasibility studies is recommended. Similarly, if the true benefits of FPV and APV systems are realised, these systems can be employed to meet renewable energy targets. However, to achieve the target for 2050, it may be necessary to extend the grid to connect all potential GPV, FPV, and APV sites. However, realising RPV potential can be an alternative to grid extension to remote areas for connecting sites. Furthermore, to promote the optimal use of valuable land in Bangladesh, we highly recommend considering the dual use of land as a priority.

Limitations and outlook of the study

Limitations

Our research utilised state-of-the-art spatial and non-spatial datasets that are available openly, with OpenStreetMap's building footprint data serving as the primary source for estimating RPV potential. However, it's important to acknowledge limitations such as potential human errors in drawing building footprints and the absence of building typology, age, and use data, which could affect the accuracy of our results. Furthermore, incorporating high-resolution DSM or LiDAR data could have improved the accuracy of our RPV model by simulating shadow effects more precisely. To reduce the level of complexity, we also kept local substation capacity out of scope.

Although the bathymetry data we used is state-of-the-art, it is not up to date. Using up-to-date onshore water body bathymetry data could have provided valuable insights into the feasibility of FPV systems.

Due to time and scope constraints, we could not gather crop yield information necessary for estimating the LER for APV systems, limiting our understanding of their potential integration with agricultural practices.

Acknowledging these limitations, future research could explore these aspects further to refine solar PV potential assessments and contribute to more informed decision-making in renewable energy planning.

Outlook

Bangladesh's current electricity demand profile exhibits a peak in the evening, presenting a significant challenge for realising the identified potential of solar energy. While the projected demand profile for the net-zero scenario anticipates a daytime peak due to expected economic transitions, it's crucial to estimate the extent to which the identified potential can be actualised while considering future demand trends and grid capacity. This estimation is essential to prevent situations like the duck curve. Therefore, a comprehensive analysis of future demand patterns, grid line and substation capacity, and the integration of renewable energy sources is necessary to ensure a stable and sustainable energy transition in Bangladesh.

Conclusion

In support of Bangladesh's sustainable energy transition plan and its ambition to achieve net-zero emissions, our research focused on reassessing the potential of solar PV energy. This reassessment specifically aimed to address the diversification of PV systems and the constraints posed by land availability.

By utilising high-resolution data and a spatial overlay model within a GIS framework, we have identified substantial geographic and technical potential for various PV systems, including RPV, GPV, FPV, and APV systems. Our estimates indicate that Bangladesh has the potential to achieve 30 GWp of RPV, 9 GWp of GPV, 81 GWp of APV, and 5 GWp of FPV, requiring approximately 1600 km^2, or 1.08 % of the total land area. Compared to previous studies, our results show a significantly higher potential. For instance, Chowdhury (2020) proposed a total capacity of 12 GWp for mixed solar power hubs on government-owned lands, while

Table 15
PV system capacities by grid proximity category. The values in the table are in MWp.

Grid Proximity	Very Close (<1 km)	Close (1–5 km)	Far (5–15 km)	Very Far (>15 km)
GPV	28	1157	2129	6524
FPV	–	90	1649	4214
APV	365	4284	28,528	29,046
APV SIL	129	2434	8749	7523
Total	521	7929	41,054	47,306

Shiraishi et al. (2019) estimated 5.3–84 GWp for GPV systems, including 1–10 % of cropland, and 0.2–2 GWp for RPV using 1–10 % of urban areas. Mondal and Islam (2011) estimated a total potential of 50 GWp, assuming 1.7 % of the total land area for unspecified PV systems. Unlike previous studies, our system-specific potential assessment delineates boundaries between land uses, providing an alternative approach to addressing land use conflicts in the country. Therefore, our research not only aligns with but also extends beyond these previous estimates, providing a more detailed and diversified strategy for PV system implementation.

Furthermore, our study uses design parameters by thoroughly assessing the existing design practices, which is a unique approach compared to other previous studies. Analysing land cover and water occurrence data, we proposed a new variant of APV systems, such as APV SIL, for low-lying geography. This system concept adds new knowledge to the solar PV system domain.

In our discussion, we underscored the implementation perspectives of the identified geographic and technical potential by focusing on energy generation costs and access to grid infrastructure. Our cost estimation indicated RPV as the most economical option compared to other systems, emphasising its preference for implementation amid Bangladesh's changing land use. Furthermore, we demonstrated how implementation can be prioritised by using settlement model data and grid substation locations.

We presented results at the divisional level for informed decision-making towards developing a distributed energy system with diverse PV systems. Our research serves as a Solar PV atlas for Bangladesh, guiding policymakers, practitioners, and project developers. Despite conservative assumptions, we identify substantial solar PV potential. The estimated RPV potential of 30 GW alone could facilitate the target of 28 GWp of Solar PV by 2050. Hence, we anticipate our study will bolster confidence among Bangladeshi policymakers in achieving renewable energy targets and dispelling the land scarcity myth towards net-zero scenario.

Finally, assessing five types of traditional and emerging PV systems in one study represents a unique contribution to the literature.

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Declaration of generative AI in scientific writing

During the preparation of this work the authors used generative AI tools, Grammarly and ChatGPT language assistance, in order to improve readability and clarity. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

A.S.M. Mominul Hasan: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Prin Kesapabutr:** Writing – original draft, Visualization, Methodology, Investigation, Data curation. **Bernd Möller:** Writing – review & editing, Visualization, Validation, Supervision, Software, Methodology, Investigation, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Input data and simulation output will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esd.2024.101511.

References

ADB. (2020a). *Floating PV Candidate Site Report: Bukbhara Baor, Bangladesh*. File number Rev 03..pdf.

ADB. (2020b). *Floating PV Candidate Site Report: Joydia Baor, Bangladesh*. File number Rev 03..pdf.

ADB. (2021). *Floating PV Candidate Site Report: Barapukuria Lakes, Bangladesh*. File number Rev 01..pdf.

Alam, Majbaul, & Bhattacharyya, Subhes (2017). Are the off-grid customers ready to pay for electricity from the decentralized renewable hybrid mini-grids? A study of willingness to pay in rural Bangladesh. *In Energy, 139*, 433–446. https://doi.org/10.1016/j.energy.2017.07.125

Alamgir, Mahiuddin, Mohsenipour, Morteza, Homsi, Rajab, Wang, Xiaojun, Shahid, Shamsuddin, Shiru, Mohammed, et al. (2019). Parametric Assessment of Seasonal Drought Risk to Crop Production in Bangladesh. *In Sustainability, 11*(5), 1442. https://doi.org/10.3390/su11051442

Anas, Rahman, Akash, Sharma, Florian, Postel, Siddharth, Goel, Kritika, Kumar, & Tara, Laan (2023). *Agrivoltaics in India: Challenges and opportunities for scale-up*. International Institute for Sustainable Development, IISD. Available online at https://www.iisd.org/publications/report/agrivoltaics-in-india. checked on 5/26/2023.

Asare-Addo, Mary (2022). Optimal techno-economic potential and site evaluation for solar PV and CSP systems in Ghana. A geospatial AHP multi-criteria approach. *In Renewable Energy Focus, 41*(4), 216–229. https://doi.org/10.1016/j.ref.2022.03.007

Aziz, Md. Abdullah, Hossain, A. B. M. Zahid, Moniruzzaman, Md, Ahmed, Rokib, Zahan, Taslima, Azim, Saiful, et al. (2022). Mapping of Agricultural Drought in Bangladesh using Geographic Information System (GIS). *In Earth Syst Environ, 6*(3), 657–667. https://doi.org/10.1007/s41748-021-00231-8

Bao, Keyu, Kalisch, Louis, Santhanavanich, Thunyathep, Thrän, Daniela, & Schröter, Bastian (2022). A bottom-up GIS-based method for simulation of ground-mounted PV potentials at regional scale. *In Energy Reports, 8*, 5053–5066. https://doi.org/10.1016/j.egyr.2022.03.187

BARC. (2022). *Database I Bangladesh Agricultural Research Council*. Bangladesh Agricultural Research Council (BARC). Available online at https://barc.gov.bd. updated on 10/7/2023, checked on 10/7/2023.

Barron-Gafford, Greg A., Pavao-Zuckerman, Mitchell A., Minor, Rebecca L., Sutter, Leland F., Barnett-Moreno, Isaiah, Blackett, Daniel T., et al. (2019). Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands. *In Nat Sustain, 2*(9), 848–855. https://doi.org/10.1038/s41893-019-0364-5

Benalcazar, Pablo, Komorowska, Aleksandra, & Kamiński, Jacek (2024). A GIS-based method for assessing the economics of utility-scale photovoltaic systems. *In Applied Energy, 353*, Article 122044. https://doi.org/10.1016/j.apenergy.2023.122044

Bódis, Katalin, Kougias, Ioannis, Jäger-Waldau, Arnulf, Taylor, Nigel, & Szabó, Sándor (2019). A high-resolution geospatial assessment of the rooftop solar photovoltaic potential in the European Union. *In Renewable and Sustainable Energy Reviews, 114*, Article 109309. https://doi.org/10.1016/j.rser.2019.109309

BPDB. (2024). *Annual Report 2022–2023*. Available online at: Bangladesh Power Development Board. https://www.bpdb.gov.bd.

Buchhorn, Marcel, Smets, Bruno, Bertels, Luc, De Roo, Bert, Lesiv, Myroslava, Tsendbazar, Nandin-Erdene, et al. (2020). *Copernicus Global Land Service: Land Cover 100m: Version 3 Globe 2015–2019: Product User Manual*.

Bunting, Pete, Rosenqvist, Ake, Hilarides, Lammert, Lucas, Richard M., Thomas, Nathan, Tadono, Takeo, et al. (2022). Global mangrove extent change 1996–2020: Global mangrove watch version 3.0. *Remote Sensing, 14*(15), 3657. https://doi.org/10.3390/rs14153657

Chowdhury, Shahriar Ahmed (2020). *National Solar Energy Roadmap, 2021–2041*. Dhaka: Sustainable and Renewable Energy Authortiy SREDA. Available online at http://www.sreda.gov.bd/sites/default/files/files/sreda.portal.gov.bd/notices/fba98896_568a_4efd_a48b_8d92bfc04049/2020-10-22-17-12-7b0e5a0c0dabd4c17492bcf3bd7488b4.pdf. checked on 1/15/2021.

Datta, Ujjwal, Kalam, Akhtar, & Shi, Juan (2020). The economic prospect of rooftop photovoltaic (PV) system in the commercial buildings in Bangladesh: A case study. *In*

Clean Techn Environ Policy, 22(10), 2129–2143. https://doi.org/10.1007/s10098-020-01963-3

Debnath, Kumar Biswajit, & Mourshed, Monjur (2024). Although feasible, falling renewables costs might not benefit Bangladesh's energy sector's decarbonisation: Is this another 'debt-fossil fuel production trap'? *In Energy for Sustainable Development, 79*, Article 101416. https://doi.org/10.1016/j.esd.2024.101416

Dewan, Ashraf, Shahid, Shamsuddin, Bhuian, Md Hanif, Hossain, Shaikh M. Jobayed, Nashwan, Mohamed Salem, Chung, Eun-Sung, et al. (2022). Developing a high-resolution gridded rainfall product for Bangladesh during 1901-2018. *Scientific Data, 9*(1), 471. https://doi.org/10.1038/s41597-022-01568-z

EPSG.io. (2021). *WGS 84 / TM 90 NE - EPSG:9680*. Klokan Technologies GmbH. Available online at https://epsg.io/9680. updated on 9/1/2024, checked on 10/1/2024.

ESMAP. (2021). *Global Report: ASSESSMENT OF TECHNICAL ROOFTOP SOLAR ENERGY POTENTIAL IN SELECT CITIES. Energy Sector Management Assistance Program (ESMAP)*.

Esri. (2023). *World imagery wayback*. Esri. Available online at https://livingatlas.arcgis.com/wayback/#active=64776&mapCenter=91.25238%2C24.09561%2C7. checked on 12/12/2023.

Finance Division. (2023). *Bangladesh economic review 2023*. Finance Division, Ministry of Finance, Government of the People's Republic of Bangladesh. Available online at https://mof.portal.gov.bd/site/page/28ba57f5-59ff-4426-970a-bf014242179e/Bangladesh-Economic-Review-2023. checked on 7/1/2023.

Fraunhofer ISE. (2022). Agrivoltaics: Opportunities for agriculture and the energy transition. Available online at https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/APV-Guideline.pdf. checked on 5/3/2023.

Fraunhofer ISE. (2023). *Photovltaic report*. Fraunhofer ISE. Available online at https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf. checked on 9/7/2023.

Gagnon, Pieter, Margolis, Robert, Melius, Jennifer, Phillips, Caleb, & Elmore, Ryan (2018). Estimating rooftop solar technical potential across the US using a combination of GIS-based methods, lidar data, and statistical modeling. *In Environ. Res. Lett., 13*(2), 24027. https://doi.org/10.1088/1748-9326/aaa554

GHSL-Global Human Settlement Layer. (2018). Country fact sheets based on the degree of urbanisation: Bangladesh. In *Testing the Degree of Urbanisation at the global level*. European Commission. Available online at https://ghsl.jrc.ec.europa.eu/CFS.php. checked on 3/25/2023.

GlobalMLBuildingFootprints. (2023). GlobalMLBuildingFootprints. Available online at https://github.com/microsoft/GlobalMLBuildingFootprints#will-there-be-more-data-coming-for-other-geographies. checked on 6/10/2023.

Haas, J., Khalighi, J., de La Fuente, A., Gerbersdorf, S. U., Nowak, W., & Chen, Po-Jung (2020). Floating photovoltaic plants: Ecological impacts versus hydropower operation flexibility. *In Energy Conversion and Management, 206*, Article 112414. https://doi.org/10.1016/j.enconman.2019.112414

Halder, P. K., Paul, N., Joardder, M. U. H., & Sarker, M. (2015). Energy scarcity and potential of renewable energy in Bangladesh. *In Renewable and Sustainable Energy Reviews, 51*, 1636–1649. https://doi.org/10.1016/j.rser.2015.07.069

Hasan, A. S. M. Mominul (2022): Virtual net-metering option for Bangladesh: An opportunity for another solar boom like solar home system program. In *Energies* 15 (13), p. 4616. DOI: https://doi.org/10.3390/en15134616.

Hasan, A. S. M. Mominul (2020). Electric Rickshaw charging stations as distributed energy storages for integrating intermittent renewable energy sources: A case of Bangladesh. *In Energies, 13*(22), 6119. https://doi.org/10.3390/en13226119

Hossain, Murad (2023). *PV system category by capacity and their installation and maintenance cost to Solshare Ltd.*, 7/5/2023.

Hossain, Shah Mohazzem, Biswas, Sagor, & Raihan Uddin, Md (2023). Sustainable energy transition in Bangladesh: Challenges and pathways for the future. *Engineering Reports, 6*(1), Article e12752. https://doi.org/10.1002/eng2.12752

IEA. (2024). *Energy statistics data browser*. International Energy Agency. Available online at https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser. checked on 4/1/2024.

IRENA. (2023). *Statistical profiles*. International Renewable Energy Agency (IRENA). Available online at https://www.irena.org/Data/Energy-Profiles. checked on 3/2/2023.

Isihak, Salisu, Akpan, Uduak, & Bhattacharyya, Subhes (2022). Evolution of GIS-based rural electrification planning models and an application of OnSSET in Nigeria. *In Renewable and Sustainable Energy Transition, 2*, Article 100019. https://doi.org/10.1016/j.rset.2022.100019

Islam, Md Rabiul, Islam, Md Rakibul, & Imran, Hosen M. (2022). Assessing wind farm site suitability in Bangladesh: A GIS-AHP approach. *In Sustainability, 14*(22), 14819. https://doi.org/10.3390/su142214819

Islam, Md. Rabiul, Aziz, Md. Tareq, Alauddin, Mohammed, Kader, Zarjes, & Islam, Md. Rakibul (2024). Site suitability assessment for solar power plants in Bangladesh: A GIS-based analytical hierarchy process (AHP) and multi-criteria decision analysis (MCDA) approach. *In Renewable Energy, 220*, Article 119595. https://doi.org/10.1016/j.renene.2023.119595

Islam, Syful (2023). *Bangladesh introduces rooftop PV requirement for big, new buildings*. PV Magazine. Available online at https://www.pv-magazine.com/2023/10/12/bangladesh-introduces-rooftop-pv-requirement-for-big-buildings/. updated on 12/10/2024, checked on 10/15/2024.

Joshi, Siddharth, Mittal, Shivika, Holloway, Paul, Shukla, Priyadarshi Ramprasad, Ó Gallachóir, Brian, & Glynn, James (2021). High resolution global spatiotemporal assessment of rooftop solar photovoltaics potential for renewable electricity generation. *In Nature Communications, 12*(1), 5738. https://doi.org/10.1038/s41467-021-25720-2

Kelsey, Horowitz, Vignesh, Ramasamy, Jordan, Macknick, & Robert, Margolis (2020). *Capital costs for dual-use photovoltaic installations: 2020 benchmark for ground-mounted PV systems with pollinator-friendly vegetation, grazing, and crops*. National Renewable Energy Laboratory (NREL) (NREL/TP-6A20–77811). Available online at https://www.nrel.gov/docs/fy21osti/77811.pdf.

Khazaei, Bahram, Read, Laura K., Casali, Matthew, Sampson, Kevin M., & Yates, David N. (2022). GLOBathy, the global lakes bathymetry dataset. *In Scientific Data, 9*(1), 36. https://doi.org/10.1038/s41597-022-01132-9

Kim, S.-M., Oh, M., & Park, H.-D. (2019). *Analysis and prioritization of the floating photovoltaic system potential for reservoirs in Korea, Article 395*. Available online at. https://doi.org/10.3390/app9030395.

Kirchhoff, Hannes, & Strunz, Kai (2024). Peer-to-peer microgrids for 100% renewable swarm electrification: scalable, sustainable, self-serviceable, safe, and stable design. *In IEEE J. Emerg. Sel. Top. Ind. Electron., 5*(2), 318–335. https://doi.org/10.1109/JESTIE.2024.3363667

Laub, Moritz, Pataczek, Lisa, Feuerbacher, Arndt, Zikeli, Sabine, & Högy, Petra (2022). Contrasting yield responses at varying levels of shade suggest different suitability of crops for dual land-use systems: A meta-analysis. *In Agron. Sustain. Dev., 42*(3). https://doi.org/10.1007/s13593-022-00783-7

Magazine, Pv (2023). *Bangladesh*. PV Magazine. Available online at https://www.pv-magazine.com/region/bangladesh/. updated on 07/20/2023, checked on 07/20/2023.

Md. Tamid Zami (8/24/2022): In Bangladesh, solar power brings work, but land shortage slows growth. Reuters. Available online at https://www.reuters.com/business/sustainable-business/bangladesh-solar-power-brings-work-land-shortage-slows-growth-2022-08-24/, checked on 3/22/2023.

Mentis, Dimitris, Siyal, Shahid Hussain, Korkovelos, Alexandros, & Howells, Mark (2017). Estimating the spatially explicit wind generated electricity cost in Africa - A GIS based analysis. *In Energy Strategy Reviews, 17*, 45–49. https://doi.org/10.1016/j.esr.2017.07.002

Mondal, Md. Alam Hossain, & Denich, Manfred (2010). Assessment of renewable energy resources potential for electricity generation in Bangladesh. *In Renewable and Sustainable Energy Reviews, 14*(8), 2401–2413. https://doi.org/10.1016/j.rser.2010.05.006

Mondal, Md. Alam Hossain, & Islam, A. K. M. Sadrul (2011). Potential and viability of grid-connected solar PV system in Bangladesh. *In Renewable Energy, 36*(6), 1869–1874. https://doi.org/10.1016/j.renene.2010.11.033

Moser, Raphael, Xia-Bauer, Chun, Thema, Johannes, & Vondung, Florin (2021). Solar prosumers in the German energy transition: A multi-level perspective analysis of the German 'Mieterstrom' model. *In Energies, 14*(4), 1188. https://doi.org/10.3390/en14041188

MPEMR. (2023). *Integrated Energy and Power Master Plan (IEPMP) 2023*. With assistance of Japan International Cooperation Agency (JICA), the Institute of Energy Economics, Japan (IEEJ). Government of the People's Republic of Bangladesh. Dhaka, Bangladesh. Available online at https://powerdivision.portal.gov.bd/sites/default/files/files/powerdivision.portal.gov.bd/npfblock/IEPMP_Report_2023.pdf. checked on 1/1/2024.

Nandi, Sanjoy Kumar, Hoque, Mohammad Nasirul, Ghosh, Himangshu Ranjan, & Chowdhury, Riku (2013). Assessment of wind and solar energy resources in Bangladesh. *In Arab J Sci Eng, 38*(11), 3113–3123. https://doi.org/10.1007/s13369-012-0429-5

Nasim, M., Shahidullah, S. M., Saha, A., Muttaleb, M. A., Aditya, T. L., Ali, M. A., & Kabir, M. S. (2017). Distribution of crops and cropping patterns in Bangladesh. *Bangladesh Rice Journal*. Available online at https://brri.portal.gov.bd/sites/default/files/files/brri.portal.gov.bd/page/9f8ef38c_8bd5_4bd3_a786_c064aed9bb76/Article_1_21_2.pdf. checked on 8/5/2023.

Nebey, Abraham Hizkiel, Taye, Biniyam Zemene, Workineh, Tewodros Gera, & Benghanem, Mohamed (2020). GIS-based irrigation dams potential assessment of floating solar PV system. *Journal of Energy, 2020*, Article 1268493. https://doi.org/10.1155/2020/1268493

NREL. (2024). Simple levelized cost of energy (LCOE) calculator documentation. Available online at https://www.nrel.gov/analysis/tech-lcoe-documentation.html. updated on 5/1/2024, checked on 5/1/2024.

OpenStreetMap (05/23/2023): OpenStreetMap. OpenStreetMap. Available online at https://www.openstreetmap.org/#map=7/23.785/92.538, updated on 05/23/2023, checked on 05/23/2023.

OpenStreetMap Contributors. (2023a). OSM data: Building footprint-Bangladesh. Available online at http://download.geofabrik.de/asia/bangladesh.html. checked on 6/9/2023.

OpenStreetMap Contributors. (2023b). OSM data: Military zone, major road, industrial, land use, major river, airport, railway, chimney, power plants, substation. Available online at https://overpass-turbo.eu/.

OpenTopography. (2016). *ALOS World 3D - 30m*.

Pekel, Jean-François, Cottam, Andrew, Gorelick, Noel, & Belward, Alan S. (2016). High-resolution mapping of global surface water and its long-term changes. *In Nature, 540* (7633), 418–422. https://doi.org/10.1038/nature20584

Pesaresi, Martino (2022). *GHS-BUILT-S R2022A - GHS built-up surface grid, derived from Sentinel2 composite and Landsat, multitemporal (1975–2030)*.

Peters, Jared L., Remmers, Tiny, Wheeler, Andrew J., Murphy, Jimmy, & Cummins, Valerie (2020). A systematic review and meta-analysis of GIS use to reveal trends in offshore wind energy research and offer insights on best practices. *In Renewable and Sustainable Energy Reviews, 128*, Article 109916. https://doi.org/10.1016/j.rser.2020.109916

PGCB. (2023). *Grid substation information*. Power Grid company of Bangladesh Ltd.. Available online at http://www.pgcb.gov.bd/site/download/174e55d2-2780-4d33-9d71-057c38647695/-. checked on 06/15/2023.

Pogson, Mark, & Smith, Pete (2015). Effect of spatial data resolution on uncertainty. *In Environmental Modelling & Software, 63*, 87–96. https://doi.org/10.1016/j.envsoft.2014.09.021

QGIS.org (12/30/2023): QGIS 3.28. Geographic information system developers manual. QGIS Association. Available online at https://www.qgis.org/en/site/forusers/visualchangelog328/index.html, updated on 12/30/2023, checked on 10/1/2024.

Ramachandra, T. V., & Shruthi, B. V. (2007). Spatial mapping of renewable energy potential. *In Renewable and Sustainable Energy Reviews, 11*(7), 1460–1480. https://doi.org/10.1016/j.rser.2005.12.002

Ramdas, Ashwin, Kelsey, A. W., Horowitz, & Ben, Sigrin (2019). *Quantifying the relationship between higher photovoltaic module efficiency and the adoption of distributed solar*. National Renewable Energy Laboratory (NREL) (NREL/CP-6A20–74008). Available online at https://www.nrel.gov/docs/fy19osti/74008.pdf. checked on 11/20/2023.

Raza, Muhammad Ali, Yousif, Muhammad, Hassan, Muhammad, Numan, Muhammad, Kazmi, Abbas, & Ali, Syed (2023). Site suitability for solar and wind energy in developing countries using combination of GIS- AHP; a case study of Pakistan. *In Renewable Energy, 206*, 180–191. https://doi.org/10.1016/j.renene.2023.02.010

Rekik, Sassi, & El Alimi, Souheil (2023). Optimal wind-solar site selection using a GIS-AHP based approach: A case of Tunisia. *In Energy Conversion and Management: X, 18*, Article 100355. https://doi.org/10.1016/j.ecmx.2023.100355

Ruiz, H. S., Sunarso, A., Ibrahim-Bathis, K., Murti, S. A., & Budiarto, I. (2020). GIS-AHP multi criteria decision analysis for the optimal location of solar energy plants at Indonesia. *In Energy Reports, 6*, 3249–3263. https://doi.org/10.1016/j.egyr.2020.11.198

Schiavina, M., Melchiorri, M., Pesaresi, M., Politis, P., Freire, S., Maffenini, L., et al. (2022). *GHSL data package 2022. Public release GHS P2022*. Luxembourg: Publications Office of the European Union.

Sebastian, Hermann, Asami, Miketa, & Nicolas, Fichaux (2014). *Estimating the renewable energy potential in Africa*. Abu Dhabi: International Renewable Energy Agency (IRENA).

Seyam, Md Mahadi Hasan, Haque, Md Rashedul, & Rahman, Md Mostafizur (2023). Identifying the land use land cover (LULC) changes using remote sensing and GIS approach: A case study at Bhaluka in Mymensingh, Bangladesh. *In Case Studies in Chemical and Environmental Engineering, 7*, Article 100293. https://doi.org/10.1016/j.cscee.2022.100293

Shiraishi, Kenji, Shirley, Rebekah G., & Kammen, Daniel M. (2019). Geospatial multi-criteria analysis for identifying high priority clean energy investment opportunities: A case study on land-use conflict in Bangladesh. *In Applied Energy, 235*, 1457–1467. https://doi.org/10.1016/j.apenergy.2018.10.123

Sojib Ahmed, M., Rezwan Khan, M., Haque, Anisul, & Ryyan Khan, M. (2022). Agrivoltaics analysis in a techno-economic framework: Understanding why agrivoltaics on rice will always be profitable. *In Applied Energy, 323*, Article 119560. https://doi.org/10.1016/j.apenergy.2022.119560

Solargis. (2023). Solar resource maps of Asia. In *Global horizontal irradiation*. Available online at https://solargis.com/maps-and-gis-data/download/asia. updated on 2023, checked on 03.20.2023.

SREDA. (2024). *National database of renewable energy, SREDA*. Dhaka, Bangladesh: Sustainable and Renewable Energy Development Authority (SREDA). Available online at http://www.renewableenergy.gov.bd/index.php?id=1&i=1. updated on 1/15/2024, checked on 1/15/2024.

Subrahmanyam, Pulipaka; Murali, Peparthy; Maximilian, Vorast (2023): Agrivoltaics in India. Overview on operational projects and relevant policies. National Solar Energy Federation of India (NSEFI). Delhi.

Sun, Yan-wei, Hof, Angela, Wang, Run, Liu, Jian, Lin, Yan-jie, & Yang, De-wei (2013). GIS-based approach for potential analysis of solar PV generation at the regional scale: A case study of Fujian Province. *In Energy Policy, 58*, 248–259. https://doi.org/10.1016/j.enpol.2013.03.002

Syful Islam (5/21/2021): Minister highlights Bangladesh's lack of land for solar. Dhaka, Bangladesh. pv magazine group GmbH & Co. KG. Available online at https://www.pv-magazine.com/2021/05/25/minister-highlights-bangladeshs-lack-of-land-for-solar/, checked on 1/12/2023.

TBS Report (10/31/2023): Floating solar plants can produce 11GWp power. Dhaka, Bangladesh. The Business Standard. Available online at https://www.tbsnews.net/bangladesh/energy/floating-solar-plants-can-produce-11gwp-power-729990, checked on 12/10/2023.

The World Bank. (2023). *World Bank open data*. The World Bank. Available online at https://data.worldbank.org/. checked on 7/1/2023.

UNEP-WCMC and IUCN (2023): Protected planet: The World Database on Protected Areas (WDPA) and World Database on Other Effective Area-based Conservation Measures (WD-OECM). Cambridge, UK: UNEP-WCMC and IUCN. Available online at https://www.protectedplanet.net/en.

University of Oregon. (2023). UO SRML: Sun path chart. Available online at https://solardata.uoregon.edu/SunPathChart.html. updated on 9/25/2023, checked on 9/26/2023.

Varriale, Vincenzo, Cammarano, Antonello, Michelino, Francesca, & Caputo, Mauro (2024). The role of digital technologies in production systems for achieving sustainable development goals. *In Sustainable Production and Consumption, 47*, 87–104. https://doi.org/10.1016/j.spc.2024.03.035

Willockx, Brecht, Lavaert, Cas, & Cappelle, Jan (2022). Geospatial assessment of elevated agrivoltaics on arable land in Europe to highlight the implications on design, land use and economic level. *In Energy Reports, 8*, 8736–8751. https://doi.org/10.1016/j.egyr.2022.06.076

Wu, Grace C., Deshmukh, Ranjit, Ndhlukula, Kudakwashe, Radojicic, Tijana, Reilly-Moman, Jessica, Phadke, Amol, et al. (2017). Strategic siting and regional grid interconnections key to low-carbon futures in African countries. *In Proceedings of the National Academy of Sciences of the United States of America, 114*(15), E3004–E3012. https://doi.org/10.1073/pnas.1611845114

Zanaga, Daniele, van de Kerchove, Ruben, Daems, Dirk, Keersmaecker, Wanda de, Brockmann, Carsten, Kirches, Grit, et al. (2022). *ESA WorldCover 10 m 2021 v200*.

Appendix A: Supplementary Materials

Bangladesh´s pathways to Net-Zero Transition: Reassessing country´s solar PV potential with high-resolution GIS data

ASM Mominul Hasan*, Prin Kesapabutr and Bernd Möller

The purpose of this supplementary material is to offer detailed methodological insights to readers and prospective researchers, aiding in the comprehension and replication of the models utilized in the study.

- List of Figures

- List of Tables

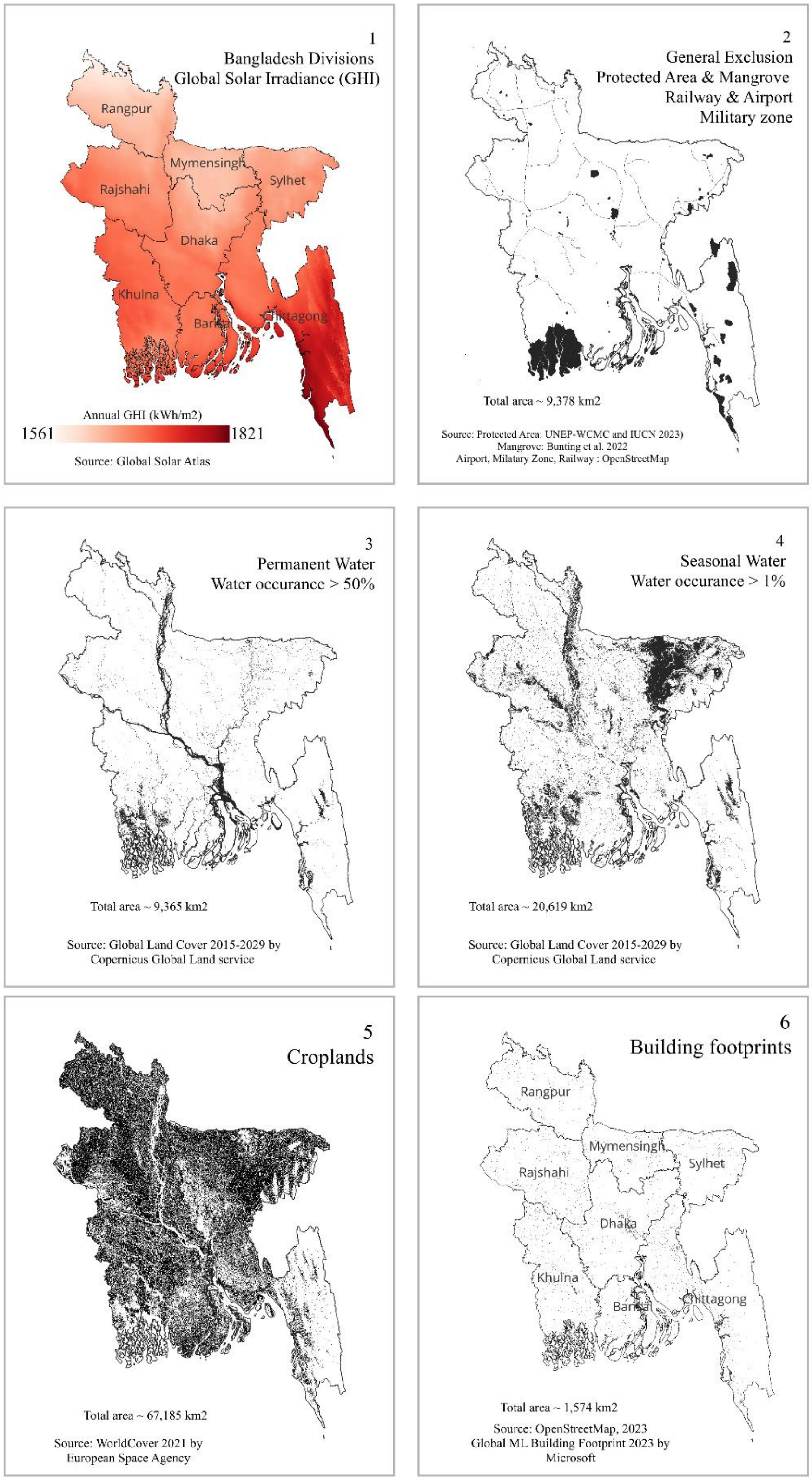

Figure S1. Data used in the geoprocessing

1. Block Diagrams

1.1. Rooftop PV system

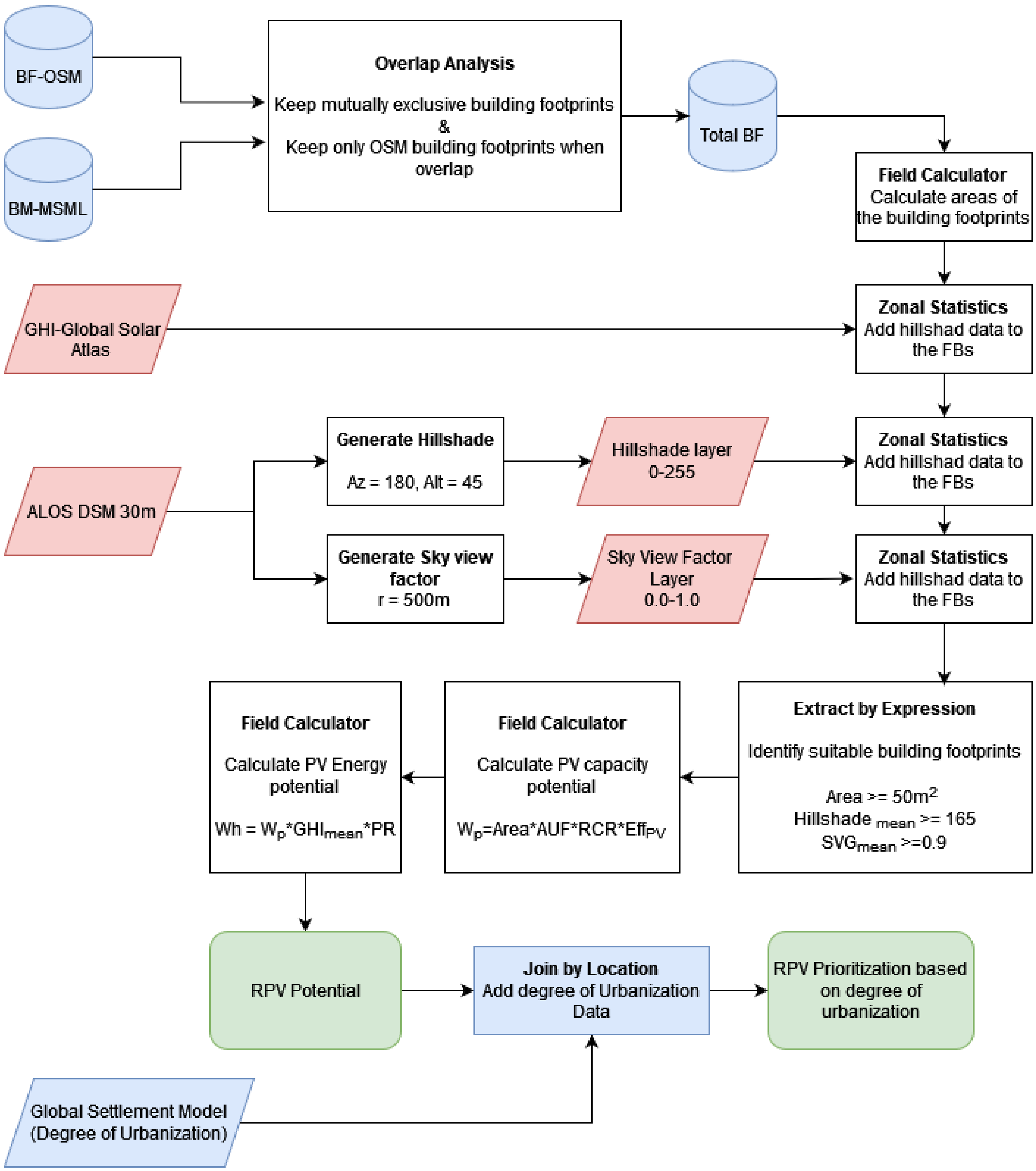

Figure S2: Block diagram for RPV Potential

1.2. General exclusion

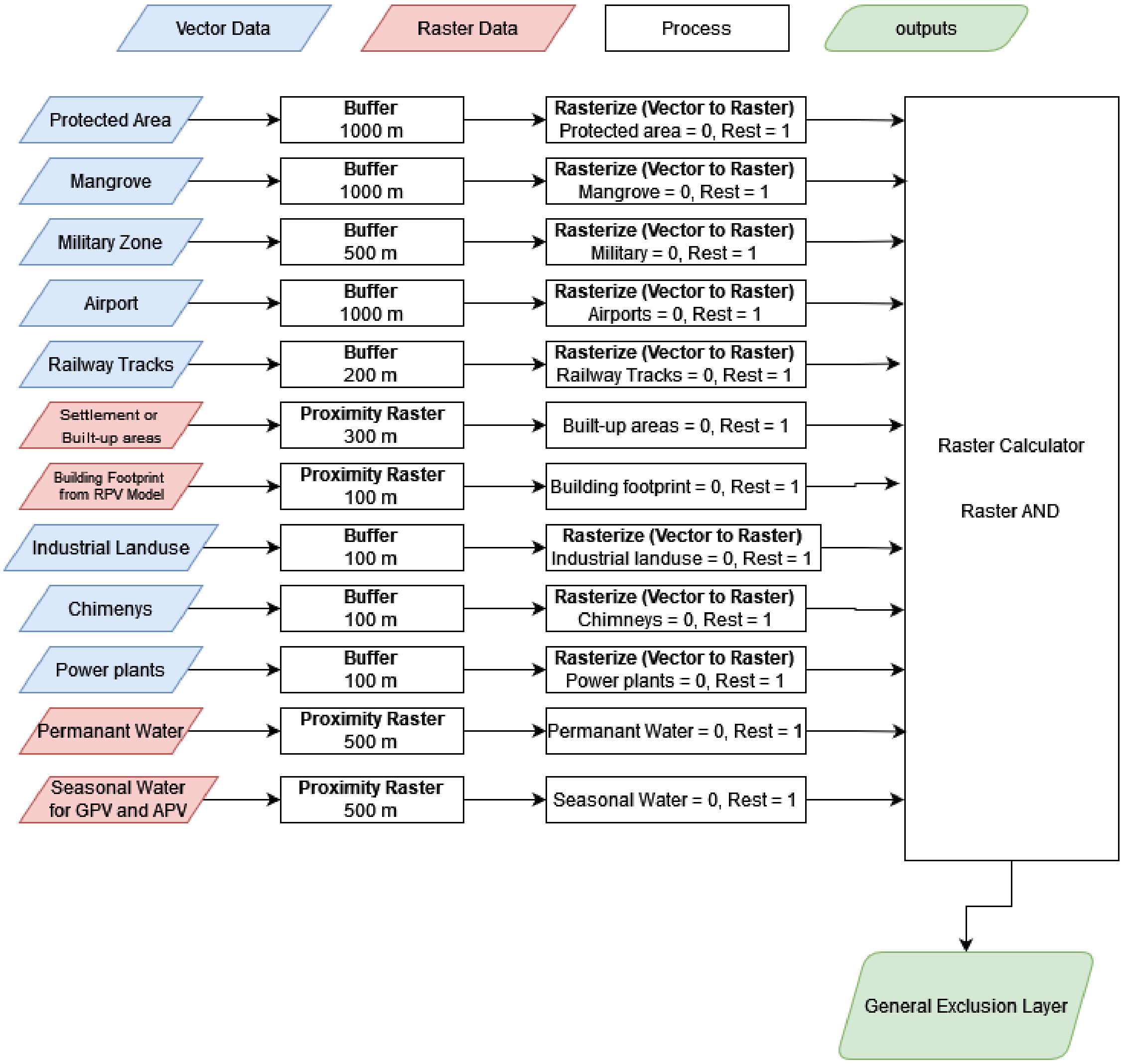

Figure S3: Block diagram for General exclusion

1.3. Ground-based PV systems

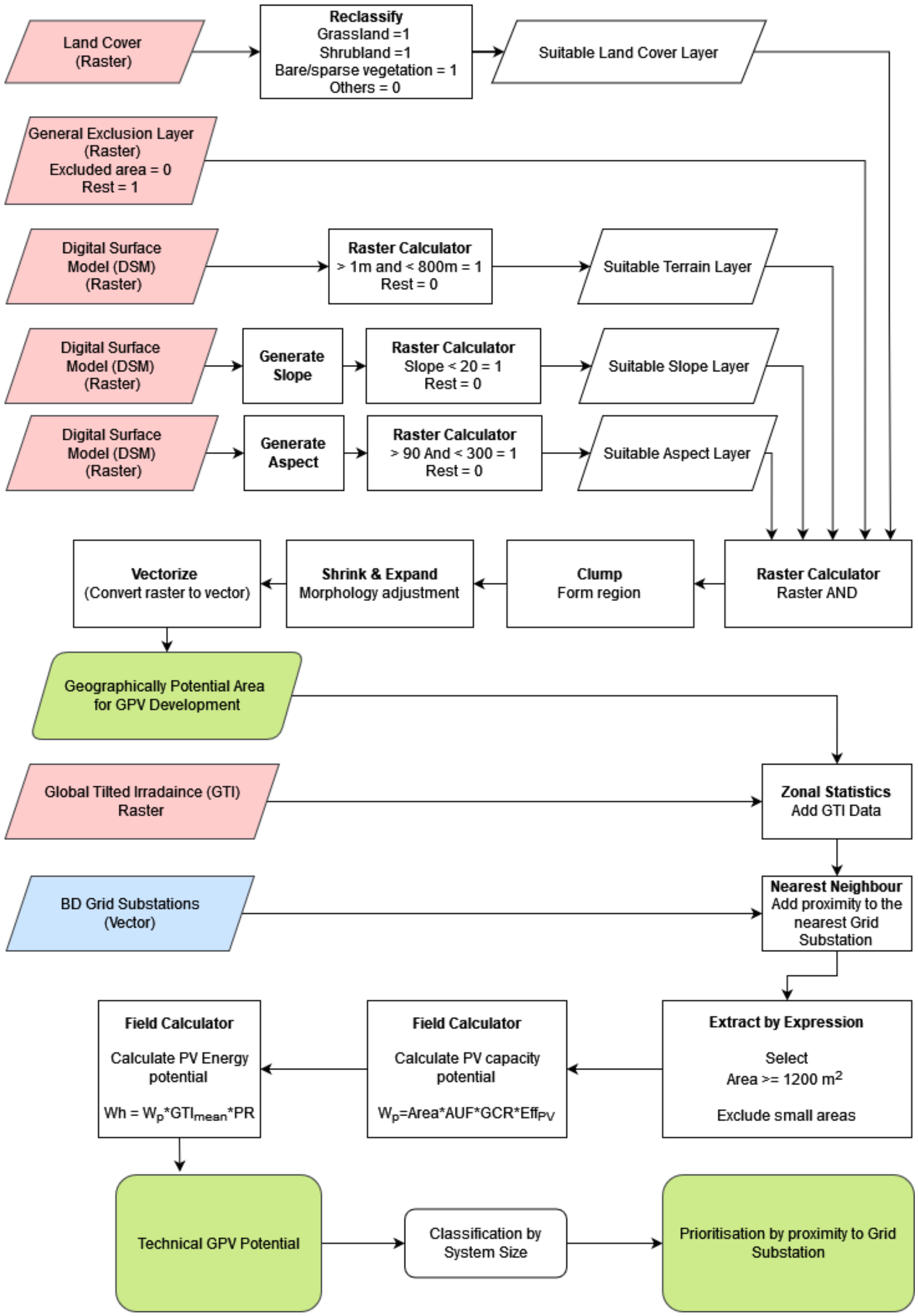

Figure S4: Block diagram for GPV Potential, also (partly valid for APV and APV SIL)

1.4. Floating PV Systems

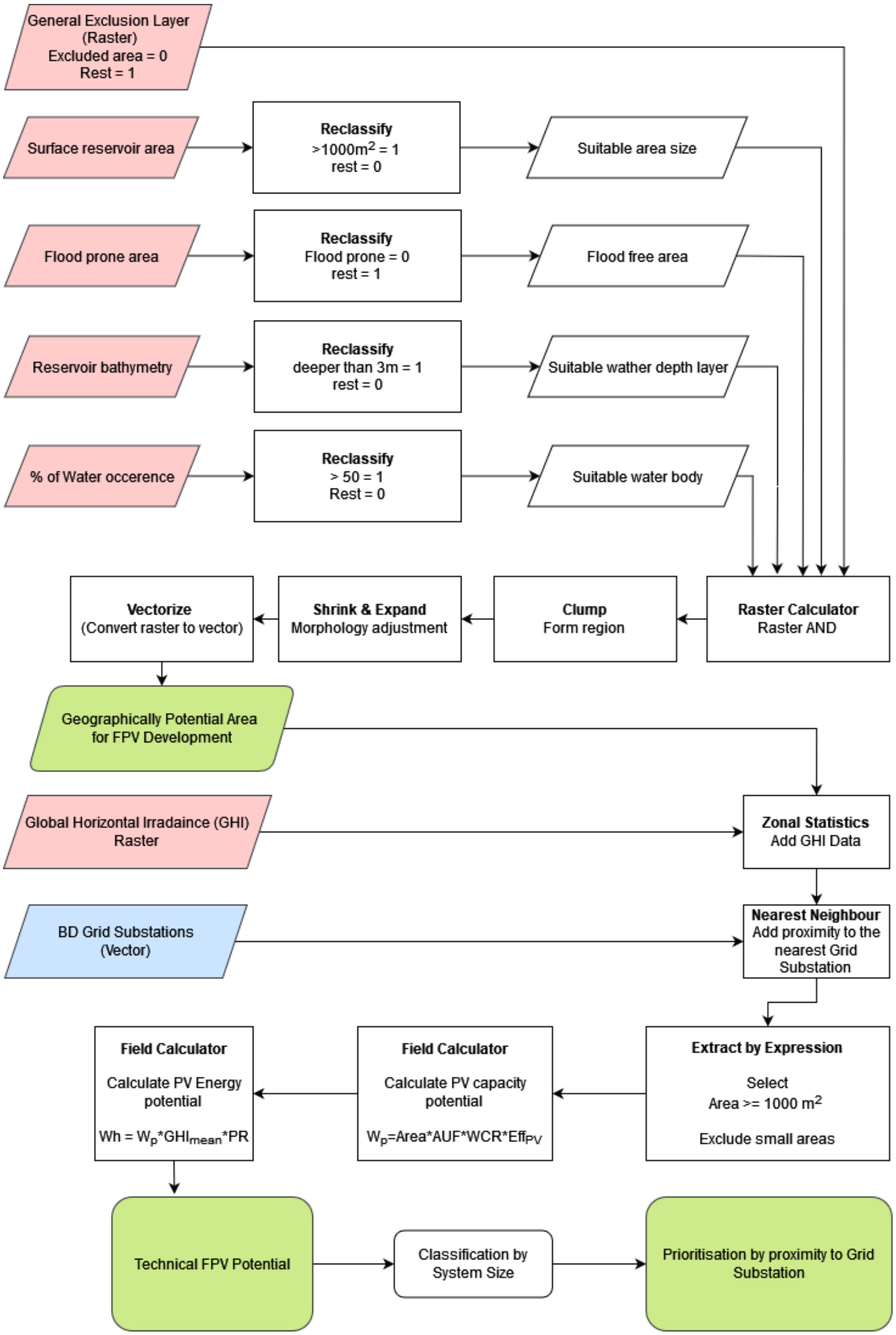

Figure S5: Block diagram for FPV Potential

2. System size categories and cost assumptions

LCOE

$$\boldsymbol{Capacity\ Factor} = \frac{\boldsymbol{Annual\ Energy\ Generation}\ (\boldsymbol{MWh})}{\boldsymbol{Installed\ Capacity}\ (\boldsymbol{MW})\ \times \boldsymbol{Time}\ (\boldsymbol{hour})}$$

Table S1: Rooftop PV

RPV System Size Category	Capex MUSD/MWp	O &M Cost % of Capex	Discount Rate %	Lifetime Year	CRF
Very Large (>500kWp)	0.5	1.20%	6%	25	0.078
Large (100-500kWp)	0.6	1.40%	6%	25	0.078
Medium (30-100kWp)	0.7	1.60%	6%	25	0.078
Small (10-30kWp)	0.8	1.80%	6%	25	0.078
Very Small (3-10kWp)	0.9	2.00%	6%	25	0.078

Table S2: Ground-mounted PV

GPV System Size Category	Capex MUSD/MWp	O &M Cost % of Capex	Discount Rate %	Lifetime Year	CRF
Very Large (>100 MWp)	1.1	1.00%	8.0%	25	0.093
Large (50-100 MWp)	1.2	1.00%	8.0%	25	0.093
Medium (20-50 MWp)	1.3	1.10%	8.0%	25	0.093
Small (5-20 MWp)	1.4	1.20%	8.0%	25	0.093
Very Small (1-5 MWp)	1.5	1.20%	8.0%	25	0.093

Table S3: Floating PV

FPV System Size Category	Capex MUSD/MWp	O &M Cost % of Capex	Discount Rate %	Lifetime Year	CRF
Very Large (>100 MWp)	0.90	2.5%	8.0%	25	0.093
Large (50-100 MWp)	0.95	3.0%	8.0%	25	0.093
Medium (20-50 MWp)	1.00	3.0%	8.0%	25	0.093
Small (5-20 MWp)	1.30	4.0%	8.0%	25	0.093
Very Small (1-5 MWp)	1.50	5.0%	8.0%	25	0.093

Table S4: Agrivoltaics (APV)

APV	Capex MUSD/MWp	O &M Cost % of Capex	Discount Rate %	Lifetime Year	CRF
Very Large (>50)	2.2	3.00%	8.0%	25	0.093
Large (15-50 MWp)	2.4	3.00%	8.0%	25	0.093
Medium (5-15MWp)	2.6	3.50%	8.0%	25	0.093

Small (1-5MWp)	2.8	4.00%	8.0%	25	0.093
Very small (0.1-1 MWp)	3	5.00%	8.0%	25	0.093

Chapter 3 Policy

Shared rooftop space used for installing multiple Solar Home Systems.

Photo: Author

The content of the chapter was published in the Energies journal in May 2024.

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3.0 Chapter highlights

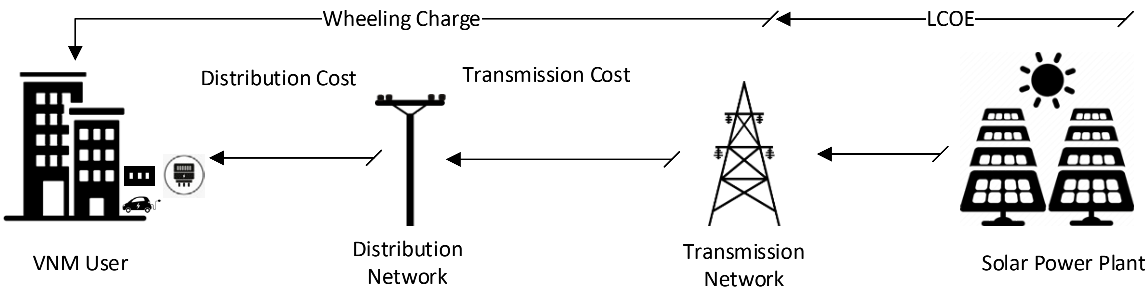

Figure 3.1. Concept of Virtual Net Metering (VNM) with remote solar PV plant

Enhanced Accessibility to Solar Investment: VNM allows consumers without rooftop access, such as those in multi-family or multi-story buildings, to invest in solar energy remotely.

Cost Savings for Consumers: The VNM model offers substantial electricity bill savings, with commercial consumers potentially reducing costs by over 50%, encouraging broader solar adoption.

Increased Solar Penetration: VNM could replicate Bangladesh's successful Solar Home System (SHS) program, driving further solar adoption aligned with national energy goals.

Optimised Use of Smart Prepaid Meters: Bangladesh's extensive use of smart prepaid meters facilitates VNM implementation, allowing for precise tracking and billing adjustments for users.

Policy and Economic Impact: By broadening investment access, VNM enhances grid stability, reduces fossil fuel reliance during peak hours, and generates economic benefits through decreased imported fuel dependency.

energies

Article

Virtual Net-Metering Option for Bangladesh: An Opportunity for Another Solar Boom like Solar Home System Program

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Abstract: This study explores the virtual net-metering (VNM) option for enabling inclusive investment opportunities in renewable energy for self-consumption in Bangladesh. It focuses on consumers, such as households and businesses in multi-family and multi-story buildings, who cannot participate in traditional net-metering policy due to technical and space constraints. The study adopted the classical socket parity method to identify suitable consumers for VNM. Then it determined the consumer benefits of using VNM by calculating the net present cost (NPC) and discounted payback period. The results reveal that several consumer categories can significantly save on electricity costs through VNM. For example, commercial consumers can save more than 50% of their electricity bills by investing in a VNM-enabled remote solar power plant with a discounted payback period of fewer than six years. The discussion articulates more comprehensive benefits of VNM. It addresses challenges for renewable energy development by identifying local opportunities. Therefore, this research can help initiate policy dialogues and create momentum for citizen investments in the energy transition. The proposed approach can also be used to analyze the economic feasibility and potential of VNM in other countries.

Keywords: virtual net-metering; energy wheeling; remote solar power plant; community energy; citizen investment in renewable energy; Bangladesh

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1. Introduction

Research Background

Energy transition in South Asian countries is considered to be critical due to the high dependency on fossil fuels in the region [1]. However, the good news is that among South Asian countries, Bangladesh aims to follow an ambitious roadmap for solar PV installation, despite its high population density (>1100 people per km^2). The most optimistic scenario for this roadmap indicates an installed capacity of 30 GWp of solar photovoltaic (PV) systems by 2041 [2]. To achieve this target, the government must overcome several challenges, such as a lack of investment and land availability issues, to implement this sustainable energy transition roadmap [3,4]. Therefore, there is a need to escalate these issues through research and investigate innovative solution options.

Currently, Bangladesh relies on native natural gas and imported liquid and solid fuels, such as crude oil, hard coal and other oil products, for electricity generation (see Figure 1) [5]. According to the current proven reserves, native natural gas is only expected to power the country for another decade, accounting for the growing energy demand [6]. To cope with this situation, Bangladesh announced a power system master plan in 2016 that articulates the import and use of local renewable energy sources until 2041. However, as of February 2022, the total installed capacity of renewable energy systems was 780 MW, comprising 70% solar PV and 29% hydro power [7]. Bangladesh needs an average annual pace of 950 MW more solar PV capacity to reach the 30 GWp destination, while the current install capacity totals only 546 MW. The country is experiencing several challenges in attracting investors for PV system development, such as the unavailability of suitable land and high investment risks [2,3,8].

Energies **2022**, *15*, 4616. https://doi.org/10.3390/en15134616 https://www.mdpi.com/journal/energies

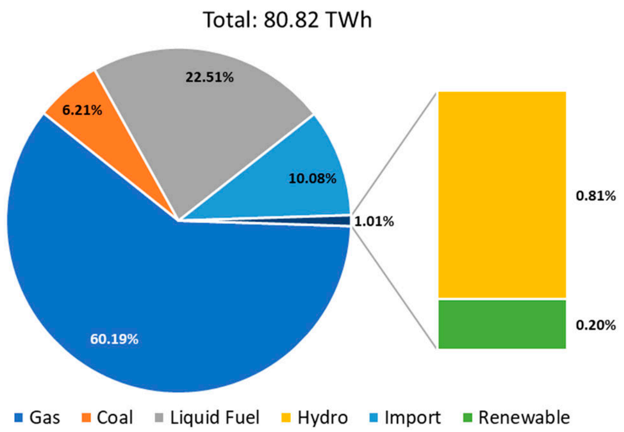

Figure 1. Shares of primary sources of electricity generation in Bangladesh in the financial year of 2020/21. Import indicates electricity imported from other countries. Data source: [9].

Furthermore, based on recent power purchase agreements, PPA, Bangladesh has not yet achieved grid parity for solar PV electricity due to high investment costs and subsidies in the power sector [10–13]. As a result, the government has to buy electricity from private-sector-developed solar PV plants at higher prices to achieve RE targets. To encourage rooftop installation, Bangladesh introduced a net-metering (NEM) policy in 2018. The policy brought about 1500 systems, equivalent to 36 MWp, into the grid as of February 2022 [7]. Due to power system stability issues, the NEM policy allows only 3-phase consumers to install rooftop PV systems [14]. Therefore, the policy only encourages those with roof space and a 3-phase connection to install PV systems. On that account, NEM policy fails to ensure inclusiveness for investment, as it only allows a narrow band of the consumer spectrum [15].

Thus, it is necessary to explore additional policy and system types that can help overcome space availability constraints and attract investors, especially citizens. In this context, the author argues that the current NEM policy needs an upgrade to attract a wide range of citizens to RE investment. Hence, this research investigates virtual net-metering (VNM) as an option to promote citizen investment and deal with space constraints. The study aims to (1) identify opportunities that can facilitate the implementation of VNM to overcome the barriers to renewable energy development, (2) investigate the economic feasibility of VNM, and (3) discuss its implications. Technical and environmental aspects are out of the scope of this study. These aspects are discussed as the outlook of the research.

2. Virtual Net-Metering (VNM)

VNM, as illustrated in Figure 2, is a concept that allows remote energy generation and virtual consumption via the grid to receive credits in electricity bills. Hence, it is also known as remote net-metering. Unlike traditional net-metering, which is a system installed behind-the-meter (BTM), VNM is characterized as a front-of-the-meter (FTM) system. Hence, it involves distribution system operators (DSO), and in some cases, transmission system operators (TSO) [16]. On that account, VNM users are obliged to pay additional charges for transporting energy via the grid, such as distribution and transmission costs—wheeling costs.

Countries such as the United States, Australia, Jamaica, and Brazil have adopted the VNM concept with various terms and conditions and modifications [17,18]. In [19], the authors also characterized VNM as a geographical compensation scheme and net-metering in groups. According to the authors of [18], there are two main ideas behind the different topologies of VNM: (1) generator and consumer are the same entity, also known as one-to-one, and (2) there may be multiple consumers sharing a generator, also known as one-to-many.

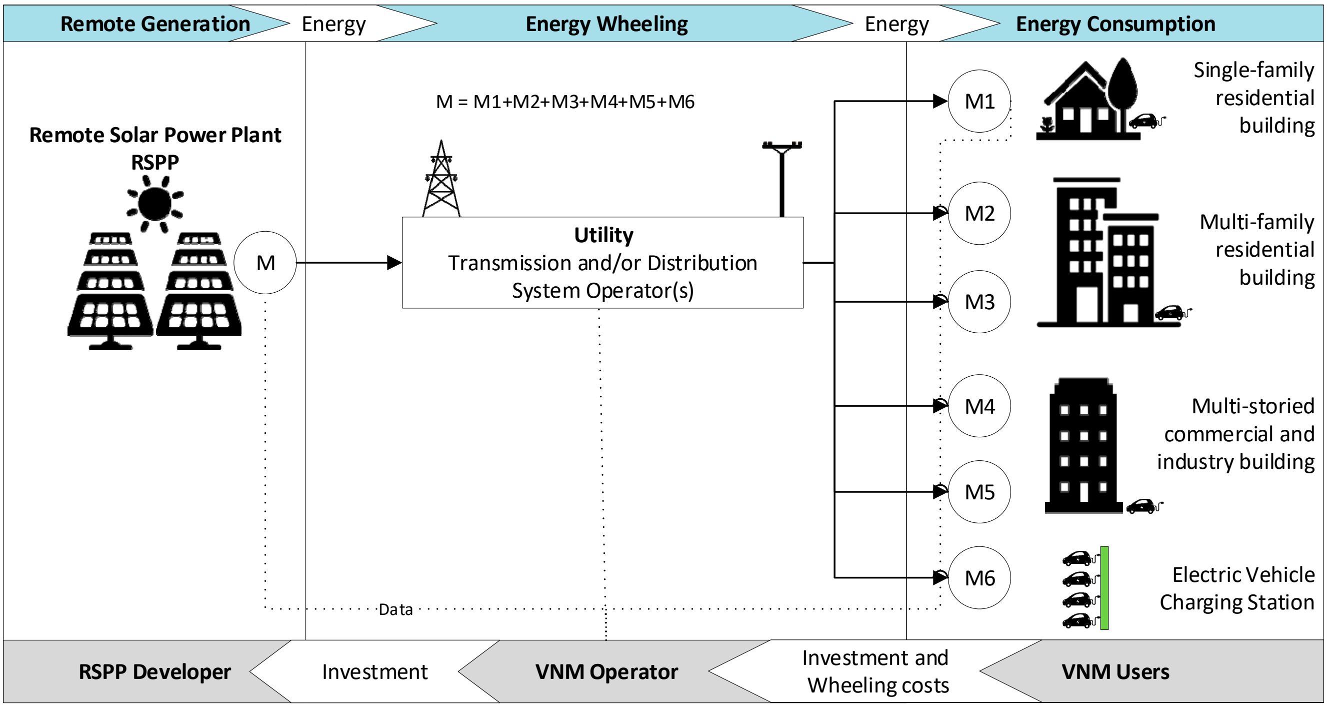

Figure 2. Concept of virtual net-metering. Energy is generated in a remote solar power plant that is owned by a group of consumers. Then the energy is transported via utility grids to those consumers. VNM users share investment and operation costs and pay wheeling charges. An independent VNM operator aggregates the meter, and the RSPP developer develops solar power plants. (illustration by author).

Langham et al. in [20] characterized VNM into four typologies: single entity, third-party, community group VNM and retail aggregation for Australia, as shown in Table 1. A USAID study recommended similar categories for VNM adoption in India [18]. Considering technological and regulatory complexities, the authors of [19] suggest that VNM concepts should not be adopted before implementing traditional net-metering. The authors of [20] identified the wheeling charge as one of the most critical issues for implementing VNM. Countries use various wheeling charge determination methods around the globe, such as cost recovery, historical cost, forward-looking, and nodal pricing methodologies [21]. The most common practice for wheeling charge calculation is the cost recovery and the postage and stamp methods. These methods consider historical investment, operation and maintenance costs, and system losses to identify total revenue requirements for the utility. Then it calculates per unit wheeling cost (e.g., $/kWh) by using the total energy supplied by a utility [22]. The downside of this method is that it does not consider wheeling distances and power; therefore, it raises the issue of fairness [21–23].

Business models of VNM also vary according to the types of VNM, as described below:

- **Single-entity VNM** follows a straightforward business model where a single investor develops a larger solar power plant at any site to meet energy demands for other sites. The generator site uses electricity at the rate of LCOE, and other sites pay wheeling costs. This model is also known as multi-site meter aggregation. Examples of such VNM can be found in [20,24].
- **Third-party VNM** follows the typical producer–retailer business model. An entity develops and operates a power plant to produce energy and sells the energy to one or multiple consumers. In Germany, this model is known as tenant electricity, where the tenants can purchase cheaper power from the landlord [25,26]. In the case of solar farms, the model is comparable with the synthetic or virtual power purchase agreement (vPPA) between a producer and consumers. The price of energy is agreed be-

tween two parties for a certain period of time. In addition to power price, consumers pay network charges for transferring the power.

- **Community VNM** allows a group of consumers to form a community to invest in a shared power plant to meet their energy demand, as shown in Figure 2 [24,27]. The business model for the community VNM can be complicated, as different types of consumers can form a community to produce and consume. Since electricity tariffs differ for different consumer categories, a community power plant will not generate the same benefits for everyone. SOM Energia in Spain and the Clean Energy Collective in the USA are examples of shared generation for roofless consumers [24].
- The **retail aggregation VNM** model uses the concept of a common platform business concept, such as the Uber and Airbnb model. In the case of energy, the aggregator virtually collects excess power from various generators and sells it to consumers [28]. Consumers receive a reduced energy price compared to the grid electricity tariff. Solshare Ltd., a private company, has implemented this concept by interconnecting and aggregating solar home systems in Bangladesh [29]. However, unlike other European companies, such as Sonnen in Germany, Solshare builds its own distribution networks.

Table 1. Typologies of VNM, description, and potential users. Adapted from [20].

Type of VNM	Description	Potential User
Single entity (one-to-one)	An entity offsets the electricity of site B from the excess production from site A	Organizations with multiple meters
Third-party (One-to-many)	An entity sells exported electricity generation to separate entity(s)	Any generator (solar farm or landlord) or consumer
Community group VNM (One-to-many)	People of a community invest in a power plant and transfer the power to the investors/owners via the grid.	People of a community, residents of multi-family housing, commercial community
Retail aggregation (Many-to-many)	Multiple entities sell exported generation to a retailer for resale to multiple consumers.	Local generators with exportable electricity Retailers, including community retailers

In [24], the authors reviewed several policies and business models for different types of prosumer aggregation policies and business models, especially in Europe and the United States. However, the study includes no examples from developing countries. The literature on VNM or similar concept is also rare for the South Asian region and developing countries. Scholarly articles, such as [29] and [30], introduce emerging concepts, such as prosumer aggregation in Bangladesh and India. However, those articles rarely consider the inclusiveness issue and do not focus on articulating challenges and opportunities in those countries.

In the literature, VNM's economic feasibility predominantly focuses on parameters such as Net Present Value (NPV) and payback periods [30–32]. The author argues that the retail grid parity or socket parity and net present costs (NPC) [33] method would be more suitable for analyzing the economic feasibility of VNM. These methods are rarely used for conducting a country-level feasibility study for VNM. The background for using the NPC method is that spending on electricity is an essential cost or expenditure for each consumer. For example, paying electricity bills to the utility, or investing in a renewable energy power plant to offset electricity bills, is an expenditure or cost for the consumers. The socket parity method on the other hand can identify the potential consumer categories in a country based on individual retail tariff rates.

Although all four models of VNM may be suitable for Bangladesh, this study adopts the community group VNM option and the cost recovery method for energy wheeling for further elaboration to limit the scope. The community VNM also addresses the inclusiveness of RE investment. Furthermore, this study considers rooftop PV (RPV) and ground-mounted PV (GPV) for remote generations. The term remote solar power plant (RSPP) addresses remote generation stations in this study.

3. Rationale for VNM and This Research in Bangladesh

There are several opportunities in Bangladesh to facilitate the implementation of VNM. At the same time, VNM can address several challenges in the country. The following sections articulate both.

3.1. Opportunities for Implementing VNM

Smart metering has a significant role in facilitating the implementation of emerging energy system concepts such as VNM, especially for meter aggregation [30,31]. Bangladesh is already well ahead in this step by distributing smart prepaid energy meters (SPEM) for electricity billing. Until 2021, the country has distributed 4 million SPEM and aims to distribute 8 million more by 2022 [9,34]. Bangladesh showed relatively high success in deploying smart energy meters compared to European countries, such as Germany [35]. Therefore, the country can leverage the benefit of SPEM for implementing VNM. Similarly, the country can use its simple tariff mechanism for implementing VNM. For example, as shown in Figure 3, the cost of energy and grid charges dominate more than 90% of the tariff composition in Bangladesh, whereas in Germany, the share of energy and grid costs is about half of the tariff. This tariff structure of Bangladesh makes it suitable for VNM implementation. This energy-dominant tariff structure facilitates achieving retail grid or socket parity for consumer-owned renewable energy systems without competing with the non-energy components of the tariff.

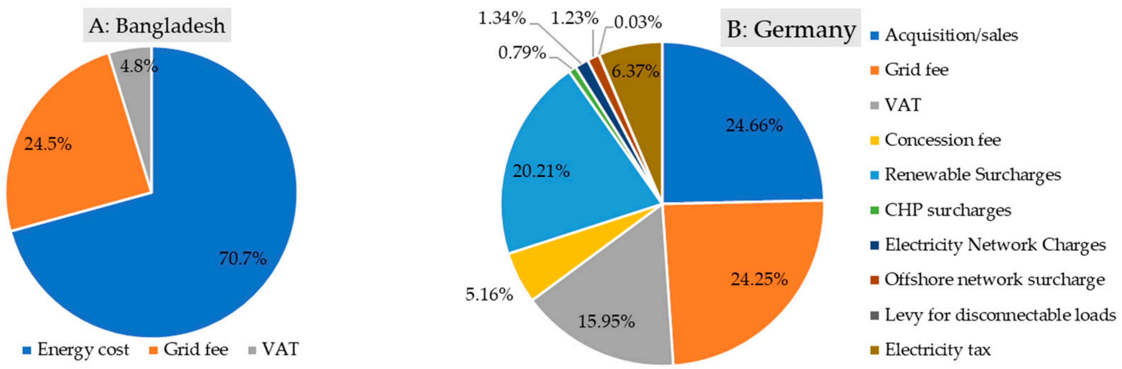

Figure 3. Components of retail electricity tariffs in Bangladesh (**A**) and Germany (**B**). Data source: Bangladesh—an average consumer tariff charged by BPDB in 2020 [36]; German tariff for the residential consumers in 2021 [37].

3.2. Challenges to Overcome through Implementing VNM

Through VNM, Bangladesh can address several challenges for increasing renewable energy share in the grid and sector coupling, such as:

- VNM could provide an inclusive opportunity to invest in PV systems for those who do not have roof space. At the same time, as energy can be generated in three phases and consumed with a single-phase connection through VNM, it can also address the 3-phase policy barrier for installing PV systems. As a result, residents in multi-family buildings and commercial and small industries in multi-storied establishments can install or own PV systems despite space and single-phase connection limitations.
- VNM could promote transportation electrification in Bangladesh. The country hosts more than a million electric 3-wheelers, which consume a significant amount of energy from the grid [38]. According to the distribution operators, there are more than 10,000 registered 3-wheeler charging stations around the country [39–41]. These charging stations are primarily located in urban or semi-urban areas where space availability is insufficient for developing solar systems to meet the electric vehicle charging energy

demands. VNM could enable the charging station owners to invest in PV systems to offer green electricity for electric three-wheelers. At the same time, it can promote the adoption of electric vehicles among VNM users.

Based on the above, the author argues that VNM may bridge the challenges and take advantage of the opportunities to play a vital role in the energy transition in Bangladesh. Therefore, this research scrutinizes the economic feasibility and potential of VNM in the country, considering all the consumer categories. To the best of the author's knowledge, no scientific studies on this topic outline the potential and benefits of VNM or similar concepts in the country, and studies like this are rare in South Asia. On that account, this study is necessary (1) to open a new research avenue and (2) to initiate a policy-level dialogue in Bangladesh on emerging system concepts for creating a participatory renewable energy investment environment and tackling these challenges.

4. Materials and Methods

Figure 4 shows the methodological overview for analyzing economic feasibility and benefits of VNM. Two models, socket parity and VNM, were developed for a systematic economic feasibility analysis. The socket parity model was used as a traffic signal for applying the VNM model. The following subsections describe each model.

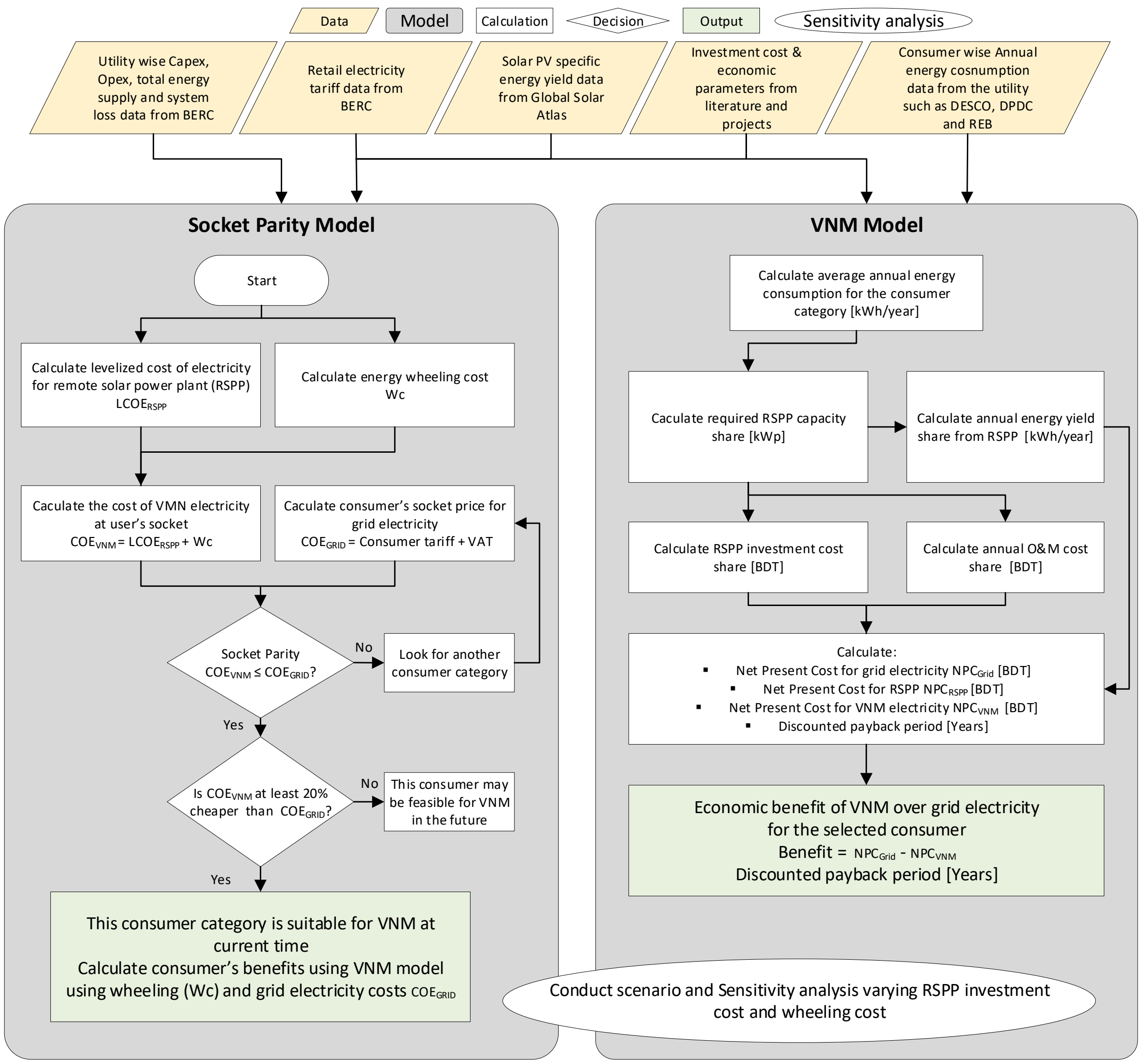

Figure 4. Overview of the research methods.

4.1. Socket Parity Model

Socket parity is a graphical situation when the cost of renewable energy generation equals the cost of energy actually paid by the users as energy bills [42]. Unlike grid parity, socket parity considers grid fees, value-added tax (VAT), and other charges. In this study, the socket parity model aims to identify whether the electricity from VNM would be cheaper than grid electricity for consumers. It considers grid electricity tariffs, investment, and energy wheeling costs. However, the model omits demand charges from the calculation. Since in traditional net-metering users have to pay demand charges, it assumes that the policy for VNM would be the same. The model determines the cost of VNM energy by calculating the levelized cost of electricity (LCOE) of fictitious remote solar power plants (RSPP) and wheeling costs.

LCOE of RSPP: Equation (1) calculates the LCOE for two types of fictitious remote solar power plants (RSPP) in Bangladesh. The equation is inspired by the National Renewable Energy Laboratory's (NREL) LCOE calculator, which can be found in [43]. The equation includes degradation of a PV plant and follow-up investment for equipment replacement. This study assumes the community group VNM approach, as mentioned in Table 1. It assumes medium-sized (1 MWp $\geq$ capacity $\geq$ 3 MWp) PV systems, such as large rooftop PV systems (RPV) and ground-mounted PV systems (GPV). The discount rate was considered according to the value suggested in [44]. The model uses energy yield (kWh/kWp) data from [45] for each type of RSPP as first-year energy yield. Table 2 shows the other values used in the equation.

$$LCOE_{RSPP} = \frac{I + \frac{FI_t}{(1+R)^t} + \sum_{t=1}^{n} \frac{O\&M \times (1+O\&M_{ER})^t}{(1+R)^t}}{\sum_{t=1}^{n} \frac{EY \times (1-PDR)^t}{(1+R)^t}} \quad (1)$$

where $LCOE_{RSPP}$ is the calculated $LCOE$ of each type of $RSPP$. I stands for initial investment,, and FI denotes follow-up investment, such as inverter replacement at the 12th year. $O\&M$ represents operation and maintenance costs and insurance for the current asset, and $O\&M_{ER}$ represents the escalation factor. EY is the energy yield, and PDR accounts for the plant degradation factor. t represents the calculation year and n the $RSPP$ lifetime. R is the discount rate.

Table 2. Input parameters for RSPP LCOE calculations.

Parameter	Value		Unit	Comment/Source
RSPP Type	Rooftop PV	Ground-mounted PV		
Investment cost, *I*	50,000	65,000	BDT/kWp	Values were collected from local project developers via email
In USD	~588	~765	USD/kWp	1 USD (2022) = 85 BDT
Follow-up investment, FI	25%		Of investment	SREDA
O&M Cost, *M*	1%		Of Investment	Values were collected from project developers via email
Energy Yield, *EY*	1373	1418	kWh/kWp	[45]
RSPP Capacity	1000		kWp	
Discount rate, *R*	6.4%		Per year	[44]
Project Life	25		Year	
Plant degradation (*PDR*)	0.7%		Per year	[46]
Depreciation	Linear, 4%		Per year	
O&M Cost Escalation (*OCER*)	2.5%		Per year	Values were collected from local project developers via email

Wheeling cost: Bangladesh follows the cost recovery (or postage and stamp) model for calculating wheeling charge and distribution costs for transmission and distribution of electricity [36]. The model uses the historical costs and energy transactions of the operators. Equations (2) and (3) represent the equations for the cost recovery in Bangladesh.

$$D_{Wc} = \frac{NtD_C + C_{Systm\ loss}}{E_T} \quad (2)$$

where D_{WC} stands for distribution wheeling charge; NtT_C is the net total CAPEX and OPEX of the transmission network for a financial year, also known as required revenue. $C_{System\ loss}$ represents the cost of system loss, and E_T is the total delivered to the distributor in the same year.

$$TD_{Wc} = \frac{NtTD_C + C_{Systm\ loss} + W_{C-Grid}}{E_D} \quad (3)$$

where TD_{WC} stands for distribution wheeling charge and $W_{C\text{-}Grid}$ is the wheeling cost paid by the distribution operators. Table 3 shows the values used in the equation.

Table 3. Parameters for utility-wise distribution and transmission wheeling cost estimation. Data source: [36]. Data year: 2020. MBDT = Million Bangladeshi Taka.

Utility	Net Distribution Cost (NtDc)	System Loss	Total Distributable Energy (E_T)	Wheeling Cost ($W_{C\text{-}Grid}$)	Puchase Cost per unit	Cost of Lost Energy (C)
	MBDT	%	MkWh	MBDT	BDT/kWh	MBDT
BPDB	11,495	7.08%	12,515	3742	6.17	5887
BREB	51,210	10.65%	35,819	11,057	4.60	19,644
DPDC	8448	7.15%	9669	3014	6.69	4982
DESCO	4728	6.94%	5749	1871	6.75	2897
WZPDC	3707	8.59%	3618	1147	5.67	1926
NESCO	4085	10.26%	3980	1272	5.34	2430
Bangladesh Total	83,673	8.45%	71,350	22,103	5.41	38,922

Wheeling scenario: Energy wheeling can have two scenarios depending on the consumption and the RSPP feed-in points. Table 4 shows these two cases.

Table 4. Wheeling scenarios based on consumption and RSPP feed-in points.

Notation	Wheeling Scenario	Definition
D_{Wc}	Wheeling through a distribution network.	When the point of generation (RSPP) and consumption are under the same distribution network
TD_{Wc}	Wheeling through both a transmission and a distribution networks	When the RSPP feeds to the transmission grid and energy is consumed through a distribution grid

Socket cost of VNM electricity: Equation (4) calculates the VNM energy cost at the users' socket for both wheeling scenarios.

$$SCOE_{VNM} = \begin{cases} LCOE_{RSPP} + D_{WC}\ ;\ for\ D_{Wc}\ energy\ whelling \\ LCOE_{RSPP} + TD_{WC}\ ;\ for\ TD_{Wc}\ energy\ wheeling \end{cases} \quad (4)$$

Here, $SCOE_{VNM}$ refers to the cost of VNM energy.

Socket cost of grid electricity: The socket cost of grid electricity $SCOE_{Grid}$ considers the consumer tariff ($T_{Consumer}$) and value-added tax (VAT). Utilities in Bangladesh charge 5% VAT on top of consumer tariffs during billing. The retail electricity tariff rates in Bangladesh can be found in [47].

$$SCOE_{Grid} = T_{Consumer} + VAT \quad (5)$$

Socket parity: Equation (8) represents the method for identifying socket parity considering wheeling scenarios.

$$\text{Socket } Parity = \begin{cases} SCOE_{VNM\ D_{WC}} \le COE_{Grid}\ for\ Dwc\ energy\ whelling \\ SCOE_{VNM\ TD_{WC}} \le COE_{Grid}\ for\ TDwc\ energy\ wheeling \end{cases} \quad (6)$$

$$Consumer\ Surplus/Deficit = \frac{SCOE_{Grid} - SCOE_{VNM}}{SCOE_{Grid}} \quad (7)$$

VNM suitability: Equation (7) calculates consumer surplus or deficit by comparing the grid and VNM energy costs. The author sets a suitability threshold of 20%, meaning consumer surplus must be more than 20% to consider a consumer category suitable for VNM. The value was selected by considering the latest settled tariff rate for rooftop systems (OPEX model) between the system operator and energy consumer in Bangladesh [48]. In Germany, this value is 10% for the tenant electricity scheme known as *Mietersrtom* [25].

4.2. VNM Model

The VNM model calculates the economic benefit of VNM compared to grid electricity. It is applied to some selected consumer categories that satisfy socket parity conditions. The VNM model consists of the following steps and equations.

RSPP capacity sharing for VNM users: According to the net-metering guideline of Bangladesh, the ceiling of PV system size in AC is 70% of the sanctioned load (kW) to the consumers. However, sanctioned load varies widely among consumers and tariff classes. Therefore, the author calculated the RSPP capacity share using the average energy consumption per consumer in each tariff class. Equation (8) uses 100% of the annual energy consumption to determine the required capacity share of RSPP for the VNM schemes.

$$CS_{RSPP-kWp} = \frac{AEC_{consumer}}{AEY_{RSPP}} \quad (8)$$

where $CS_{RSPP\text{-}kWp}$ is the required capacity share, and $AEC_{consumer}$ is the annual energy consumption for a consumer category. AEY_{RSPP} is the energy yield at the respective RSPP.

Net present costs (NPCs): The model calculates NPC_{Grid} for grid electricity usage and NPC_{VNM} for VNM electricity. It identifies the least-cost option for the consumers by comparing both the NPCs. It also calculates the NPC for RSPP to provide an overview of investment expenditure. Equations (9)–(11) describe the details.

NPC for grid electricity

$$NPC_{Grid} = -\sum_{t=1}^{n} \frac{(COE_{Grid})_t}{(1+R)^t} \quad (9)$$

where NPC_{Grid} is the cost of grid electricity for the period of RSPP lifetime. $COE_{R\text{-}Grid}$ is the cost of grid electricity considering consumer demand growth and electricity price escalation factor in year t, and R represents the discount factor. n stands for the lifetime of the RSPP.

NPC for RSPP

$$NPC_{RSPP} = -I_{0_{RSPP}} - \sum_{t=1}^{n} \frac{(O\&M_{RSPP})_t}{(1+R)^t} \quad (10)$$

where NPC_{RSPP} is the lifetime cost of the RSPP, I_{0_RSPP} is the initial investment cost-share $CS_{RSPP\text{-}kWp}$, and $O\&M_{RSPP}$ is the annual share of $O\&M$ costs, including insurance premium for RSPP.

NPC for VNM

$$NPC_{VNM} = -I_{0_{VNM}} - \sum_{t=1}^{n} \frac{(O\&M_{RSPP} + W_c + SCOE_{Residual})_t}{(1+R)^t} \quad (11)$$

where NPC_{VNM} is the lifetime cost of using the VNM scheme and W_c accounts for the cost of energy wheeling. Additionally, $SCOE_{Residual}$ was determined by Equation (12):

$$SCOE_{Residual} = \begin{cases} E_{Deficit} \times SCOE_{Grid} \times VAT, & if\ AED_{consumer} > SGE_{RSPP-kWp} \\ -E_{RSPP-Excess} \times COE_{Feed-in}, & if\ AED_{consumer} < SGE_{RSPP-kWp} \\ O, & otherwise \end{cases} \quad (12)$$

where $COE_{Residual}$ is the cost or revenue for deficit and excess energy from the grid or RSPP, respectively. Since the required capacity is based on 100% of the consumption, the expected revenue is zero.

The NPC calculation also considers the consumer tariff escalation factor of 1.8% per year, which was annualized from previous tariff growth rate data from the Bangladesh Energy Regulatory Commission (BERC) [36]. Furthermore, the consumer energy demand growth rate was set to a negligible value (0.1%), as consumption per consumer growth rate was found insignificant from the data of Dhaka Electricity Supply Company (DESCO) [39].

VNM user benefit: Equation (13) calculates the consumer category's economic benefit by using VNM. It compares the NPC of VNM electricity with the NPC of the grid. The equation determines the total cost savings potential by using VNM during the lifetime of RSPP. It considers the absolute values of the NPCs.

$$\text{Savings, \% of grid} = \frac{NPC_{Grid} - NPC_{VNM}}{NPC_{Grid}} \times 100 \quad (13)$$

Discounted payback period (DPBT): Equation (14) calculates the payback period of RSPP based on savings from the VNM scheme by considering the time value of money.

$$DPBT_{VNM-RSPP} = \frac{Cost\ of\ Investment}{Discounted\ annual\ cost\ saving} \quad (14)$$

where $DPBT_{VNM\text{-}RSPP}$ stands for the discounted payback period of RSPP.

4.3. Scenario and Sensitivity

- **Scenarios**: Two scenarios for energy wheeling were considered for each RSPP type, as shown in Table 5.

Table 5. Scenarios for sensitivity analysis.

Scenario	Definition
$RPV_{RSPP} + D_{Wc}$ $GPV_{RSPP} + D_{Wc}$	Large Rooftop and Ground-mounted PV systems located within the distribution network of consumers
$RPV_{RSPP} + TD_{Wc}$ $GPV_{RSPP} + TD_{Wc}$	Large Rooftop and Ground-mounted PV systems are located outside the distribution network of consumers, and they require the transmission network for energy wheeling

- **Sensitivity**: Investment cost and wheeling charge were varied to analyze the sensitivity on user benefit, as shown in Table 6.

Table 6. Base values and ranges of the variables for the sensitivity analysis.

Parameter	Application	Base Value [Unit]	Sensitivity	Output Parameter
Investment cost	RPV_{RSPP} GPV_{RSPP}	50,000 [BDT/kWp] 65,000 [BDT/kWp]	± 20%	VNM user benefit [%]
Wheeling cost	D_{Wc} TD_{Wc}	1.55 [BDT/kWh] 1.86 [BDT/kWh]	Minimum and maximum wheeling charges by utilities	

4.4. Data Collection

Data used in this study were gathered from the latest annual reports and monthly operational data available on the websites of all the utilities in Bangladesh. Table 7 shows the sources and application of the data in this study.

Table 7. Collected data, applications of data and sources.

Data	Application of Data	Source
Transmission and distribution operators' costs.	Wheeling costs	[36]
Bangladesh electricity tariff	Socket parity and grid electricity cost	[36]
Tariff-wise Energy consumption Tariff-wise no. of Consumers	Required capacity share of RSPP and user benefit calculation	[12,39–41]

Energy consumption per consumer: This study used tariff-wise energy consumption data from [39–41] to determine consumption per consumer in each tariff class using Equation (15). Energy consumption data for the financial year 2020/21 were used as annual energy consumption.

$$AEC_{Consumer} = \frac{Annual\ Energy\ Consumption\ in\ each\ tariff\ class}{Total\ number\ of\ consumer\ in\ the\ tariff\ class} \quad (15)$$

5. Results

5.1. Cost of VNM Energy and Socket Parity

The socket parity model was used to calculate the cost of VNM electricity by determining the LCOEs of RSPPs and two energy wheeling cost scenarios, as shown in Figure 5A. The LCOE calculator calculated LCOEs for RPV and GPV, 3.78 and 4.75 BDT/kWh, respectively. It identified that the LCOE of ground-mounted PV systems is higher than that of rooftop PV systems. This is the opposite case compared to other countries, such as India. In Bangladesh, private lands are expensive due to the high population density. This results in higher investment cost for GPV systems.

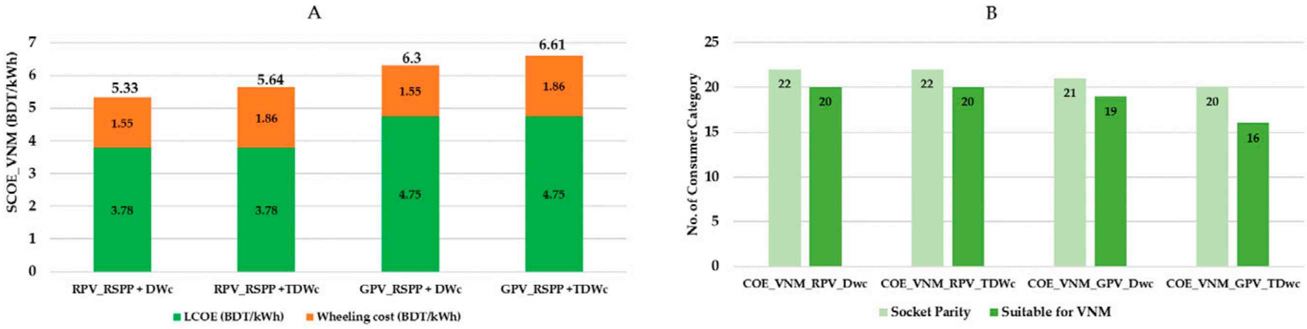

Figure 5. Socket cost of VNM electricity ($SCOE_{VNM}$) and socket parity by number of consumers. (**A**) The sums of LCOEs and wheeling costs, and (**B**) the number of consumer categories that meet socket parity and are suitable for VNM.

The wheeling costs in Figure 5A are the calculated average values among all the six DSOs in Bangladesh for both wheeling scenarios. The average wheeling costs were found 1.55 and 1.86 BDT/kWh for DWc and TDWc scenarios, respectively (see Table 8). The cost of system loss was embedded with wheeling cost by considering the monetary value of system loss (energy) according to the bulk price of electricity for the utilities. Therefore, wheeling energy loss was omitted while calculating VNM electricity costs. Table 8 shows the estimated wheeling costs for all the utilities in Bangladesh.

Considering flat tariff rates in Bangladesh, the socket parity model evaluates 25 tariff classes among different consumer categories. Since low-voltage residential consumers pay their electricity bills according to block tariff, five categories of households were considered considering five levels of average monthly energy consumption. These categories can be seen in Figure 6.

Table 8. Utility-wise distribution and transmission wheeling costs in Bangladesh (with and without system losses).

Utility	Net Dc without System Loss	Net Dc, Including System Loss	Net Dc and Tc without System Losses	Net Dc and Tc, Including System Losses
BPDB	0.92	1.39	1.22	1.69
BREB	1.43	1.98	1.74	2.29
DPDC	0.87	1.39	1.19	1.70
DESCO	0.82	1.33	1.15	1.65
WZPDC	1.02	1.56	1.34	1.87
NESCO	1.03	1.64	1.35	1.96
Mean	1.02	1.55	1.33	1.86

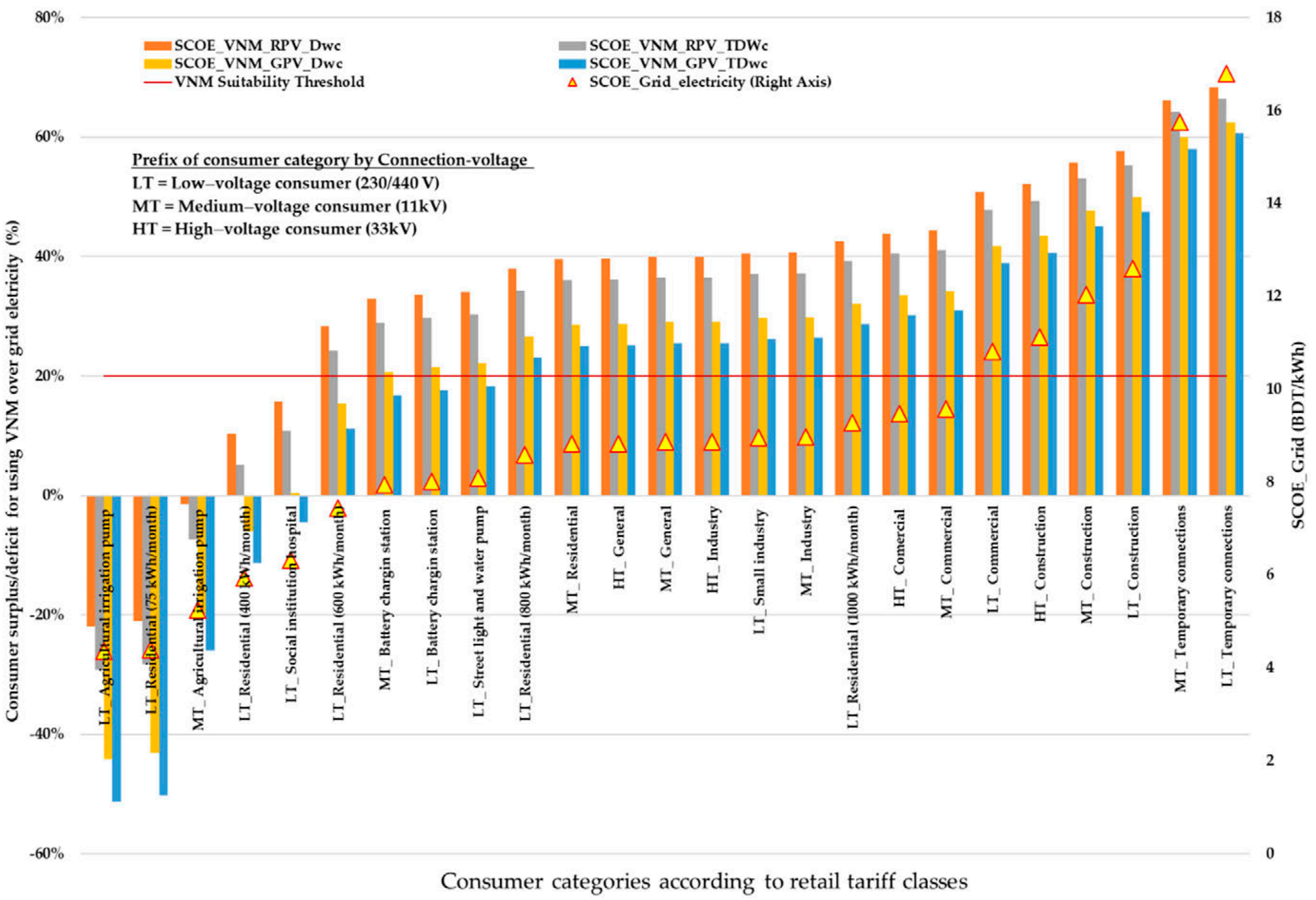

Figure 6. Consumer surplus/deficit for using VNM over grid electricity for 25 consumer categories in Bangladesh. Positive values on the left vertical axis indicate consumer surplus, and negative values indicate deficit. The right vertical axis shows the socket cost of grid electricity for each consumer category.

Figure 5B presents the results of socket parity. It shows the number of consumer categories that achieve socket parity in four scenarios. According to the current tariff, 22 consumer categories meet socket parity for both wheeling scenarios with RPV-based RSPP. Of those 22 consumer categories, 90% are suitable for VNM considering the 20%-suitability threshold. Similarly, for GPV-based RSPP, the suitable numbers of consumer categories were found to be 19 with DWc and 16 with TDWc wheeling scenarios.

Figure 6 summarizes the results of the socket parity model for all consumer categories in Bangladesh. It shows consumer surpluses and deficits while using VNM. According to the figure, the estimated socket cost of VNM electricity is significantly lower than the grid electricity socket cost for several consumers, making VNM suitable for them. The figure also shows the consumers who are not suitable for VNM, such as agricultural consumers, social institutions, and low-energy consuming residential households. In Bangladesh, electricity for agricultural purposes and low-energy consuming households is highly subsidized. On the other hand, despite the high consumer surplus for VNM electricity, a number of consumer categories may not be suitable for VNM due to their consumer definitions and energy use cases—for example, the temporary connection consumer categories. At the same time, it can be assumed that the medium and high-voltage industry consumers have sufficient space to build their own PV systems under traditional NEM policy. In that case, VNM policy can allow industry consumers to transport over-production from PV systems to their commercial entities in other locations. For example, the garment and textile industries can produce energy in their industrial park (site A) and transport excess electricity to their commercial offices (site B) using the single-entity VNM model, as shown in Table 1.

Since many consumer categories were found suitable for VNM, the author narrowed the scope for applying the VNM model to specific consumer categories, as discussed in Section 3.2. Those categories are residential, commercial, industry, and charging station consumers.

5.2. Economic Benefit of Using VNM

The VNM model estimates the potential economic benefit of using VNM for different consumer categories. Table 9 presents the cost-saving potential in four different scenarios of VNM for the selected consumers. According to the table and Figure 7, commercial consumers can save more than 50% of their electricity costs with a payback period of 6 years under the DWc scenario. Under the same scenario, the minimum savings and maximum discounted payback periods were found for residential consumers that consume 600 kWh per month. The lower benefit comes from their lower electricity tariff rates. RPV with the TDWc wheeling scenario reduces the savings by about 3% and increases the payback period by 1–2 years for different consumer categories. At the same time, GPV-based RSPP offers 8–10% lower savings and 2–4 years higher payback periods for similar wheeling scenarios. The author identified that higher consumer tariffs positively influence the savings and discounted payback periods in all the scenarios.

Table 9. Saving and discounted payback period overview for all scenarios.

Parameters	Residential (600 kWh/mo)	Residential (800 kWh/mo)	Residential (1000 kWh/mo)	Commercial	Small Industry	Battery Charging Station
Scenario: RPV-DWc						
Savings, BDT	271,525	514,384	746,854	609,880	1948,642	1710,575
Saving, % of Grid	34%	42%	45%	52%	44%	38%
Discounted Payback, yr	10	8	7	6	7	9
Scenario: RPV-TDWc						
Savings, BDT	240,858	473,493	695,741	578,910	1806,377	1550,450
Saving, % of Grid	30%	38%	42%	49%	40%	34%
Discounted Payback, yr	11	8	7	6	8	9
Scenario: GPV-DWc						
Savings, BDT	190,630	406,523	612,028	528,187	1573,375	1288,198
Saving, % of Grid	24%	33%	37%	45%	35%	29%
Discounted Payback, yr	14	11	9	7	10	12
Scenario: GPV-TDWc						
Savings, BDT	159,962	365,632	560,915	497,217	1431,111	1128,073
Saving, % of Grid	20%	30%	34%	42%	32%	25%
Discounted Payback, yr	15	11	10	8	10	13

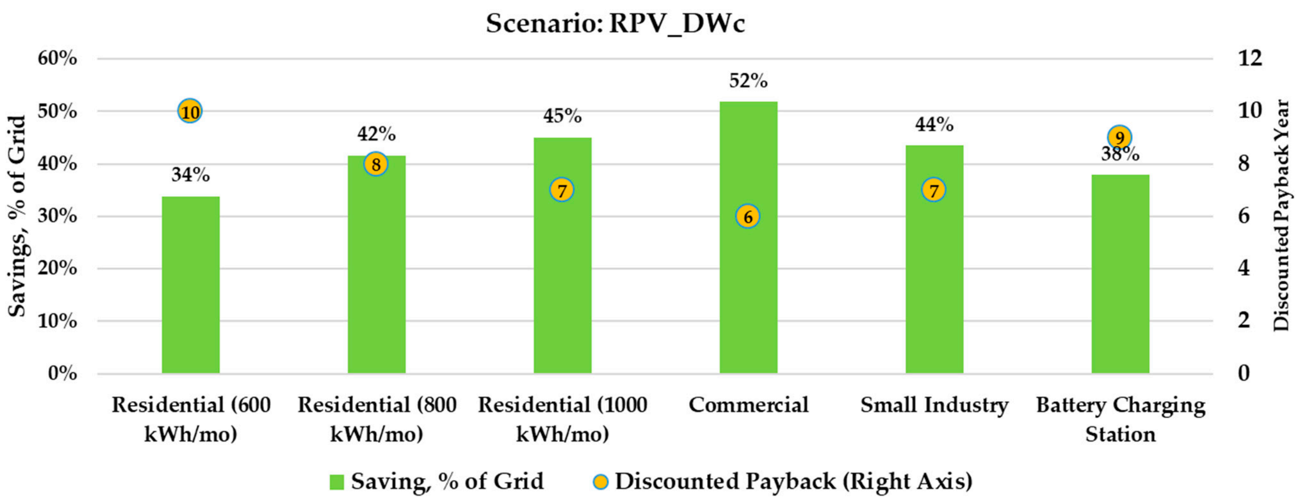

Figure 7. Estimated savings and discounted payback periods for low-voltage consumers. Scenario: rooftop RSPP located within the distribution network of the consumer.

Figure 8 shows an example of annual cost savings during the lifetime of the RSPP for charging station consumers. According to the figure, if charging station owners share a GPV-based RSPP located nearby or within the same distribution network, they can save nearly 30% of their electricity costs through VNM. The aggregated savings offer a return on investment (ROI) of more than three-fold. Table 10 summarizes the investment and annual cost parameters for the selected consumer categories. The required capacity shares are different for RPV and GPV-RSPP, as the energy yields for rooftop systems are lower than those of ground-mounted systems.

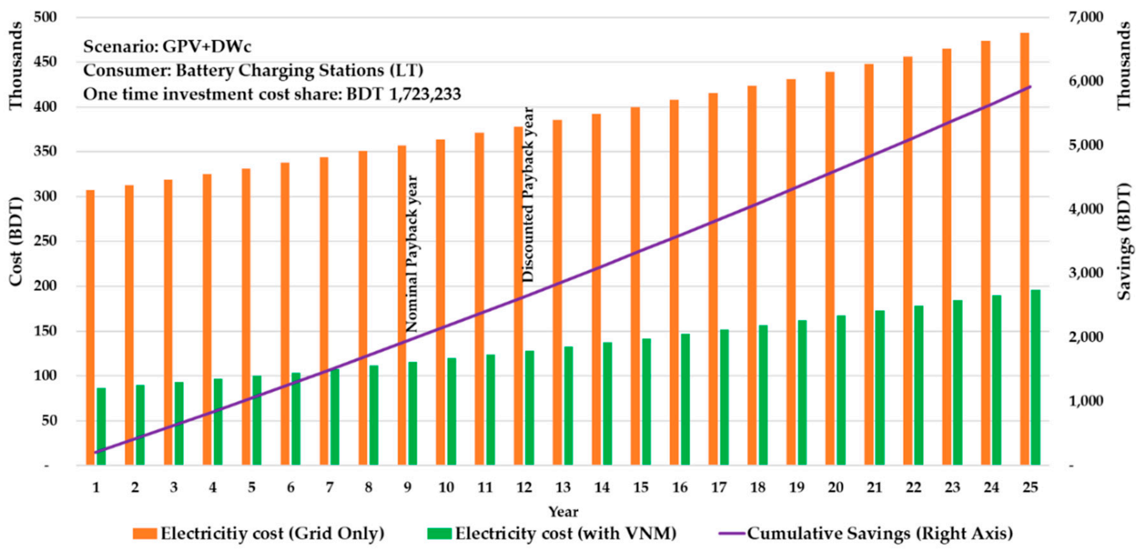

Figure 8. Annual electricity cost comparison between grid-only and with VNM for charging station consumers. Cumulative savings at the end of RSPP life is 5.91 Million BDT.

5.3. Sensitivity Analysis

Since the investment cost of RSPP is volatile and wheeling costs vary based on utility, the model considers that investment and wheeling costs are the major variables for sensitivity. The sensitivity analysis was performed on both models: socket parity and VNM. The impacts of varied investment and wheeling costs on socket parity are shown in Figure 9. According to Figure 9A, 20% volatility of investment cost and the maximum and minimum wheeling costs do not significantly impact socket parity.

Table 10. Average annual consumption, consumer-wise RSPP capacity shares and estimated costs. The annual O&M cost includes an annual insurance premium for RSPP.

Consumer Information			RPV			GPV		
Consumer Category	Annual Consumption, kWh	Tariff BDT/kWh	Required RSPP Capacity Share, kWp	One Time Capital Share, BDT	Annual O&M Share, BDT	Required RSPP Capacity Share, kWp	One Time Capital Share, BDT	Annual O&M Share, BDT
LT_Residential (600 kWh/mo)	7200	7.1	5.24	262,200	2622	5.08	330,042	3300
LT_Residential (800 kWh/mo)	9600	8.2	6.99	349,599	3496	6.77	440,056	4401
LT_Residential (1000 kWh/mo)	12,000	8.8	8.74	436,999	4370	8.46	550,071	5501
LT_Commercial	7271	10.3	5.30	264,785	2648	5.13	333,297	3333
LT_Small Industry	33,400	8.53	24.33	1,216,315	12,163	23.55	1,531,030	15,310
LT_Battery Charging Station	37,593	7.64	27.38	1,369,009	13,690	26.51	1,723,233	17,232

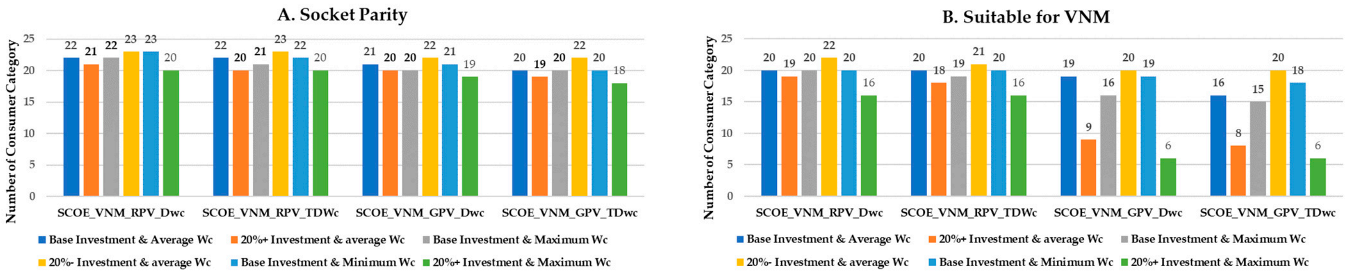

Figure 9. Impacts of investment and wheeling costs on socket parity. The base investment costs for RPV and GPV were 50,000 and 65,000 BDT/kWp, respectively. Additionally, the base wheeling costs for DWc and TDWc were 1.55 and 1.86 BDT/kWh, respectively. The minimum and maximum wheeling costs came from the wheeling costs of all the utilities in Bangladesh.

However, with the same parameters, the number of suitable consumer categories reduced significantly for GPV-based RSPP, as shown in Figure 9B. It can be seen that only the commercial consumer category remained suitable for the extreme case, which is a 20% higher investment cost and the maximum wheeling cost (2.29 BDT/kWh). Hence, the sensitivity analysis concludes that commercial consumers are highly suitable for VNM in Bangladesh. According to Figure 10A, there are nearly 3 million commercial consumers in the country, which indicates significant market potential for VNM. However, consumers in charging stations, residential, and small industry categories may require incentives and support to adopt VNM in the event of higher investment and wheeling costs.

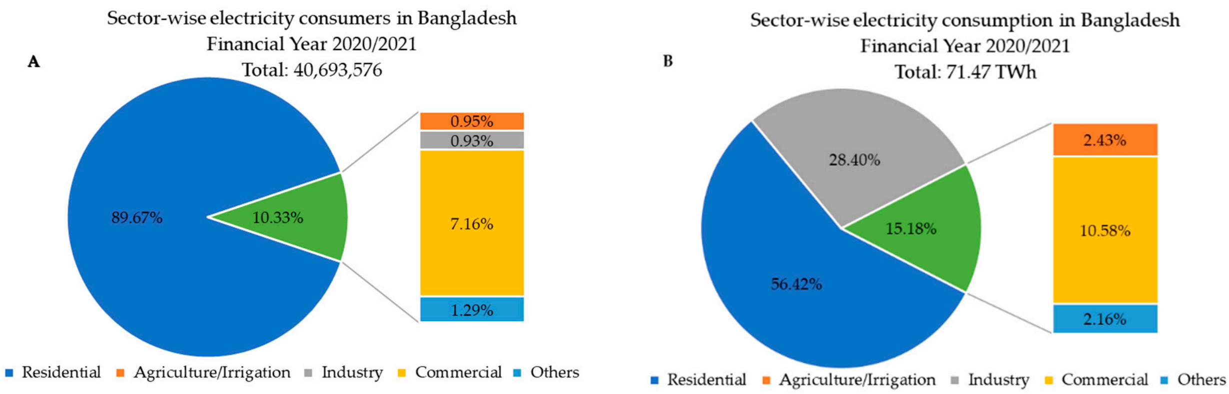

Figure 10. Sector-wise consumer (**A**) and energy consumption (**B**) in Bangladesh in the financial year 2020/2021. Data source: [9].

Figure 11 shows the impacts of investment and wheeling costs on the savings of VNM users. The figure shows that a 20% reduction in investment cost for GPV-based RSPP can make VNM more attractive for charging stations and high-energy-consuming residential consumer categories, encouraging them to invest in RE. Since the wheeling costs are different for different utilities, as shown in Table 8, the savings will also vary based on utility. However, it is essential to pay attention to the wheeling costs, as they negatively affect the benefits of VNM. For example, wheeling through BREB is the most expensive, whereas DESCO offers the cheapest costs in the country. BREB has the lowest per kilometer consumer density in its distribution network of all the DSOs in Bangladesh—about 60 consumers/km. In addition, BREB operates through 80 sub-operators known as Pally Bidyut Samity (PBS) in Bangladesh [40]. Therefore, to offer VNM with BREB, a single PBS wheeling cost consideration would be more appropriate and fair. Furthermore, charging station consumers may require reduced wheeling costs as an incentive to adopt VNM.

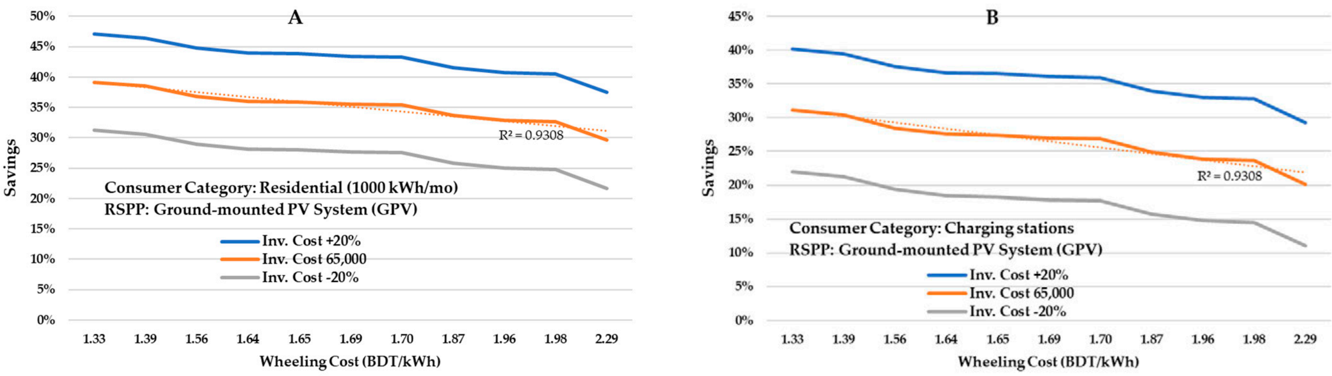

Figure 11. Impacts of investment and wheeling costs on savings for using VNM. RSPP = GPV. (**A**) For the charging station consumer category and (**B**) for the residential (1000 kWh/month) consumer category.

The study also identified several other economic factors sensitive to the benefits of VNM. Those are discount factors, consumer energy demand growth, grid electricity and wheeling cost escalation factors, RSPP performance ratio, and operation and maintenance costs of RSPP. Among those factors, only the grid electricity tariff escalation rate positively correlates with the VNM savings, whereas others have negative correlations. For example, if the discount rate reduces by 1%, the VNM saving increases by 2%.

6. Discussion

6.1. Potential of VNM for Other Developing Countries

The energy cost component dominates the tariff composition in Bangladesh. At the same time, electricity tariffs are higher for commercial and high-energy-consuming residential consumers. These situations make VNM economically feasible in the country. A similar electricity tariffing methodology is used for other south Asian countries, such as Pakistan, Nepal, and India [49]. Figure 12 shows the countries in South Asia where the commercial tariff is higher than the average residential tariff. It compares socket parity with the global average LCOEs of PV. The figure also includes the 5th percentile of the PV LCOE, which IRENA found in India in 2020 [50]. According to the figure, business consumers in this region can significantly offset their electricity bills by installing solar PV with a net-metering policy. The surplus also shows the potential for VNM in those countries. Hence, the market potential for VNM in this region could be significant, and this study can stimulate researchers and policymakers to explore it further.

6.2. Promotion of Electric Vehicles through VNM

VNM could facilitate the adoption of electric vehicles by different consumer categories in developing countries to cope with the increasing fuel prices. According to the results, the VNM offers higher benefits for the consumer categories that pay higher tariffs. Therefore, consumer categories such as high-energy-consuming residential, commercial, and small industries, can increase their benefits by replacing fossil fuel vehicles with electric vehicles (or considering EV for the new/next vehicles). For example, a weekly mileage of 150 km with an electric passenger car in Bangladesh can increase electricity demand by around 137 kWh per month, given 18 kWh/100 km [52] with 85% charging efficiency electric cars, and 7.2 L/100 [53] km for petrol at 86 BDT/liter for conventional cars. Commercial consumers could save up to 32% on energy costs compared to grid electricity to meet this demand by using VNM. Furthermore, countries such as India, Nepal, Thailand, Vietnam, and Bangladesh have a high penetration of electric three-wheelers, and the number is soaring [38]. VNM can help those countries deal with the growing energy demand and offer green rides through electric vehicles.

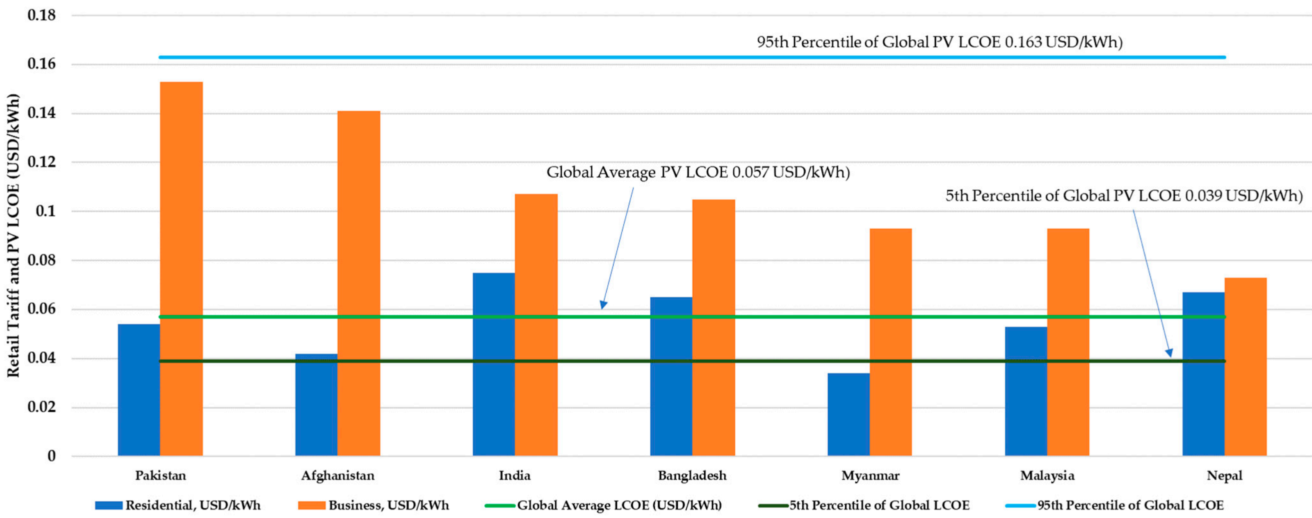

Figure 12. Average retail electricity tariff for residential and business consumers in South Asian countries and global average LCOE for utility-scale solar PV [50,51].

6.3. Dealing with Land Availability Issues for Solar PV Systems

Due to the high population density in Bangladesh, space availability is critical for deploying utility-scale ground-mounted PV systems [54,55]. This situation does not encourage commercial or third-party investors to invest in large utility-scale power plants. In addition, land ownership is another critical issue in Bangladesh, implying smaller holding sizes. More than 80% of farm holdings in Bangladesh are less than 2.5 acres [56]. Therefore, the author argues that a potential solution would be developing small-scale solar power plants (e.g., <1 MWp) of suitable system types, such as rooftop, floating, and Agri-PV systems. These plants can be operated with mechanisms like those of community power plants and VNM by nearby communities.

On the other hand, Dhaka has significant potential for rooftop PV systems. A satellite image-based solar potential mapping project [57] estimated that rooftop PV potential in Dhaka is nearly 7 GWp. However, despite such significant potential, only a handful of the roof area has been utilized for developing PV systems. According to the latest data in [58], the aggregated capacity of installed rooftop PV systems in the Dhaka region is 40 MWp. Out of this capacity, only 6 MWp was installed under the net-metering policy, and the mechanism for the other 33 MWp is unclear. Multi-family and multi-storied commercial buildings highly dominate the building footprint of Dhaka, 86% and 9%, respectively. Therefore, the traditional NEM is inadequate to attract building owners as investors. Considering this situation, VNM can enable tenants to invest in rooftop systems regardless of their lengths of stay in the buildings. Through VNM, tenants can virtually consume energy from the PV system on any other building. Thus, VNM can facilitate utilizing the roof spaces, reducing the requirement for land to develop PV systems, and attracting citizens to invest in RE for self-consumption.

6.4. VNM for Implementing Renewable Portfolio Standards (RPS) and Mandates

Renewable policy instruments such as renewable portfolio standards (RPS) and mandates can force different entities to achieve individual RE targets [59]. However, considering the space constraints and limitations of traditional NEM, imposing individual renewable energy targets is not practical in countries such as Bangladesh. Since VNM can open the doors for RE investment for all the consumers, governments will be able to impose stricter policies, such as RPS and mandates, on high-energy-consuming consumers. In the case of Bangladesh, these consumers can be banks and other financial institutions, high-energy-consuming households, electric rickshaw charging stations, shopping malls, telecom operators, and other industrial and commercial entities.

6.5. VNM to Increase Citizen Investment in RE

Due to high-risk ratings, Bangladesh can attract few foreign investors [60]. Furthermore, investment from the private sector and the government is insufficient to achieve the RE targets of Bangladesh [3]. Hence, the country needs to seek alternative investment opportunities. The proposed VNM model is suitable for encouraging citizens or consumers in RE investment. The increasing grid electricity cost may be a catalyst for bringing citizens to RE investment [61]. The solar home systems program (SHS) of Bangladesh is considered one of the most successful off-grid projects globally. Rural people were at the center of this success. The author argues that VNM can be an opportunity for Bangladesh to facilitate another solar boom like SHS program by engaging the consumers in RE investment. Similar to the SHS program, the government can offer financial and reduced wheeling cost incentives to enable some consumers, such as charging stations and small industries, to invest.

6.6. Recommended VNM Implementation Pathway

First, it is necessary to upgrade the traditional net-metering policy to adopt VNM. However, this will require coordinated facilitation from government entities, such as ministries, utilities, and financial institutions. In Bangladesh, the Bangladesh Power Development Board (BPDB) and the Sustainable and Renewable Energy Authority (SREDA) can play the leading roles in implementing VNM. For VNM implementation, Bangladesh can adopt its affordable housing scheme (e.g., Uttara Apartment Project [62]), implemented by the Capital Development Authority (RAJUK). In the case of VNM, BPDB and SREDA can play the role of RAJUK in developing solar power plants and selling their kWp shares to consumers. Additionally, solar PV system project developers can play the role of real estate developers in the country to develop solar power plants as saleable assets. A proposed model is shown in Figure A1 in Appendix A.

6.7. Limitations and Outlook

The author used the cost recovery method for calculating the wheeling cost for the VNM. This may not reflect the actual wheeling cost for VNM. Therefore, further research is necessary to identify the cost-reflective and fair energy wheeling cost using the advanced methods described in the Introduction. Furthermore, this study was based on energy consumption and electricity tariff data from different utilities. Hence, a field study is essential to understand the views of citizens and consumers toward RE investment, which could identify the market potential of VNM and suitable policies.

The proposed VNM concept may play a significant role in offsetting electricity generation from fossil fuels during the day, reducing carbon emissions. At the same time, utilities can save by reducing energy purchase and grid wheeling costs. These benefits for the government and utility were not studied.

The author leaves the geographic feasibility of RSPP for VNM and emission reduction potential as future research outlooks. Additionally, since the cost of energy generation during the non-solar time (nights and cloudy days) is expensive, higher penetration of VNM may raise fairness issues among consumers. On that account, further policy measures, such as virtual net-billing [63], can be explored.

7. Conclusions

This study introduced VNM as a new concept in Bangladesh for creating an inclusive investment opportunity in RE to offset electricity costs. It identified VNM as a timely and economically feasible option for the country. Based on the literature review and analysis, the findings of this study can be generalized as follows:

− The crucial challenges for renewable energy development in highly populated developing countries are land/space scarcity and lack of investment.
− There are several under-explored opportunities, such as energy cost-dominant electricity tariffs, availability of smart energy meters, and rising demand sectors (e.g., electric 3-wheelers), in developing countries for adopting emerging system concepts such as VNM.
− There are a significant number of consumer categories for whom adopting VNM is suitable in Bangladesh and the region.
− VNM is an economically feasible alternative to grid electricity for consumers such as commercial, industry, and high-energy-consuming households.
− VNM is a potential pathway for involving consumers in renewable energy investment to address the lack of investment challenges.
− VNM could foster the implementation of rooftop PV systems and address the land/space availability challenges.
− VNM could help tackle growing energy demands for EVs, and it could be a catalyst for promoting EVs in developing countries.
− The existing housing models could be used for implementing VNM and developing RSPPs.

This study also enriches the literature on emerging RE concepts in the South Asian region and developing nations. The scholarly contributions of this research are as follows:

− The research customized the socket parity method for identifying suitable consumers for VNM and prosumer aggregation concepts.
− The net present cost method was applied for analyzing comparable cost-saving benefits between grid and VNM electricity.
− A combined model with socket parity and NPC was developed for determining the country-level economic feasibility of VNM prosumer aggregation concepts.

The economic feasibility identification approach developed in this research is novel, and all the equations increase the transparency of the calculation. Hence, other researchers can adopt this approach for analyzing the feasibility of similar emerging RE system concepts. In addition, the results can inform citizens regarding the advantages of VNM and investment opportunities in RE. The discussion can help policymakers see the broader benefits and perspectives of VNM for addressing several challenges on the way to the energy transition.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

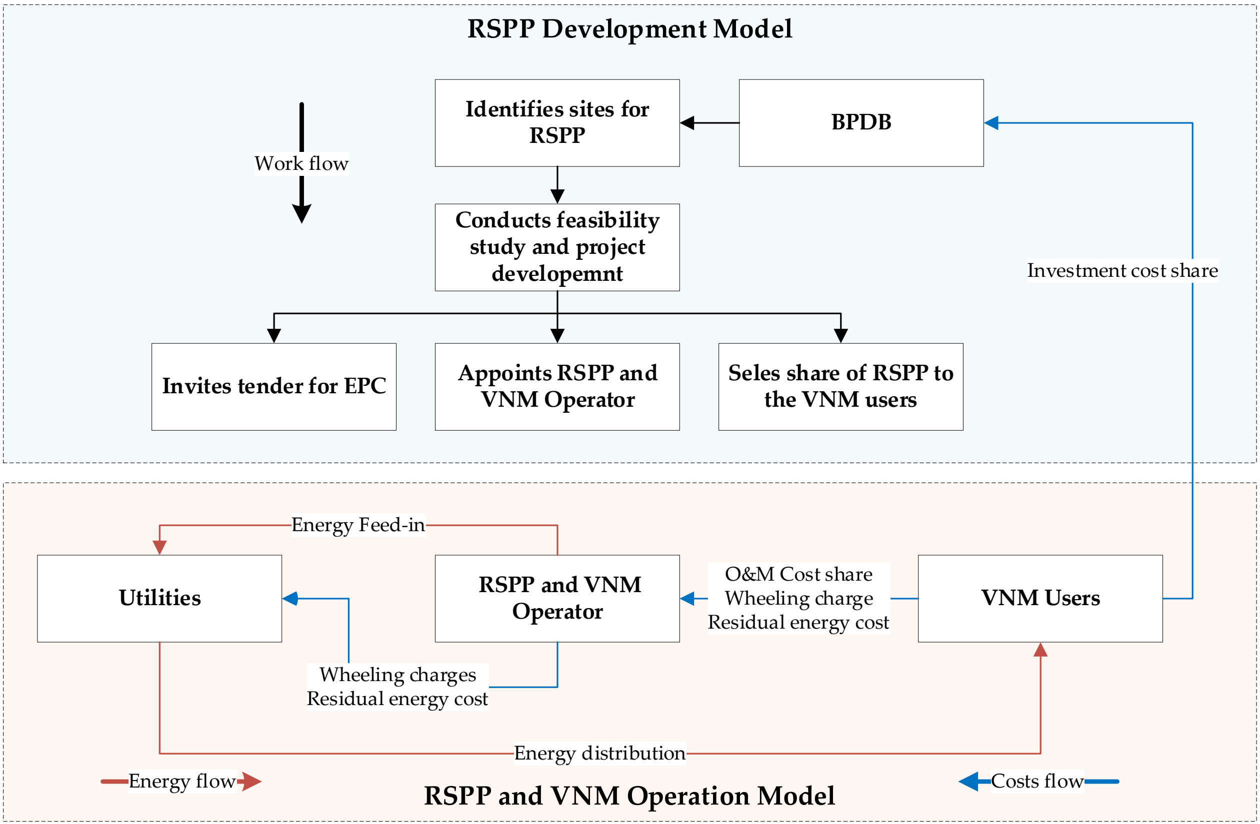

Figure A1. Proposed model for VNM implementation in Bangladesh.

References

1. Chen, G. Energy Transition in South Asia Is Critical to Reaching Global Net-Zero. Available online: https://blogs.worldbank.org/endpovertyinsouthasia/energy-transition-south-asia-critical-reaching-global-net-zero (accessed on 2 June 2022).
2. Chowdhury, S.A. National Solar Energy Roadmap, 2021–2041, Sustainable and Renewable Energy Authortiy SREDA, Dhaka. 2020. Available online: http://www.sreda.gov.bd/sites/default/files/files/sreda.portal.gov.bd/notices/fba98896_568a_4efd_a48b_8d92bfc04049/2020-10-22-17-12-7b0e5a0c0dabd4c17492bcf3bd7488b4.pdf (accessed on 15 January 2021).
3. Barua, S.; Aziz, S. (Eds.) Chapter 15—Making green finance work for the sustainable energy transition in emerging economies. In *Energy-Growth Nexus in an Era of Globalization*; Elsevier: Berkeley, CA, USA, 2022.
4. Qaiser, I. A comparison of renewable and sustainable energy sector of the South Asian countries: An application of SWOT methodology. *Renew. Energy* **2021**, *181*, 417–425. [CrossRef]
5. IEA. Data and Statistics—Bangladesh. Available online: https://www.iea.org/data-and-statistics/data-tables?country=BANGLADESH (accessed on 26 May 2022).
6. Shetol, M.H.; Rahman, M.M.; Sarder, R.; Hossain, M.I.; Riday, F.K. Present status of Bangladesh gas fields and future development: A review. *J. Nat. Gas Geosci.* **2019**, *4*, 347–354. [CrossRef]
7. SREDA. RE Generation Mix | National Database of Renewable Energy. Available online: http://www.renewableenergy.gov.bd/ (accessed on 21 September 2020).
8. Hossain, M. *Green Finance in Bangladesh: Policies, Institutions, and Challenges*; Tokyo ADBI Working Paper No. 892; Asian Development Bank Institute (ADBI): Tokyo, Japan, 2018.
9. Power Division. *Power Division Annual Report FY 2020–2021*; Bangladesh Power Division: Dhaka, Bangladesh, 2022.

10. Islam, S. Christmas Day Could Usher in Bangladesh's Biggest Solar Field. Available online: https://www.pv-magazine.com/2021/12/23/christmas-day-could-usher-in-bangladeshs-biggest-solar-field/ (accessed on 26 May 2022).
11. Islam, S. Bangladesh Set to Approve 70MW Solar Plant. Available online: https://www.pv-magazine.com/2022/01/04/bangladesh-set-to-approve-70mw-solar-plant/ (accessed on 26 May 2022).
12. BPDB. *Annual Report 2019–2020*; Bangladesh Power Development Board (BPDB): Dhaka, Bangladesh, 2022.
13. Islam, S. Bangladeshi Fabrics Maker Invests in 100 MW Solar Plant. Available online: https://www.pv-magazine.com/2022/04/15/bangladeshi-fabrics-maker-invests-in-100-mw-solar-plant/ (accessed on 15 April 2022).
14. *Bangladesh Net-Metering Guideline 2018*; SREDA: Dhaka, Bangladesh, 2018.
15. Jager-Waldau, A.; Bucher, C.; Frederiksen, K.H.B.; Guerro-Lemus, R.; Mason, G.; Mather, B.; Mayr, C.; Moneta, D.; Nikoletatos, J.; Roberts, M.B. Self-consumption of electricity produced from PV systems in apartment buildings—Comparison of the situation in Australia, Austria, Denmark, Germany, Greece, Italy, Spain, Switzerland and the USA. In Proceedings of the 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC) (A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC), Waikoloa, HI, USA, 10–15 June 2018; pp. 1424–1430.
16. Augustine, P.; McGavisk, E. The next big thing in renewable energy: Shared solar. *Electr. J.* **2016**, *29*, 36–42. [CrossRef]
17. Toby, D. Couture, Clean Energy Solutions Center|The Future of Solar Policy. Available online: https://cleanenergysolutions.org/training/isa/future-solar-policy (accessed on 31 January 2022).
18. USAID; MNRE. *Case Study on Virtual Net Metering: Partnership to Advance Clean Energy Deploy-Ment (Pace-D)*; USAID: Washington, DC, USA; Ministry of New and Renewable Energy: Delhi, India, 2018. Available online: https://solarrooftop.gov.in/knowledge/file-14.pdf (accessed on 6 April 2022).
19. Roux, A.; Anjali, S. *Net Metering and PV Self-Consumption in Emerging Countries*; Photovoltaic Power Systems Programme EA-PVPS T9-18:2018; International Energy Agency (IEA): Paris, France, 2018. Available online: https://iea-pvps.org/wp-content/uploads/2020/01/T9_NetMeteringAndPVDevelopmentInEmergingCountries_EN_Report.pdf (accessed on 26 March 2022).
20. Langham, E.; Cooper, C.; Ison, N. *Virtual Net Metering in Australia: Opportunities and Barriers*; Institute for Sustainable Futures, UTS: Sydney, Australia, 2013. Available online: https://opus.lib.uts.edu.au/bitstream/10453/31943/1/2012004596OK.pdf (accessed on 3 November 2021).
21. Office of Utilities Regulation. *Electricity Wheeling Methodologies*; Consultation Document ELE2012004_CON001; Office of Utilities Regulation: Kingston, Jamaica, 2012. Available online: https://our.org.jm/wp-content/uploads/2021/01/electricity_wheeling_methodologies_-_consultation_document.pdf (accessed on 9 March 2022).
22. Hamada, H.; Yokoyama, R. Wheeling Charge Reflecting the Transmission Conditions based on the Embedded Cost Method. *J. Int. Counc. Electr. Eng.* **2011**, *1*, 74–78. [CrossRef]
23. USAID. *Developing the Fee for Wheeling Electricity in Pakistan: Sustainable Energy for Paki-Stan (SEP) Project*; USAID: Arlington, TX, USA, 2020. Available online: https://pdf.usaid.gov/pdf_docs/PA00XJVQ.pdf (accessed on 23 February 2022).
24. Moura, R.; Brito, M.C. Prosumer aggregation policies, country experience and business models. *Energy Policy* **2019**, *132*, 820–830. [CrossRef]
25. Moser, R.; Xia-Bauer, C.; Thema, J.; Vondung, F. Solar Prosumers in the German Energy Transition: A Multi-Level Perspective Analysis of the German '*Mieterstrom*' Model. *Energies* **2021**, *14*, 1188. [CrossRef]
26. BMWi. Gesetz zur Förderung von Mieterstrom und zur Änderung Weiterer Vorschriften des Erneuerbare-Energien-Gesetzes. Available online: https://www.bmwi.de/Redaktion/DE/Artikel/Service/mieterstrom.html (accessed on 8 March 2022).
27. Feldman, D.; Brockway, A.M.; Ulrich, E.; Margolis, R. *Shared Solar: Current Landscape, Market Potential, and the Impact of Federal Securities Regulation*; NREL: Lakewood, CO, USA, 2015. Available online: https://www.nrel.gov/docs/fy15osti/63892.pdf (accessed on 7 January 2022).
28. Iria, J.; Scott, P.; Attarha, A.; Gordon, D.; Franklin, E. MV-LV network-secure bidding optimisation of an aggregator of prosumers in real-time energy and reserve markets. *Energy* **2021**, *242*, 122962. [CrossRef]
29. Agnihotri, A.; Bhattacharya, S. *SOLshare: Revolutionary Peer-to-Peer Solar Energy Trading in a Developing Market*; SAGE Publications, SAGE Business Cases Originals: London, UK, 2022.
30. Thakur, J.; Chakraborty, B. Impact of compensation mechanisms for PV generation on residential consumers and shared net metering model for developing nations: A case study of India. *J. Clean. Prod.* **2019**, *218*, 696–707. [CrossRef]
31. Shaw-Williams, D.; Susilawati, C. A techno-economic evaluation of Virtual Net Metering for the Australian community housing sector. *Appl. Energy* **2019**, *261*, 114271. [CrossRef]
32. Christoforidis, G.C.; Panapakidis, I.P.; Papadopoulos, T.A.; Papagiannis, G.K.; Koumparou, I.; Hadjipanayi, M.; Georghiou, G.E. A Model for the Assessment of Different Net-Metering Policies. *Energies* **2016**, *9*, 262. [CrossRef]
33. HOMER-Energy, Net Present Cost. Available online: https://www.homerenergy.com/products/pro/docs/latest/net_present_cost.html (accessed on 9 March 2022).
34. The Financial Express. 8.8m more prepaid meters to be set up by 2022. *The Financial Express*. 28 February 2021. Available online: https://thefinancialexpress.com.bd/national/88m-more-prepaid-meters-to-be-set-up-by-2022-1614513449 (accessed on 15 June 2021).
35. Zhou, S.; Brown, M.A. Smart meter deployment in Europe: A comparative case study on the impacts of national policy schemes. *J. Clean. Prod.* **2017**, *144*, 22–32. [CrossRef]

36. BERC. Bangladesh Tariff Ornance 2020. Available online: https://berc.portal.gov.bd/site/page/a7258783-743a-4145-95a1-9156e4984b7e/ (accessed on 31 January 2022).
37. BDEW. BDEW-Strompreisanalyse April 2022. Available online: https://www.bdew.de/service/daten-und-grafiken/bdew-strompreisanalyse/ (accessed on 10 May 2022).
38. Hasan, A.M. Electric Rickshaw Charging Stations as Distributed Energy Storages for Integrating Intermittent Renewable Energy Sources: A Case of Bangladesh. *Energies* **2020**, *13*, 6119. [CrossRef]
39. DESCO. Monthly Operational Data. Available online: https://www.desco.org.bd/newsysadmin/mod_b.php (accessed on 4 February 2022).
40. BREB. Annual Report 2020–2021. Available online: http://www.reb.gov.bd/site/page/b1c41e26-5e60-45b8-a9c0-a53295dd52e5/%E0%A6%AC%E0%A6%BE%E0%A6%B0%E0%A7%8D%E0%A6%B7%E0%A6%BF%E0%A6%95-%E0%A6%AA%E0%A7%8D%E0%A6%B0%E0%A6%A4%E0%A6%BF%E0%A6%AC%E0%A7%87%E0%A6%A6%E0%A6%A8 (accessed on 9 March 2022).
41. DPDC. *Annual Report 2021*; Dhaka Power Distribution Company Ltd.: Dhaka, Bangladesh, 2022. Available online: https://dpdc.org.bd/page/view/32 (accessed on 21 March 2022).
42. Smets, A.; Jäger, K.; Isabella, O.; van Swaaij, R.; Zeman, M. *Solar Energy: The Physics and Engineering of Photovoltaic Conversion, Technologies and Systems*; UIT Cambridge: Cambridge, UK, 2016.
43. Ramasamy, V.; David, F.; Jal, D.; Robert, M.U.S. *Solar Photovoltaic System and Energy Storage Cost Benchmarks: Q1 2021*; NREL: Golden, CO, USA, 2021. Available online: https://www.nrel.gov/docs/fy22osti/80694.pdf (accessed on 29 February 2022).
44. World Bank. *Bangladesh Scaling-Up Renewable Energy Project*; The World Bank Report No: PAD2413; World Bank: Washington, DC, USA, 2019. Available online: https://documents1.worldbank.org/curated/en/218251551754892999/pdf/Bangladesh-Scaling-Up-Renewable-Energy-Project.pdf (accessed on 5 January 2022).
45. Solargis, Global Solar Atlas. Available online: https://globalsolaratlas.info/support/methodology (accessed on 23 February 2022).
46. Klaus, K.; Boris, F.; Björn, M.; Reinartz, K.; Igor, R.; Christian, K. Degradation in PV Power Plants: Theory and Practice. In Proceedings of the 6th European PV Solar Energy Conference and Exhibition, Brussels, Belgium, 24–28 September 2018. Available online: https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/conference-paper/36-eupvsec-2019/Kiefer_5BO75.pdf (accessed on 23 March 2022).
47. DPDC. Tariff Rate. Available online: https://dpdc.org.bd/page/view/18 (accessed on 13 June 2022).
48. Islam, S. Bangladesh's Highest-Opex Rooftop PV Plant Goes Online: Bangladesh Has Inaugurated Its Largest Rooftop Solar Array under the Opex Model, at a Location South of Dhaka. Available online: https://www.pv-magazine.com/2022/04/12/bangladeshs-highest-opex-rooftop-pv-plant-goes-online/ (accessed on 21 April 2022).
49. Siyambalapitiya, T. *Tariff Appraisal Study: Balancing Sustainability and Efficiency with Inclusive Access*; Asian Development Bank (ADB): Manila, Philippines, 2018. [CrossRef]
50. IRENA. *Renewable Power Generation Costs in 2020*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2021.
51. GlobalPetrolPrices.com, Electricity Prices around the World | GlobalPetrolPrices.com. Available online: https://www.globalpetrolprices.com/electricity_prices/ (accessed on 24 May 2022).
52. Holmberg, K.; Erdemir, A. The impact of tribology on energy use and CO_2 emission globally and in combustion engine and electric cars. *Tribol. Int.* **2019**, *135*, 389–396. [CrossRef]
53. IEA. Tracking Fuel Consumption of Cars and Vans 2020—Analysis—IEA. Available online: https://www.iea.org/reports/tracking-fuel-consumption-of-cars-and-vans-2020-2 (accessed on 28 April 2022).
54. United News of Bangladesh. *Solar Power Investors Face Land Crisis*; New Age: Dhaka, Bangladesh, 2022. Available online: https://www.newagebd.net/article/162612/solar-power-investors-face-land-crisis (accessed on 15 May 2022).
55. Islam, S. Minister highlights Bangladesh's lack of land for solar. *PV Magazine*. 25 May 2021. Available online: https://www.pv-magazine.com/2021/05/25/minister-highlights-bangladeshs-lack-of-land-for-solar/ (accessed on 15 March 2022).
56. Bangladesh Planning Commission. *Bangladesh Delta Plan 2100: Land Use and Infrastructure Development*; General Economics Division (GED), Bangladesh Planning Commission, Ministry of Planning, Government of Bangladesh: Dhaka, Bangladesh, 2018. Available online: http://www.plancomm.gov.bd/site/files/0adcee77-2db8-41bf-b36b-657b5ee1efb9/Bangladesh-Delta-Plan-2100 (accessed on 3 April 2022).
57. NEO. *Global Report Assessment of Technical Rooftop Solar Energy Potential in Select Cities*; Netherlands Geomatics & Earth Observation B.V.: Amersfoort, The Netherlands, 2021.
58. SREDA. National Database of Renewable Energy. Available online: http://www.renewableenergy.gov.bd/index.php (accessed on 25 May 2022).
59. IRENA. *Renewable Energy Policies in a Time of Transition*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2018; Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Apr/IRENA_IEA_REN21_Policies_2018.pdf (accessed on 16 April 2022).
60. Export Finance. Bangladesh—Country Profiles—Country Risk. Available online: https://www.exportfinance.gov.au/resources/country-profiles/bangladesh-test/country-risk/ (accessed on 25 May 2022).

61. UNB. Public hearing on proposed hike in bulk power tariff Wednesday; Dhaka Tribune, 17 May 2022. Available online: https://www.dhakatribune.com/bangladesh/2022/05/17/public-hearing-on-proposed-hike-in-bulk-power-tariff-wednesday (accessed on 25 May 2022).
62. RAJUK. Uttara Apartment Project. Available online: http://www.rajuk.gov.bd/site/project/511989bf-117b-4382-9b94-c62b1f898d92/উত্তরা-এপার্টমেন্ট-প্রকল্প (accessed on 29 April 2022).
63. Gjorgievski, V.Z.; Cundeva, S.; Markovska, N.; Georghiou, G.E. Virtual net-billing: A fair energy sharing method for collective self-consumption. *Energy* **2022**, *254*, 124246. [CrossRef]

Chapter 4 Technology Innovation

Electric-Three Wheelers/ Easy Bike/Electric Rickshaws in Bangladesh

Photo: Author

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4.1 Chapter highlights

- **Community Battery Energy Storage Potential:** Electric rickshaw battery swapping and charging stations could act as community battery storage systems to reduce reliance on national grid.
- **Support for Renewable Energy Integration:** Electric rickshaw batteries at the swapping and charging station can help integrate VRE like solar PV.
- **Economic and Environmental Benefits:** Widespread use of lead-acid batteries in e-rickshaws leads to short lifespans and poor recycling practices. Regulated stations can enhance battery lifecycle management, addressing economic and environmental issues.
- **Stackable Business Opportunities:** Battery-swapping stations could offer stackable services like rural virtual power plants (RVPP), grid services, and energy arbitrage, creating economic opportunities in underserved areas.

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Electric Rickshaw Charging Stations as Distributed Energy Storages for Integrating Intermittent Renewable Energy Sources: A Case of Bangladesh

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Abstract: This exploratory research outlines an opportunity for increasing renewable energy share in Bangladesh by using electric rickshaws (e-rickshaws) as a catalyst. The overall objective of this research is to show how to utilise an existing opportunity, such as e-rickshaws, as energy storage options for integrating renewable energy sources. It proposes a grid-connected local energy system considering a battery swapping and charging station (BSCS) for e-rickshaws as a community battery energy storage (CBESS). This system was simulated using the HOMER Pro software. The simulation results show that such systems can help communities significantly reduce their dependency on the national grid by integrating solar PV locally. The proposed BSCS also shows an opportunity for battery demand reduction and circular battery management for electric rickshaws. The research also discusses the economies of scale of the proposed method in Bangladesh, and pathways for implementing microgrids and smart energy systems. The innovative concepts presented in this research will start a policy-level dialogue in Bangladesh for utilising local opportunities to find an alternative energy storage solution and provide momentum to the researchers for further studies.

Keywords: electric rickshaw; battery swapping station; battery energy storage system; community energy storage; renewable energy integration; microgrids; smart energy systems

1. Introduction

The intermittent characteristics of renewable energy (RE) sources, especially solar and wind, is a major challenge for integrating them into the grid [1]. Energy storage systems are considered to beg the most suitable add-ons along with variable energy technologies for technically and economically safe integration in the grid [2]. The literature offers a diversity of energy storage options, such as pumped hydro, batteries and compressed air, some of which are considered to be economically attractive in the current time horizon [3]. However, there is a serious lack of studies in the literature that outline suitable energy storage options for developing countries, such as Bangladesh. Bangladesh is considering using hydro resources from Nepal and Bhutan through cross-border electricity trade for meeting its increasing energy demand, which can also be used as storage to handle the variability of local renewable resources [4]. However, this option is still in an initiation phase and lacks sufficient economic, technical, and geopolitical studies. Realising a need for studies to foster RE integrations in developing countries, the Energy Sector Management Assistance Program (ESMAP) of the World Bank Group has launched a new initiative in 2019 called Energy Storage Partnership (ESP) for developing energy storage solutions [5]. Similarly, the Asian Development Bank (ADB) has also released a handbook on battery energy storage systems (BESSs) in 2018 for the promotion of RE integrations [1]. This book mentions several options for BESS and emphasises lithium-ion technology considering the market growth due to electric vehicles (EVs). However, this study completely overlooks the proliferation of informal EVs, such as electric rickshaws, and consequent growth of lead-acid battery market. Considering these facts, taking Bangladesh as a case country, the author scrutinises how existing opportunities, such as electric rickshaw, can be utilised as energy storage options with the help of modern technologies. The remainder of this article continues with a background study on electric rickshaws and renewable energy situation in Bangladesh, a comprehensive technology review for developing suitable storage option, simulation of a case using HOMER Pro software and results, and discussions on the result showing implications, economies of scale, and perceived challenges. The conclusions section summarises the findings and contributions of this work.

2. Background Study and Research Objective

2.1. Electric Rickshaw and Relevant Issues

Battery-powered three-wheelers, also known as electric rickshaws, tuk-tuks or easy bikes, are one of the prevalent modes of public transports in developing Asian countries, such as India, Bangladesh, Cambodia, and Vietnam [6,7]. E-rickshaws are popular in these countries for first and last-mile connectivity. Nowadays, it is also one of the predominant means of daily commuting for people in many urban, semi-urban, and rural areas [7,8]. In this study, the term 'e-rickshaw' is chosen to address all the battery-powered three-wheelers available in developing countries. In Bangladesh, a typical e-rickshaw uses 4–5 lead-acid batteries that offer around 4.8–6 kWh of energy at 48–60 V. On average, an e-rickshaw can carry 4–6 passengers.

The market for e-rickshaws in developing countries is thriving without proper planning to meet the growing transportation demand [9,10]. The deployment of e-rickshaw also lacks appropriate legislation. Because of unplanned growth, it puts on an additional burden on the existing energy infrastructure [7,11]. For example, in Bangladesh, while brownouts are frequent events because of insufficient energy supply to the grid, the additional energy demand of over a million of e-rickshaws adds fuel to the fire [12,13]. Considering energy issues, the Government of Bangladesh has already taken initiatives to promote solar photovoltaic (PV)-powered charging stations. However, so far, only 14 charging stations have been built, which have an aggregated capacity of less than 300 kW. All these charging stations are built off-grid and offer plug-in charging options, which is time consuming and does not add any other value. The author argues that with the help of modern technologies, the charging of e-rickshaws can be improved significantly from the technical and economic points of view.

Lead-acid batteries (LABs) are the commonly used energy carriers for e-rickshaws in Bangladesh. Recently, the domestic market size of LABs in Bangladesh has grown to nearly 1 billion USD [14]. At the same time, in India, the market is expected to reach 7.6 billion USD by 2030 [15]. In [14,15] the authors point out that this boom is especially due to the proliferation of local electric vehicles (e.g., e-rickshaws). Bangladesh alone hosts more than 25 LAB manufacturers. The retail battery market is the primary procurement source of e-rickshaw batteries. The lack of proper standardisation of e-rickshaw batteries causes considerable quality variation in the retail market. Also, there is no distinct policy for battery take-back and recycling for the used lead-acid batteries (ULABS) of e-rickshaws. In Bangladesh, despite some recognised recycling facilities, most ULABs are poorly managed. As a result, ULABs end up in scrap material businesses near human settlements. A study on toxic site identification in Bangladesh by Pure Earth 2018 identified that ULABs are predominantly responsible for 175 toxic sites located in different places in the country [16]. Some other sources [17,18] have reported a similar situation in India. According to the report, the Indian capital of Delhi alone discards nearly 1 million e-rickshaw ULABs annually. Therefore, despite offering zero tail-pipe emissions, e-rickshaws are also considered a threat to the environment because of the unregulated disposal of ULABs [17,19].

In [17,20], the authors identify the short battery life as one of the predominant factors behind the high disposal rate. They also find that e-rickshaw batteries typically last less than one year, and sometimes only 4–6 months. From a technical point of view, poor battery quality (in terms of materials), and inadequate depth of discharge (DOD) and state of charge (SOC) management are the major causes of this short battery life [21]. There are several factors that may cause poor DOD and SOC management. For example, inadequate knowledge about battery health and poor quality charge controllers [22]. The LABs used in e-rickshaws typically take 8–10 h until full charge, which affects the working hours of e-rickshaw drivers. As a result, drivers often deep discharge the batteries to extract every Ampere before recharging [22].

Being an informal and unregulated mode of transport, issues related to e-rickshaws, such as battery demand, battery disposal and relevant economic and health impact, are rarely addressed in national statistics and research. Newspapers and the grey literature are the primary sources of information on this sector, which lacks acceptance in different entities, such as science. Therefore, the author urges immediate action by policy makers and researchers to identify and address these issues of serious importance. The author also argues that with the help of modern technologies and innovative battery management, the problems related to e-rickshaws can be turned into a catalyst for sustainable development.

2.2. Renewable Energy in Bangladesh

Bangladesh is the home of over 160 million people, with a population density greater than 1100 persons per square kilometre. The country's electricity generation is highly reliant on fossil fuels, especially on its own natural gas, which represent over 60% of the total energy mix as shown in Figure 1 [23]. To date, renewable energy penetration in Bangladesh is below 5%, although the country aimed to achieve 10% penetration by 2020 [4,24].

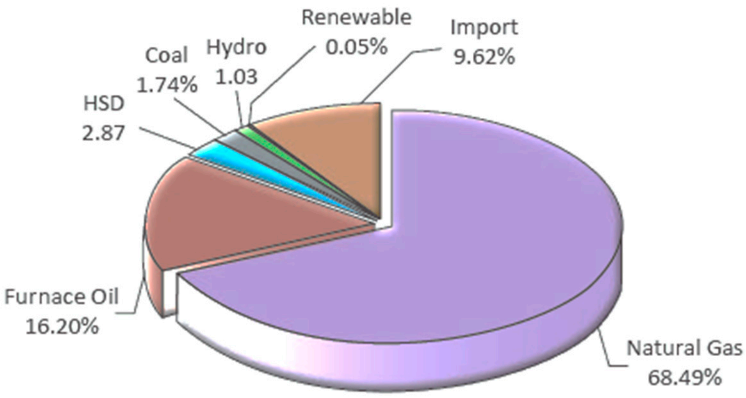

Figure 1. Grid energy generation mix of Bangladesh in financial year 2018–2019. Total generation was 70.53 GWh, which includes imports from India [23].

Solar energy is the most available and proven renewable energy resource in Bangladesh. Global horizontal irradiance (GHI) is between 4–6 kWh/m^2/day. However, up to September 2020, only a tiny portion of the potential has been realised. The total installed capacity of solar PV technologies is slightly over 400 MWp, including over 4 million solar home systems for off-grid electrification as shown in Figure 2 [25]. Land scarcity and grid constraints are the major hindrances for implementing expanded solar energy technology use [4]. To cope with the land scarcity issue, the Government of Bangladesh has announced a net metering policy in 2018 to promote rooftop solar PV. The nationwide potential of rooftop solar PV is estimated to be over 8000 MW [26]. Since variability of solar energy is a major challenge to integrate solar PV in the grid, it is not practical to implement the entire potential of solar PV considering the existing grid infrastructure and system stability. Thus, to solve these issues comprehensive studies are necessary, which calls for immediate action.

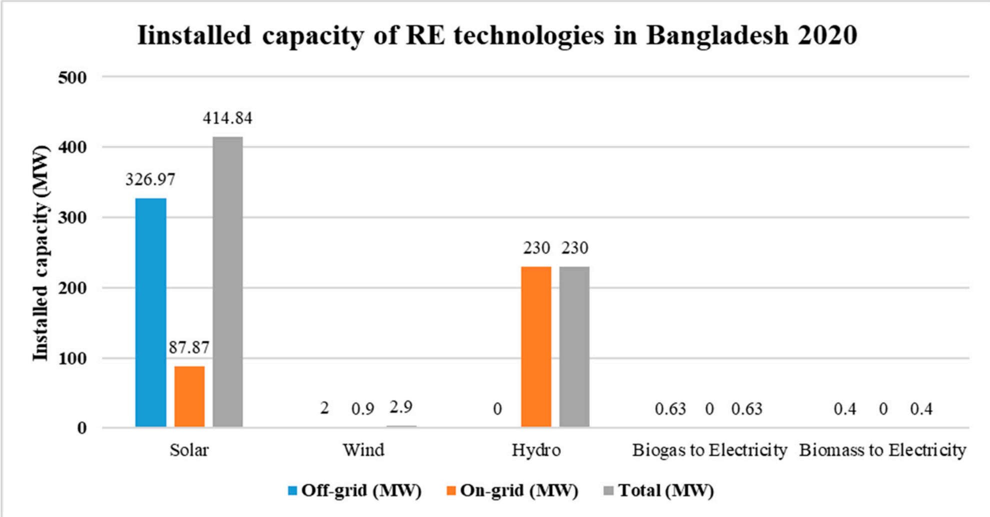

Figure 2. Installed capacity of RE technologies for electricity generation in Bangladesh as of 2020 [25].

2.3. Rationale of This Study

Growing demand for transportation and mobility deficit in Bangladesh offers the opportunity to introduce electric mobility. To date, the people of Bangladesh have successfully grabbed this opportunity and introduced electric mobility in the form of e-rickshaws. However, this introduction was neither formal nor planned. As a result, e-rickshaws may soon become a national burden. On the other hand, the Government of Bangladesh is preparing for an ambitious target for solar PV implementation without addressing technological challenges, such as variability of solar energy generation [26,27]. The author aims to couple both these issues to find a scientifically sound pathway for wider adoption. The author argues that e-rickshaws can be a catalyst for achieving the renewable energy targets of the country. The approach of this study will help to promote microgrids for decentralisation of power systems. The outcome of this study is expected to start policy level dialogues and opening new research avenues.

2.4. Objective

2.4.1. General Objective

The overall objective of this research is to outline a pathway to utilise an existing opportunity, such as e-rickshaws, as energy storage options for integrating renewable energy sources.

2.4.2. Specific Objectives

- To assess relevant technology and practices that can be materialised to find a scientific approach for creating a nexus among technologies, e-rickshaw, and renewable energy related problems.
- To assess suitability of the identified approach through a case study in Bangladesh that can address the general objective and address the problems discussed in the background section.

3. Technology Review

3.1. Battery Energy Storage System (BESS) for Integrating Renewable Energy (RE) Sources

BESS is considered being a significant catalyst for integrating RE into the grid globally [1]. BESS offers several technical features that can provide adequate support to the grid to handle the variability of wind and solar energy sources, such as energy time-shifting, voltage ramp up or load following, frequency regulation and peak shaving [1,2,28–31]. In [30], the authors recognise 13 services that can be offered by BESSs. The authors also identify relevant stakeholders who can benefit from BESS, such as independent system operators, utilities, and customers of the power system (see Figure 3). Apart from load shifting, most ancillary services required for RE integration are instantaneous power-dependent and less energy-intensive [1]. Therefore, the authors in [1,30] point out that single application of BESS may not offer a net economic benefit, hence a stackable value proposition is necessary.

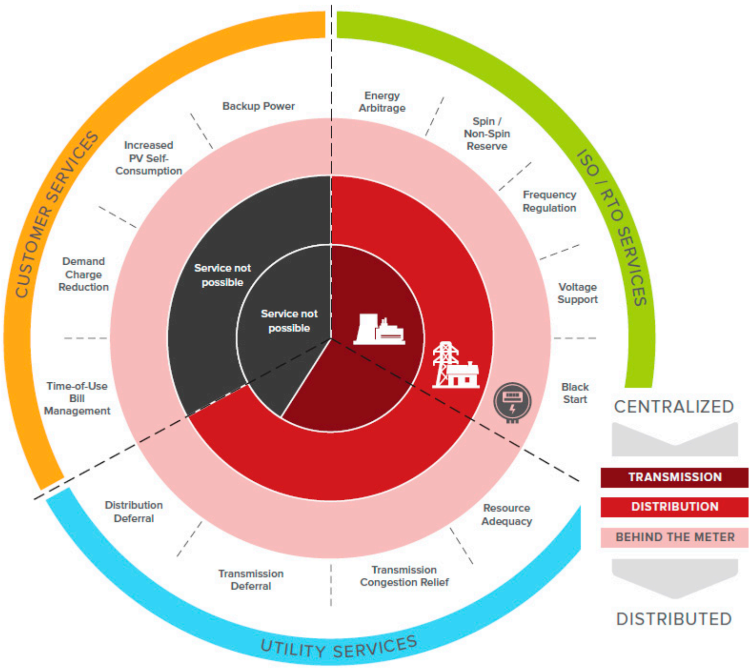

Figure 3. Illustration of 13 services offered by BESS to three main stakeholders: (1) Utility, (2) Customer, (3) Independent System Operator, ISO or Regional Transmission Organizers, RTO. Source: Fitzgerald et al. 2015 [30].

Typically, BESSs are configured as stationary and batteries are assembled in containers. An aggregated form of the batteries of electric vehicles (EVs) at a single point can also be compared as a BESS. However, this opportunity is rarely explored in the literature for providing RE integration and other ancillary services.

3.2. Community Energy Storage (CES)

Similar to community energy phenomenon [32], community energy storage (CES) is an existing concept to make communities self-sufficient in energy. In Europe, there are a handful of CES systems providing several services to different communities [33]. A case study reported in [33] identifies that the major actors of CES are network operators, such as local utility companies, energy cooperatives, and housing associations. For further adoption of CES, the authors in [34] mention that social and behavioural aspects need to be actively addressed as well as techno-economic issues. The authors in [34] present three configurations of CES, which can be implemented for communities in rural areas. The first configuration in the table “shared residential energy storage” is comparable with the concept of a peer-to-peer solar energy sharing network of the company SOLSHARE in Bangladesh [35]. In this network, energy generated by solar home systems (SHS) is stored batteries at different households. Then the energy is shared among the households connected in the network. The second configuration, “shared local energy storage”, which is are suggested to install behind the local electric transformer. Energy flow in this configuration remains mostly within the community for enhancing self-sufficiency and surplus production is either exported to the grid or curtailed. However, dual purpose of storage is rarely studied in the field of CES for example use of electric vehicle batteries as CES. The author argues that this configuration can also be imagined with the concept with aggregated batteries of EVs/e-rickshaws at a single point

3.3. Battery Swapping Station (BSS)

The battery swapping concept stands for replacing discharged batteries with a fully charged one, especially in an EV. This technology is nearly 100 years old. Because of the rapid growth of fossil fuel based vehicle and less use of electric vehicles (EVs), this technology could not flourish like petrol stations [36]. Today, battery swapping stations is becoming popular again to avoid charging time for EV. China is already in the forefront of this movement for offering battery swapping services to electric cars and motorcycles [37]. BSSs offer an energy service model rather than battery ownership, which minimises the risks of low battery lifetime to the vehicle owners [38]. BSSs also offer less investment compared to distributed EV charging points [39]. However, this option is rarely explored for e-rickshaws. Similarly, the concept of using BSSs as BESS or CES for integrating variable renewable energy sources in the grid is also seldom considered.

3.4. Microgrid and Smart Energy Systems

Nowadays, microgrids are a popular concept for decentralisation and democratisation of power systems. This concept offers utilisation of local renewable energy resources to increase self-sufficiency at the same time reduce dependency on national grid. It has a significant potential to improve reliability of electric power system, which is a wide discussion in Bangladesh [40]. In [41] the authors claims that the microgrid can also act as an electric vehicle aggregator to integrate EVs into power systems, and provide additional storage services. However, in Bangladesh, the microgrid concept is only studied for off-grid electrification. Considering the proliferation of e-rickshaws in Bangladesh, the author argues that e-rickshaws can help enhance the adoption of the microgrid concept in Bangladesh.

Sector coupling is one of the major pillars for smart energy systems towards maximising the share of renewable energy in the energy mix [42]. EVs are recognised as a potential pathway for coupling electric energy system with transportation. However, in developing countries, introducing formal EVs, such as cars and trucks, is still challenging for various reasons, such as availability of EVs, cost, technological challenge, infrastructure, and the availability of energy in the grid [43]. E-rickshaws and e-bikes are, on the other hand, bypassing these barriers and growing informally. The authors in [44] demonstrate that vehicle to grid (V2G) technology as an option for integrating RE sources in the grid. However, due to capacity constraints, the impact of a single EV on the grid is insignificant while investment cost for charging infrastructures for numerous EVs is very high [45,46].

Unlike formal EVs, the potential of V2G and G2V technologies for informal EVs (e.g., e-rickshaws) is highly underexplored from the perspective of smart energy systems. The potential reasons behind this could be bulky battery size (e.g., lead-acid battery), lifetime, and low energy content of batteries among other. Therefore, the author envisages an opportunity to explore the potential of an e-rickshaw BSCS to grid concept, which can initiate the process of smart energy systems in rural areas. Such smart energy systems can enable coupling other sectors, such as electric river transportation (e.g., ferryboats), agriculture and productive use of energy.

3.5. Potential Application of Existing Technologies for EVs/E-Rickshaws

The literature reviews on different scientific approaches and technologies presented above, can be stacked on each other to create an innovative approach for addressing the problems described in the background of this study. Figure 4 below shows an option for systematic application of the above mentioned technologies that can help to address the problems sustainably. The figure summaries that the first step is to switch from traditional plug-in charging to swap charging by establishing a BSCS. Then using the BSCS as a CES, which can adopt the technology advantages of BESS for RE integration. Then the CBESS enables the process of implementing microgrid and smart energy system.

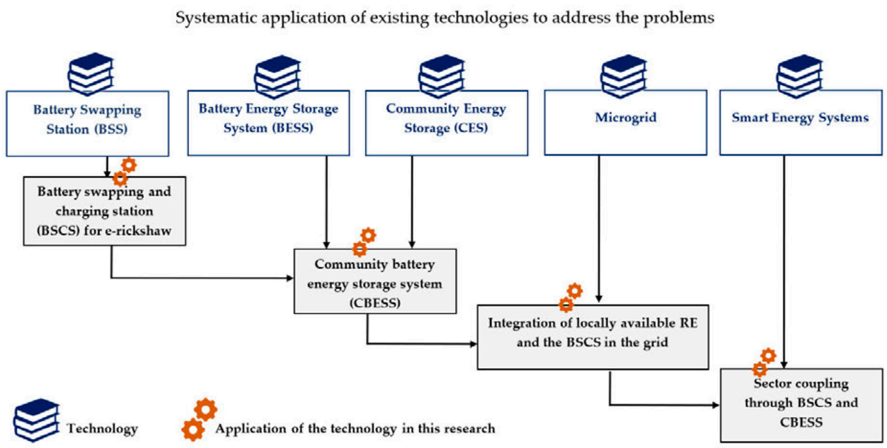

Figure 4. Application of existing technologies in this research to address the problems.

The author argues that the novel approach can offer several outcomes as outlined in Table 1. An example of this novel approach is shown in Figure 5, in terms of an energy system in rural area.

Table 1. Stackable technologies, their applications, and implications for e-rickshaws and RE promotion.

Technology	Application	Implication
BSCS	- Saving time needed for charging e-rickshaws/EVs - E-rickshaw battery management	- Supports for RE integration, such as energy-time shift, reduce curtailment and ancillary services. - Extend battery life and reduction of battery disposal
CBESS	- Storing energy from locally generated energy from RE sources. - Battery management	
Microgrid	- Aggregating local RE generators, storages, and grid to meet local demands.	- Increase RE share in local energy mix - Reduce dependency on national grid. - Enhance reliability of power system. - Migration from fossil fuel-based system to electrical energy system.
Smart Energy Systems	- Sector coupling in rural areas	

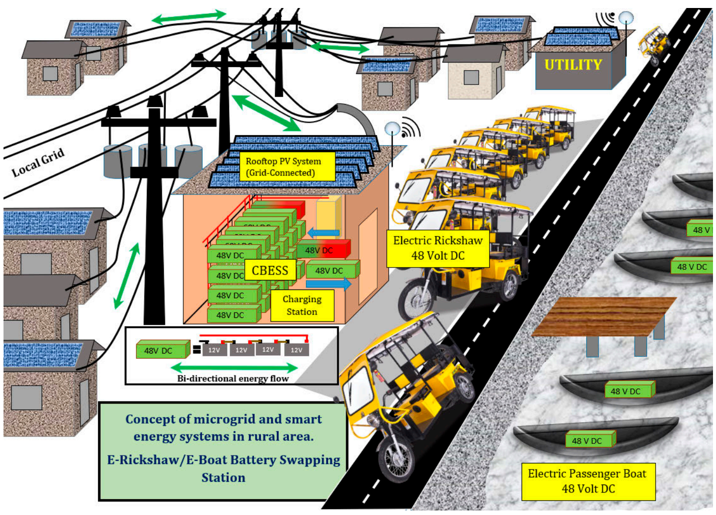

Figure 5. The concept of rural smart energy systems using a BSCS for e-rickshaws. Major components include e-rickshaw or similar transports, distributed/rooftop solar PV, local grid, local utility, and auxiliary battery sets as community battery energy storage system (author's illustration).

4. Case Study with the Identified Approach

4.1. Case Formulation

This case study considers a small grid-connected rural community in Bangladesh to realise the concept in terms of an energy system. The case community assumes a household stock of 500 households and 50 e-rickshaws for e-mobility. With this two demand groups, an energy system architecture was designed as shown in Figure 6. For the sack of simplicity, commercial and industrial sectors was kept out of scope. Solar PV technology and grid were considered as energy sources in the system. Electric rickshaws were integrated in the system through a BSCS which is represented in a combination of a CBESS and e-rickshaw charging load.

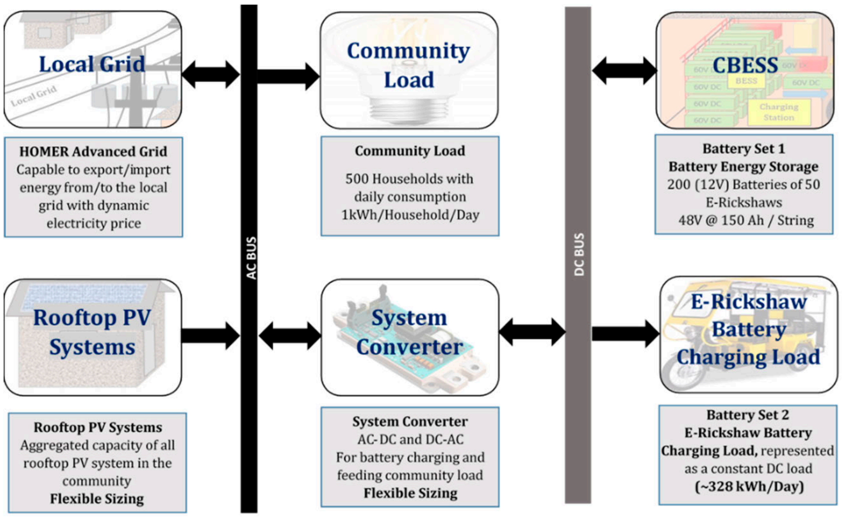

Figure 6. Architecture of the system for HOMER Pro software (author's illustration).

It assumes the BSCS comprises two sets of batteries for each e-rickshaws. The nominal operating voltage of a typical e-rickshaw in Bangladesh is 48 V DC, which is achieved using four LABs in series. Hence, the battery requirement for 50 e-rickshaws is 200. To offer one swap per day for 50 e-rickshaws, the BSCS requires 400 batteries i.e., two battery sets or battery packs for each e-rickshaw. Figure 7 shows the daily operations of two sets of batteries.

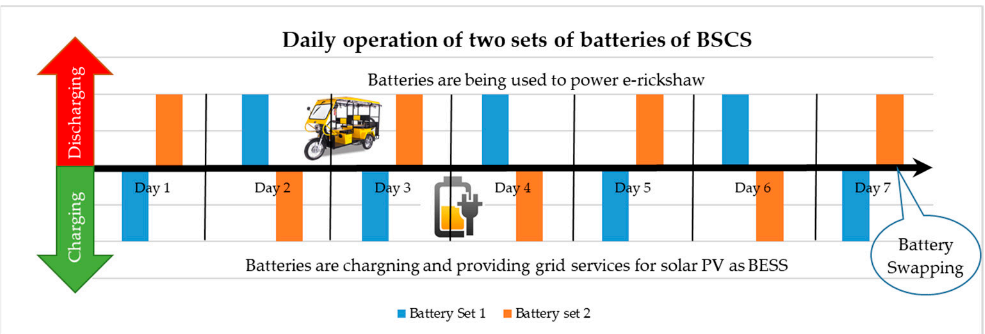

Figure 7. Daily operation of two sets of batteries.

4.2. Simulation Software

For simulation and analysis, this case study uses the HOMER Pro® microgrid software by HOMER Energy. HOMER Pro is a widely used simulation software for renewable energy systems. HOMER Pro can perform three main tasks, such as simulation, optimisation, and sensitivity analysis. HOMER pro uses least cost optimization model. It determines best possible mix of energy resources to deliver least-cost solutions. During simulation when a system configuration is found sufficient to meet the demand, it calculates the life cycle costs for that system configuration. Details of the simulation model and calculations can be found in [47–50]. The following section describes the different input parameters for the simulation. The subsequent section describes important assumptions for this case study.

4.3. Defining System Demands

Household Energy Demand for the Community: Electricity consumption of the community was assumed as per the bottom line of Tier 3 energy consumption (1 kWh/household/day), according to the multi-tier framework of the World Bank [51]. The aggregated electricity consumption for the community was calculated to be 500 kWh/day. Figure 8 shows the average daily community load. The load curve was determined by using the built-in community load profile of HOMER Pro software [47]. For simplicity, seasonal variation was omitted.

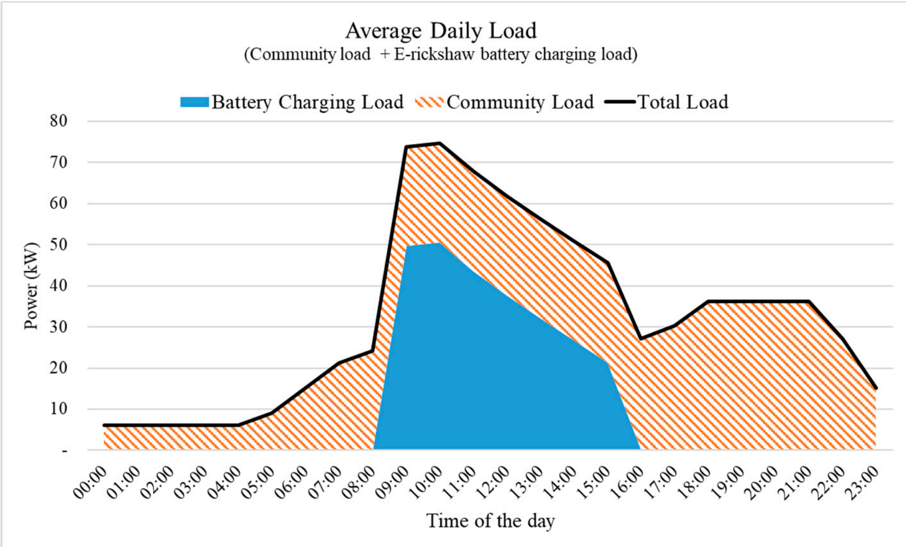

Figure 8. Average daily total load of the system. The total is the sum of community load and e-rickshaw battery charging load. The annual demand was calculated to be 256,595 kWh.

Energy Demand for E-rickshaw: For each e-rickshaw, a 7.2 kWh battery capacity was considered, which comprises four batteries, each having a capacity of 150 Ah at 12 V. Daily total energy demand for 50 e-rickshaws was calculated at 203 kWh considering DOD 50% and a charging efficiency of 89% [21]. The estimated daily energy demand for 50 e-rickshaws or 200 batteries was kept constant throughout the year. The load curve was determined by using the charging power required at 0.1 C charging rate of typical lead-acid batteries, which can be found in [52]. Figure 8 also shows the load profile of the e-rickshaw battery charging load. In the load curve, the charging duration was considered during the typical sunshine hours of a day when grid have more energy from solar PV.

4.4. Solar Resource

The solar irradiation data was collected from a location (geographic coordinates: 23.97N, 90.88E) in Bangladesh, which is a potential site for BSCS development. The data is shown on Figure 9. Annual average GHI was found to be 4.65 kWh/m^2/day. The data was populated using integrated function of data collection in HOMER Pro software, which collects data from NASA surface meteorology and solar energy.

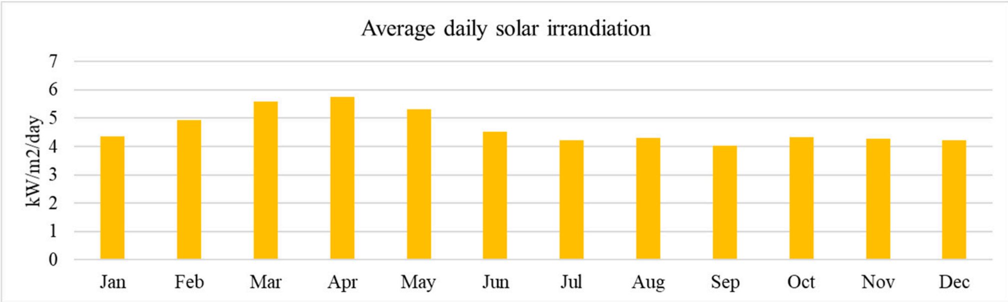

Figure 9. Monthly average daily solar irradiation for the assumed system location.

4.5. System Components and Costs

PV systems: The PV system size was determined by using the HOMER Optimizer™ algorithm, which calculates the economically optimised capacity of the PV array required for meeting the demands. The capital investment cost of PV system was considered is 600 Euro/kWp, which includes PV modules with an efficiency of 20% [26]. The annual operation and maintenance cost was set to be 8 Euro/kWp. From the implementation point of view, rooftop PV systems were considered for the system as shown in Figure 5.

Battery energy storage or CBESS: For battery energy storage or CBESS, flooded lead-acid batteries were considered. A total of 200 batteries were considered in the system as storage. The nominal capacity of each battery is 1.8 kWh. The aggregated capacity of the battery bank results to be 360 kWh. The capital investment of the battery bank was considered is 153 Euro/kWh and 110 Euro/kWh as replacement cost. The annual cost of operation and maintenance was set to 5 Euro/battery. Considering 4 years of lifetime, the DOD was set to 60%, and a round trip efficiency is assumed to be 80%.

System converter: Like the PV systems, the HOMER Optimizer™ was also used for calculating the optimum capacity of the system converter. HOMER calculates converter capacity based on maximum DC load and maximum AC load need to be served from storage. It was assumed that the converter can perform the functionalities of BESS for VRE integration. Therefore, the capital cost of the converter was set to 300 Euro/kW with an efficiency of 95% and a lifetime of 10 years [1].

Local grid: HOMER advanced grid option was considered for the grid component. The HOMER advance grid option allows energy import to and export from the local grid according to a dynamic rate definition, as shown in Figure 10. To simulate the actual situation of the rural electricity system in Bangladesh, a reliability factor was also considered. The mean outage frequency was set to be 200 times/year with a mean repair time of 30 min.

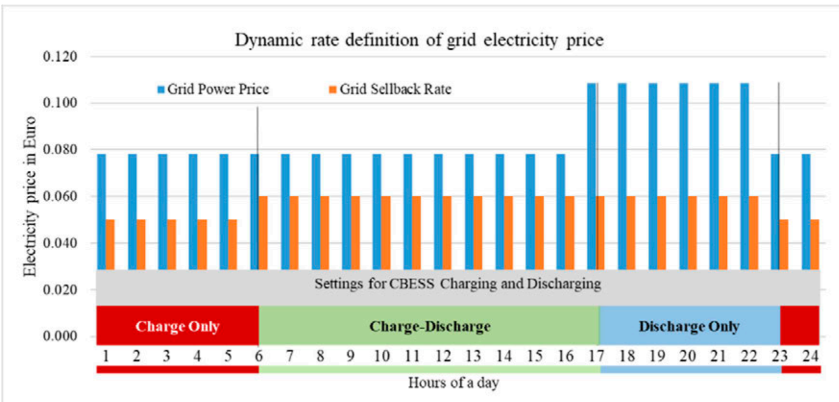

Figure 10. Dynamic rate definition of grid electricity price (power price and sellback rate) and conditions for CBESS dispatch.

4.6. Key Assumptions

4.6.1. Battery DOD and Capacity Selection

The overall DOD of batteries was set to be 60%. It assumes that when batteries are used in e-rickshaws, it can be discharged up to 50%. To keep a reserve for immediate grid services, 10% more DOD was set when batteries are returned to the BSCS. To select the value of the operational DOD of batteries, the life cycle vs. DOD curve of the LABs from the e-rickshaw battery manufacturer and literature were studied. It was found that at 60% DOD; the batteries offer around 1700 cycles, which can be translated into 4 years and 240 days considering one cycle per day [53,54].

Considering DOD of 50%, required battery capacity was calculated to be 150 Ah, which offers around 8 h of operation per day. For the calculation of operation hours Equation (1) was developed. The equation uses technical parameters of e-rickshaw presented in [55]. The authors in the reference claim that average energy consumption of an e-rickshaw is 34 Wh/km at an average speed of 13 km/h.

$$Operation\ time\ (h) = \frac{E_{batt} \times \%\ \mathrm{DOD}}{L_{batt} \times aS} \quad (1)$$

where E_{batt} is the total capacity of e-rickshaw battery in kWh, L_{batt} is average energy consumption in Wh/km, and aS is the average speed of e-rickshaw in km/h.

4.6.2. Battery Charging and Discharging

For charging and discharging of the batteries, the Homer Kinetic Battery Model [47] was used. The mathematical model for the kinetic battery model is provided in Appendix A. Table 2 shows the parameters and respective values that are used in the kinetic battery model.

Table 2. Parameters for Kinetic Battery Model in Homer Software.

Parameters	Value
Nominal Voltage (V)	12
Round Trip Efficiency (%)	80%
Minimum State of Charge (%)	40%
Maximum Charge Rate (A/Ah)	1
Maximum Charge Current (Amp)	15
Maximum Discharge Current (Amp)	300 (considering 2C rate)

4.6.3. Local Grid

A dynamic rate was set considering the electricity tariff based on the time of use (TOU) approach. In Bangladesh, TOU is defined as off-peak (23:00–17:00) and peak (17:00–23:00) hours for commercial users [56]. The values of TOU were set in the grid component primarily to prohibit charging of CBESS during peak hours when sunlight is rarely available.

Currently, in Bangladesh, there is no sellback price policy. However, the sellback rate was set in the simulation to prohibit energy selling from battery to the grid between 23:00 and 05:00. During this period, energy demand in the grid is very low, and PV systems are inactive. The sellback rate was considered allowing the batteries to be charged from the grid if SOC is below 100% before swapping. This the value of the considered sellback rate is comparable with the retail electricity price in Bangladesh. The sellback rate was also used for calculating the value of excess electricity to be sold to the grid.

4.6.4. Control Logic of Grid-Connected Solar PV

The simulation assumes the grid-connected solar PV operates independently regardless the demand in the system, any surplus power is considered to be exported to the grid. An equivalent flowchart is given in Appendix B.

4.6.5. Operational Strategy and Control Logic of CBESS

The CBESS is assumed to offer different services required for solar PV integration in the grid, such as energy time-shift and PV output smoothing. Figure 11 shows daily operations of the CBESS which is controlled by the time of a day. An equivalent flow chart is also presented in Appendix C. However, the dynamic rate as shown on Figure 10 is used in HOMER Pro software as a control logic of the functionalities.

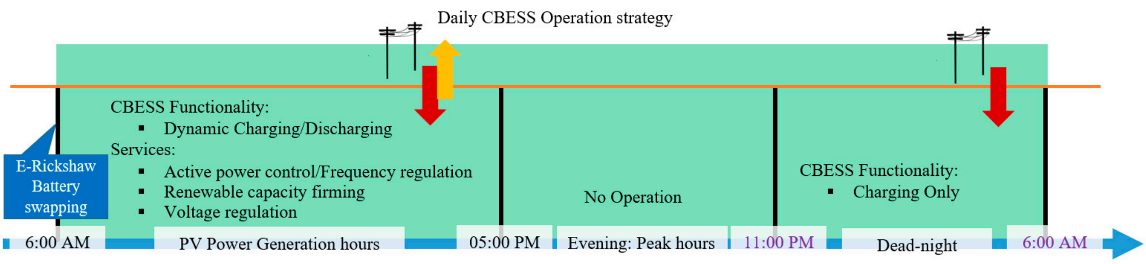

Figure 11. Time-based daily operational strategy of CBESS. Batteries are charged mainly during the day at the same time it provides grid services.

4.6.6. Economic Assumptions

The following parameters are used for economic calculations in HOMER Pro software:

- Discount rate: 12%
- Inflation rate: 5.7%
- Project lifetime: 25 years

5. Results and Discussion of the Case Study

The simulation results to be discussed here were chosen based on a maximum capacity of system converter in different system configurations, which was found to be 93 kW. The maximum capacity of the converter was chosen to assume the maximum supports for ramping up of solar PV output for compensating active power during moving cloud.

The system configurations as shown in Table 3 were sorted from a list of results by RE fraction and PV capacities at a positive cost of energy (COE). All these configurations include similar capacities of converter, batteries, and similar energy demand. The system configuration with no solar PV or grid only was considered as the base-case to compare the results with different RE fraction options. RE fraction above 94.4% showed a negative COE because of very high negative operating cost, which is not realistic. Hence, those results were omitted.

Table 3. Selected system configurations from the simulated results.

	System Configuration	Solar PV (kWp)	RE Fraction (%)	Annual Demand (kWh)	Converter Capacity (kW)
1	Grid Only (Base Case)	0	0.0		
2	RE 74.8% +Grid	235	74.8		
3	RE 87.2% + Grid	469	87.2	256,595	93
4	RE 89.3% + Grid	563	89.3		
5	RE 94.4% + Grid	1079	94.4		

The simulation result shows that a community of 500 households and 50 e-rickshaws can achieve more than 70% RE penetration by integrating 235 kWp of solar PV in the local grid. Figure 12 compares the energy balance of different system configurations. According to the figure, solar PV can help such communities to meet the energy demand for households and e-rickshaws. Integration of PV can significantly help such communities reducing dependency on fossil fuel-based national grid.

In addition, the community can also export a significant amount of energy to the grid which can help generate local economic benefits. For example, the system configuration 3 with 87% RE offers COE of 0.036 Euro, which is less than 4 Bangladeshi Taka (BDT) and less than the retail grid energy price. This configuration allows the community to export nearly 640 MWh of energy to the grid against 90 MWh of import annually. By exporting this amount of energy, the community can generate an income of nearly 15,000 Euro in each year.

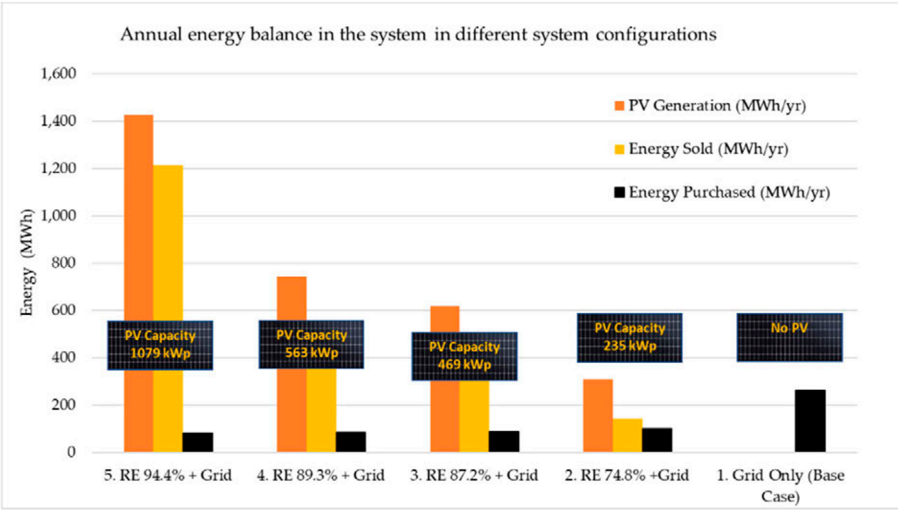

Figure 12. Annual energy balance in the systems in different system configurations.

According to the base case configuration, annual CO_2 emission is about 17 t/year because of high emission factor (670 g/kWh) in the national grid. By charging the e-rickshaw using the grid, e-rickshaws are also responsible for significant indirect CO_2 emissions. Therefore, inclusion of solar PV in the system can help the community achieve net negative CO_2 emission balance through electricity export and operating e-rickshaws. Figure 13 shows that when RE fraction reaches 87%, the community achieves net negative CO_2 balance of 410 t/year.

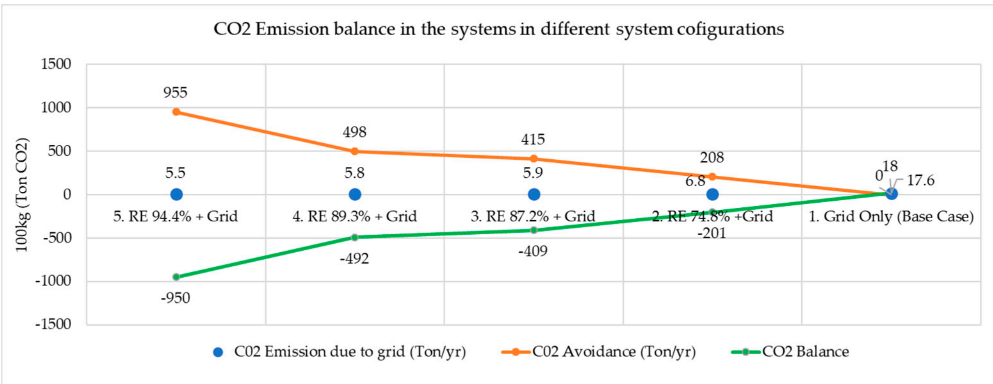

Figure 13. CO_2 emission balance in the systems. The balance was calculated considering grid emission factor of Bangladesh, which is 670 g/kWh.

Figure 14 compares net present cost (NPC), capital investment, and respective cost of energy for each of the configurations. Surprisingly, the base case shows that by charging the e-rickshaws from the grid, the community pays higher price for electricity. This also results in very high net present costs. The economic parameters can be improved substantially by integrating solar PV in the system. For example, integration of 469 kWp of solar PV in the system can help reduce the cost of energy as low as 0.036 Euro/kWh, which is still lower than the minimum retail grid electricity price in Bangladesh.

The main reason for the very low COE is because of a dramatic reduction in solar PV installation costs, which have fallen by 40% in the past 3 years in Bangladesh [26].

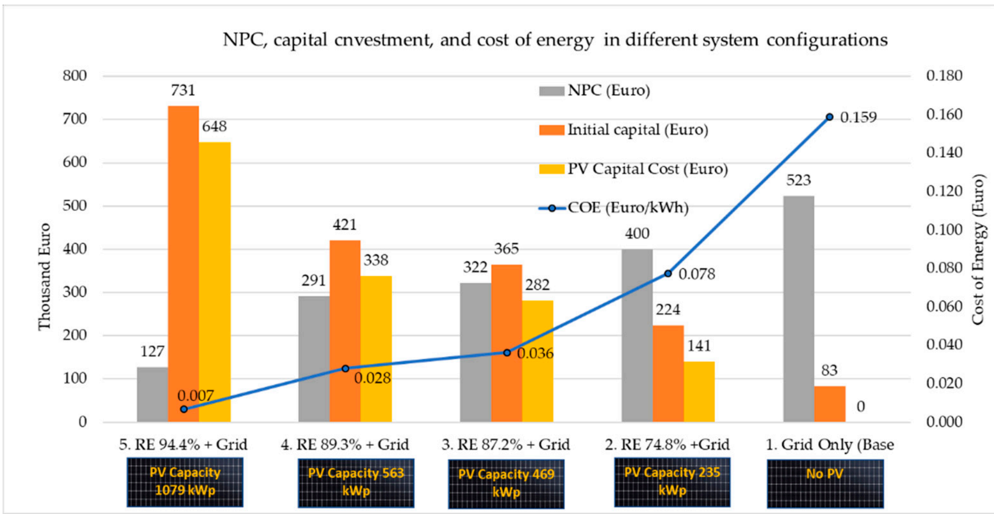

Figure 14. Net present cost (NPC), capital investment and cost of energy (COE) in different system configuration. Right axis shows the cost of energy while the left axis shows NPC (grey bars), capital investment for the whole system (orange bar) and PV capital cost (yellow bar).

To implement any of these configurations mentioned in Table 3 with solar PV, the microgrid concept can be adopted. Thanks to the grid-connected configuration of the BSCS, which can also be used as a CBESS to help integrate solar PV smoothly. Relevant supports required for solar PV integration is discussed in following subsections. To implement solar PV systems, both tooftop and ground-mounted centralised systems can be considered. Figure 5 in the earlier section shows the rooftop solar PV system concept. Since the current policy of Bangladesh does not offer a sellback price to the households, household-based rooftop PV development will not be attractive. Therefore, community owned ground-mounted system and large rooftop solar PV programs can be accelerated. In Bangladesh, a solar PV system of 469 kWp would require a surface area around 3700 m^2. These surface areas can be the rooftops of shared facilities in rural areas, such as roofs of schools, and rural marketplaces. The suitable location for the BSCS can be identified by considering solar PV injection points in the grid and common hub for e-rickshaws.

5.1. Supports for Solar PV Integration

As discussed in the literature review, stackable value streams were recommended for BESS business models to make them economically attractive [1,30]. The stackable value streams can also be imagined for the CBESS business model. The BSCS as a CBESS can support solar PV integration mentioned above by stacking two potential services of BESS. These services are electric energy time-shift and ancillary services.

5.1.1. Electric Energy Time-Shift

Typically, the main operation hours of e-rickshaw and sunshine-hours occur at the same time. Hence, to use solar energy in mobile e-rickshaws, a time-shift of PV generated energy is necessary. To cater for energy services of 50 e-rickshaws, it is necessary to shift 203 kWh of energy daily. Thanks to the BSCS concept, which makes the time shift easier without compromising working hours for battery charging. Figure 15 shows two time-shift options.

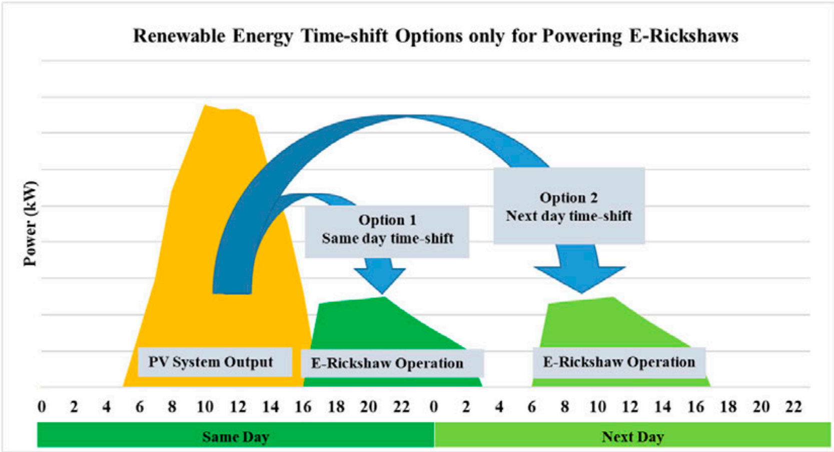

Figure 15. Renewable energy time-shift options for powering e-rickshaws. Option 1 offers same day time-shift and Option 2 offers next day time shift.

5.1.2. Capacity Firming/Solar PV Output Smoothing

Since the system was considered grid-connected, the integration of a higher amount of solar PV can potentially lead to instability. Because of moving clouds, the output of solar PV fluctuates throughout a day, which is the predominant cause for the instability. For example, it causes active power and frequency fluctuations in the power system. Thus, solar PV integration requires ancillary services for smoothing variable solar PV output. Figure 16 shows an example of PV output smoothing using energy storage.

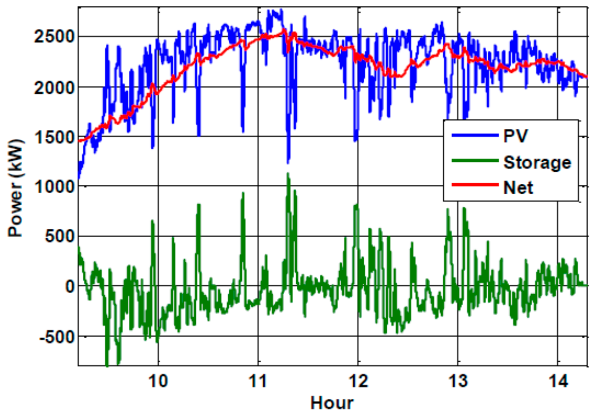

Figure 16. Example of solar PV output/ramp rate smoothing using battery energy storage on a cloudy day between 9:00–15:00 in California [57]. Blue line shows the fluctuating output of a PV system. Red line shows desired output of a PV system against its variability. The green line shows charging and discharging of the storage for smoothing PV output.

The proposed BSCS as a CBESS can play a vital role for by providing services such as active power control, voltage, and frequency regulation while batteries are charging during the day. On a time window, these services require short durations, which is instantaneous power (kW) intensive rather than energy (kWh) [1]. Therefore, to offer these services, a CBESS may not need to have a high level of SOC. Throughput based calculation of battery life can be used to identify the impact on battery life due to grid services.

5.2. An Opportunity for Reducing Battery Disposal

The lack of suitable battery management results in a shorter battery life leading to higher battery disposal. The BSCS concept can play a significant role in better battery management and extend the life of e-rickshaw batteries. To manage DOD of batteries, the battery swapping and charging station can set a pre-defined maximum DOD values in the battery boxes. The control mechanism can be similar to the concept of a prepaid solar home system. However, in this case, e-rickshaw drivers will have to return their batteries to the BSCS before the batteries reach the pre-defined DOD.

Figure 17 shows life expectancy of batteries in different DOD levels. According the graph, a battery can be used more than 4 years, if 60% DOD is maintained. Using this DOD value and lifetime, it was found that e-rickshaw battery use demand can be reduced by 3-fold without compromising energy services.

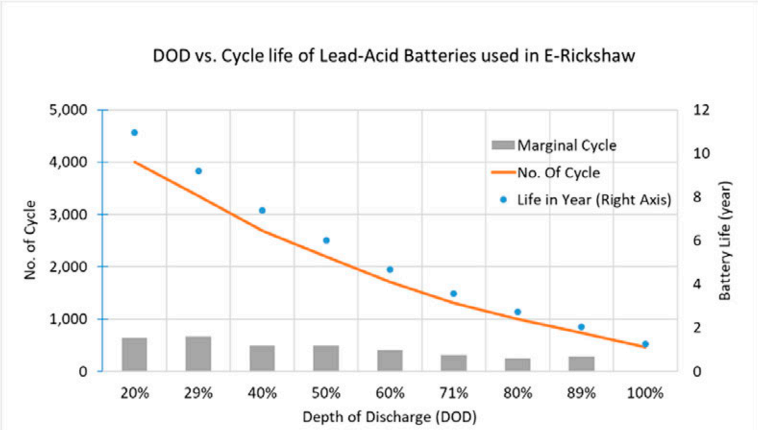

Figure 17. Depth of discharge vs cycle life (orange line) and equivalent life expectancy (blue dots) of LABs used in e-rickshaws. The grey bars show marginal cycles for every 10% additional DOD [53].

Figure 18 below compares the requirement of batteries for e-rickshaw between status quo (battery life 1 year) and BSCS option (battery life 8 years). From the figure it can be seen that over the lifetime of the project, battery demand can be reduced significantly by implementing a BSCS. Compared to status quo, the BSCS option can save nearly 3500 batteries, which will eventually reduce battery disposal. It is important to mention here that in BSCS option battery life was set to be 8 years since each battery completes a cycle in 2 days. For example, while one set of batteries is powering e-rickshaw, other set of batteries are being charged at BSCS. And the next day battery sets are altered.

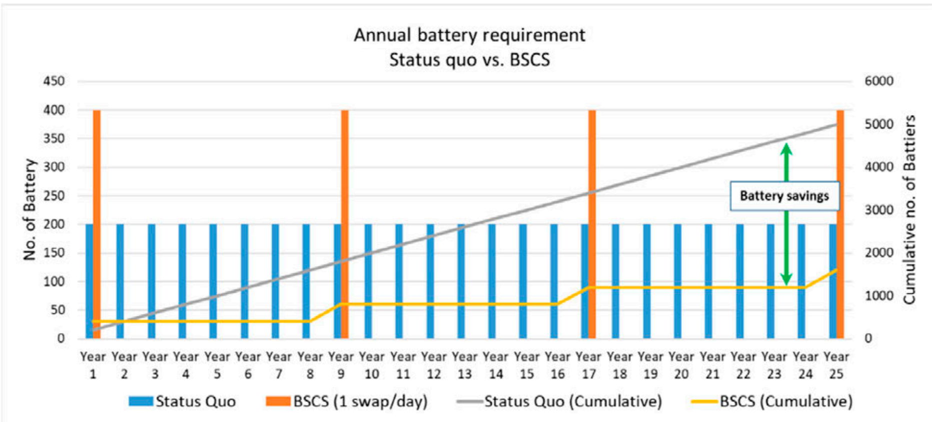

Figure 18. Annual battery requirements for 50 e-rickshaws. The blue bars represent status quo, which is no swapping and no battery management and considering 1-year lifetime. Orange bar represents battery requirements for BSCS with one swap a day with battery management to maintain 60% DOD. Battery lifetime was set to be 8 years considering one cycle in two days.

5.3. An Opportunity for Creating a Sustainable and Circular Value Chain for E-Rickshaw Batteries

To offer energy services to e-rickshaws through a BSCS, batteries need to be purchased in bulk quantity. Therefore, a BSCS can enable a sustainable value chain of e-rickshaw batteries shown in Figure 19.

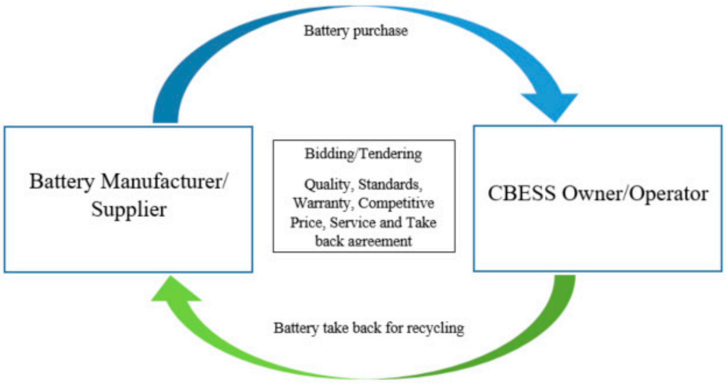

Figure 19. E-rickshaw battery value chain for BSCS option.

For example, to procure batteries for the BSCS, the owner/operator can arrange contracts with the battery manufacturer/supplier directly. Instead of the retail supply chain, bulk quantities of batteries can be purchased through an open tendering/bidding processes. This process can include specific standards, quality, and take-back ULABs. The existing business model of ULAB take-back in SHS program in Bangladesh can be consulted to implement the sustainable value chain of e-rickshaw batteries [58].

5.4. Economies of Scale

Currently, in Bangladesh, there are over 1 million of e-rickshaws and the number is still growing considerably. According to the battery life in status quo, annual demand of the batteries is around 4 million. The amount of battery disposal is also in the similar range, however, there are no clear or official statistics for this. The aggregated capacity of one million e-rickshaw batteries is around 5 GWh, considering four batteries per e-rickshaw and each battery having a capacity of 100 Ah at 12 V. Therefore, the economies of scale for implementing BSCS for all the e-rickshaws in Bangladesh is substantial. For example, if the simulated system is implemented for all e-rickshaws around the country, there is a potential for implementation of 20,000 BSCS and CBESS. These CBESS can help stable integration of nearly 5 GWp of solar PV in the grid which can help the country achieve its RE targets. Table 4 below shows economies of scale of the simulated system for whole Bangladesh. To determine this, values of the simulated system were scaled linearly. According to the table, the market size of the BSCS concept is more than 1.6 billion Euro, which can potentially open a market for solar PV a worth of 8 billon Euro. Nationwide scaling up the concept have a potential for reducing 68 million batteries in 25 years, which is equivalent to 13.6 billion Euro (nominal).

Table 4. Economies of scale of the simulated system (linear).

System Parameters	Simulated System	Economies of Scale (Bangladesh)	Unit
Battery swapping and charging station (BSCS)			
Total e-rickshaw	50	1,000,000	Nos.
Battery swapping station	1	20,000	Nos.
Individual battery capacity	1.8	1.80	kWh
Battery Requirement considering 1 Swap/day (2 sets of batteries/e-rickshaw)	400	8,000,000	Nos

Table 4. *Cont.*

System Parameters	Simulated System	Economies of Scale (Bangladesh)	Unit
Battery swapping and charging station (BSCS)			
Capacity available for CBESS	0.36	7200	MWh
Converter capacity	93	1,860,000	kW
Required initial investment for battery	€ 55,000	€ 1,100,000,000	Euro
Required initial investment for system converter	€ 27,900	€ 558,000,000	Euro
Estimated total investment for BSCS	€ 82,900	€ 1,658,000,000	Euro
Solar PV integration			
Configuration 3 (RE 87.2% + Grid) per system	0.469	9386	MW
Required initial investment (Configuration 3)	€ 0.28	€ 5632	Million Euro
Configuration 2 (RE 76% + Grid) per system	0.235	4693	MW
Required initial investment (Configuration 2)	€ 0.14	€ 2861	Million Euro
Reduction of battery disposal (25 years)			
Battery savings	3400	68,000,000	Nos.
Cost savings for batteries (Nominal)	€ 0.68	€ 13,600	Million Euro

5.5. Microgrid and Smart Snergy Systems in Rural Areas

Despite achieving remarkable progress in expanding grids for energy access, grids in many developing countries remain unreliable. According to [59], about 1.5 billion people globally, especially in developing countries, experience frequent brown and blackouts in their local grid. Lack of reliability promotes the deployment of fossil fuel backup generators and redundant systems. The CBESS can play a vital role to enhance the reliability in local grids. As a result, dependency on secondary or redundant supply systems will reduce. Implementation of microgrid can be a potential pathway for enhancing reliability in power systems combining different local and regional stakeholders.

The planning of smart energy systems is necessary towards decarburisation of energy sector. The conceptual CBESS presented can be a central component for realising such smart energy systems in rural areas as illustrated in Figure 20. The overarching application of such smart energy systems can create potential nexus among different sectors, such as transportation, agriculture, productive use of electricity.

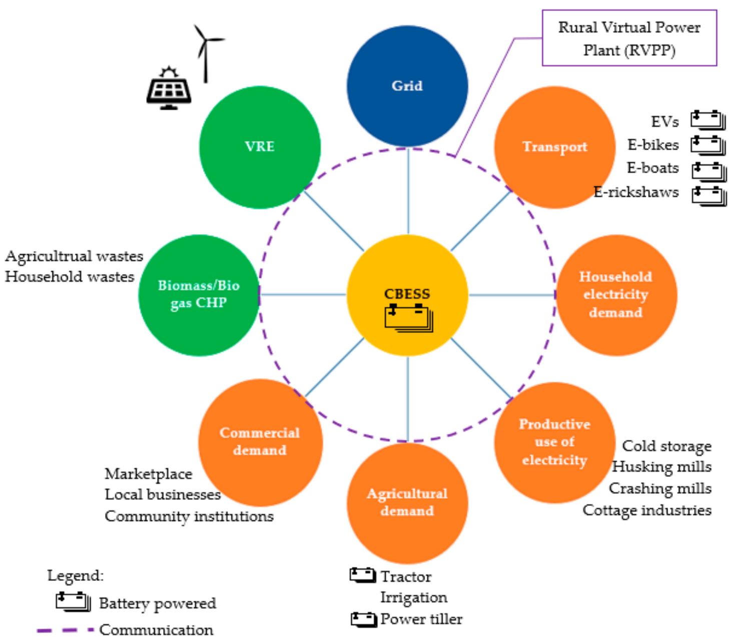

Figure 20. Concept of smart energy systems in rural areas considering the BSCS/CBESS as a central component.

5.6. Implementation Pathway and Business Bpportunities

To offer seamless energy service for e-rickshaws/EVs, a network of BSCS is required combining neighbouring communities. The network of BSCS also offers the opportunities for implementing clustered microgrids. If the BSCSs are implemented together with microgrids, new business avenues will open in rural areas. For example, energy services for e-rickshaws, grid services for local utility, energy arbitrage, and virtual power plants (VPPs). Table 5 summarises the potential business opportunities according to the business model canvas. The table shows that community, local entrepreneurs, and local utilities can play significant roles as stakeholders to generate local benefits.

The BSCS business model can be realised as the business model of energy service companies (ESCOs), which can help reduce battery-related burdens of e-rickshaw owners/drivers. For example, drivers or owners need not think of the life of the battery, brand, price, place of purchase, and disposal of the batteries. E-rickshaw drives only need to pay for energy services and rent for batteries. Such a business model can help reduce the capital cost for purchasing e-rickshaw/e-vehicle since vehicle can be purchased without batteries. As a result, additional momentum can be created for phasing out combustion engine-based and human pulled traditional public transports that can be purchased without batteries.

Lack of local human resource capacities and technology awareness, among others, are the major challenges for encouraging investment in renewable energy in rural areas in developing countries [60]. To overcome these challenges, a rural virtual power plant (RVPP) can be established either by the local utilities or the independent aggregators. RVPPs can help better management of energy in the local grids, ensuring maximum benefits for all stakeholders. At the same time, it can promote investment in the productive use of energy in rural areas. For example, it can bring rural power loads, such as rice husking, crushing mills, milk processing, and cottage industries under renewable energy supply through smart contracts and smart meters.

5.7. Challenges and Outlook

There are several challenges that need to be addressed before adopting the BSCS and CBESS concept. For example, the simulated system considers a barrier-free export of excess energy to the neighbouring community or elsewhere through the grid. Grid constraints may be a hindrance for export and import of power. Spatial analysis on the grid capacities and demand in the neighbourhood, excess energy can be optimised using site-specific design.

Bulky lead-acid batteries can be a major challenge for implementing BSCSs. This might result in a higher cost of retrofitting and a longer time for swapping. Battery swapping automation system can help reduce the time for swapping, but it would put additional investment costs. At the same time, achieving 8 years of life-time from lead-acid batteries would also be a challenge. For the sake of simplicity, these factors were omitted in this research. The author calls for an in-depth study on the economies of lead-acid battery swapping station. The study can also scrutinise issues with battery life.

Battery swapping may lead to voltage-current transients in the system and different level of battery voltage in the same bus. To study the swapping effect in details, a power system analysis is required with high-resolution data. Similarly, to realise the scale of economy geographically, a comprehensive spatial study is also necessary to identify suitable locations for the BSCSs. The author considers these issues as outlooks of this paper to initiate further studies and to attract other researchers to explore this opportunity for its applications.

Table 5. Stackable business opportunity of the BSCS and CBESS based on business model canvas.

	Stackable Business Opportunities with the CBESS			
	Battery Swapping and Charging Station	**Grid Services**	**Energy Arbitrage**	**Rural Virtual Power Plant (RVPP)**
Potential Stakeholders	- E-rickshaw/electric vehicle owners - Existing charging stations - Local entrepreneurs	- Local utility - Local entrepreneurs	- Community - PV system owners - Potential investors	- Local PV System owners - Local Utility - Independent aggregators
Key Activities/Products/Services	- Battery packs for the e-rickshaws/e-vehicles - Energy services for the e-rickshaws/e-vehicles	- Renewable capacity firming - Energy time-shifting - Frequency regulation - Voltage regulation	- Peak shaving - Energy time shift for using during peak hours - Energy services during grid outages	- Renewable Energy - Forecasting - Trading - Curtailment management - Maintenance of distributed systems in rural area
Cost Structure	- Investment cost for battery - Investment for converter - Investment cost for fixed infrastructure - Investment cost for retrofitting existing e-rickshaws - Battery swapping automation system	- Additional investment for BESS inverter - Communication infrastructure - SCADA	- Investment cost for batteries - Investment cost for converter - Energy purchase	- System communication infrastructure - Meteorological infrastructure - Capacity development
Revenue Streams	- Rent of battery packs for e-rickshaws - Sales of energy	- Sales of services based on Energy Power Service duration	- Rent of battery packs for e-rickshaws - Sales of energy	- Energy - Demand supply balancing charges - Fees for maintenance services of PV systems

6. Conclusions

To promote RE integration, especially in developing countries, this research presents the potential of taking advantage of an existing opportunity as a distributed energy storage option. Taking Bangladesh as a case country, first, it identifies the growing concerns about e-rickshaws and the challenges for RE integration. Second, through a comprehensive literature review on different technologies, it identifies that combining several technologies can help deliver a multipurpose solution that can offer several value propositions. For example, a battery swapping and charging station for electric vehicles can also be used as a community energy storage. Such community energy storage can potentially create an ecosystem for microgrid and smart energy systems, especially in rural areas. The literature also supports that concept of utilising battery swapping stations as battery-to-grid (B2G) and grid-to-battery (G2B) power transactions. In [61,62], the authors presented a similar study on battery swapping stations. The authors concluded that G2B- and B2G-enabled BSCS can benefit both customers and the utility through energy trading and eliminating the cost for new infrastructure, respectively.

The case study presented here shows an innovative control procedure for the proposed CBESS. A pre-set value of DOD and time of the day are the core control variables of this proposal. This method helps battery management and extends the operational lifetime of batteries. The method for calculating battery capacity for e-rickshaw, grid-connected configuration of the BSCS, and the concept of next day time shift ensure adequate energy services for e-rickshaws and extend battery lifetime by reducing cycle use. It also helps in keeping the e-rickshaw energy service independent from the effect of intermittent solar PV generation.

The microgrid simulation shows the RE integration potential in a small community. The simulation result revealed that integration of RE not only reduces the cost of energy, but also helps generate income through exporting energy. It also shows how such communities can become carbon neutral. The economies of scale show that currently there is a potential for 20,000 BSCS in Bangladesh. Following the CBESS approach of this research, the BSCSs can create a network of distributed energy storages throughout the country. Bangladesh has more than 60 thousand villages, therefore the network of BSCSs can be implemented either in each village or combining neighbouring villages based on household density and number of e-rickshaws in the vicinity.

Since e-rickshaws and similar modes of transports are on the rise in many developing countries, especially in South and South East Asia, there is a significant potential for wide-scale adoption of this method.

Finally, the outlook of this study shows a new avenue of research that will attract further researchers not only in e-rickshaws but also exploring other social opportunities for energy storage in developing countries.

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Conflicts of Interest: The author declares no conflict of interest.

Appendix A

Appendix A.1. Kinetic Battery Model [47]

Total battery capacity Q_{max}

$$Q_{max} = Q_1 + Q_2 \tag{A1}$$

where Q_1 is the available energy and Q_2 is the bound energy, which is bounded by limit of depth of discharge (DOD)

Appendix A.1.1. Kinetic Battery Model ($_{\text{kbm}}$) for Determining Maximum Discharging ($_{\text{dmax}}$) Power ($_{\text{Pbatt}}$)

$$P_{batt,dmax,kbm} = \frac{-kcQ_{max} + kQ_1 e^{-k\Delta t} + Qkc\left(1 - e^{-k\Delta t}\right)}{1 - e^{-k\Delta t} + c(k\Delta t - 1 + e^{-k\Delta t})} \tag{A2}$$

where Q_1 is the available energy [kWh] in the Storage Component at the beginning of the time step. Q is the total amount of energy [kWh] in the Storage Component at the beginning of the time step. Q_{max} is the total capacity [kWh] of the storage bank. c is the storage capacity ratio [unitless], c = 1 − DOD, depth of discharge. k is the storage rate constant [h−1]. And Δt is the length of the time step [h].

Maximum discharging power considering discharging efficiency

$$P_{batt,dmax} = \eta_{batt,d} P_{batt,dmax,kbm} \tag{A3}$$

Appendix A.1.2. Kinetic Battery Model ($_{\text{kbm}}$) for Determining Maximum Charging ($_{\text{cmax}}$) Power ($_{\text{Pbatt}}$)

$$P_{batt,cmax,kbm} = \frac{kQ_1 e^{-k\Delta t} + Qkc\left(1 - e^{-k\Delta t}\right)}{1 - e^{-k\Delta t} + c(k\Delta t - 1 + e^{-k\Delta t})} \tag{A4}$$

where Q_1 is the available energy [kWh] in the Storage Component at the beginning of the time step. Q is the total amount of energy [kWh] in the Storage Component at the beginning of the time step. c is the storage capacity ratio [unitless], c = 1 − DOD, depth of discharge. k is the storage rate constant [h−1]. And Δt is the length of the time step [h].

Maximum battery charging power considering maximum charge rate (Ah/h)

$$P_{batt,cmax,mcr} = \frac{\left(1 - e^{-\alpha_c \Delta t}\right)(Q_{max} - Q)}{\Delta t} \tag{A5}$$

where α_c is the storage's maximum charge rate [A/Ah] and Q_{max} is the total ca'acity of the storage bank [kWh].

Maximum battery power considering number of batteries in the storage bank

$$P_{batt,cmax,mcc} = \frac{N_{batt} I_{max}, V_{nom}}{1000} \tag{A6}$$

where N_{batt} is the number of batteries in the storage bank. I_{max} = the storage's maximum charge current [A] and V_{nom} is the storage's nominal voltage [V].

Maximum storage charge power is the power considering'charging efficiency

$$P_{batt,cmax} = \frac{MIN\left(P_{batt,cmax,kbm}, P_{batt,cmax,mcr}, P_{batt,cmax,mcc}\right)}{\eta_{batt,c}} \tag{A7}$$

Appendix B

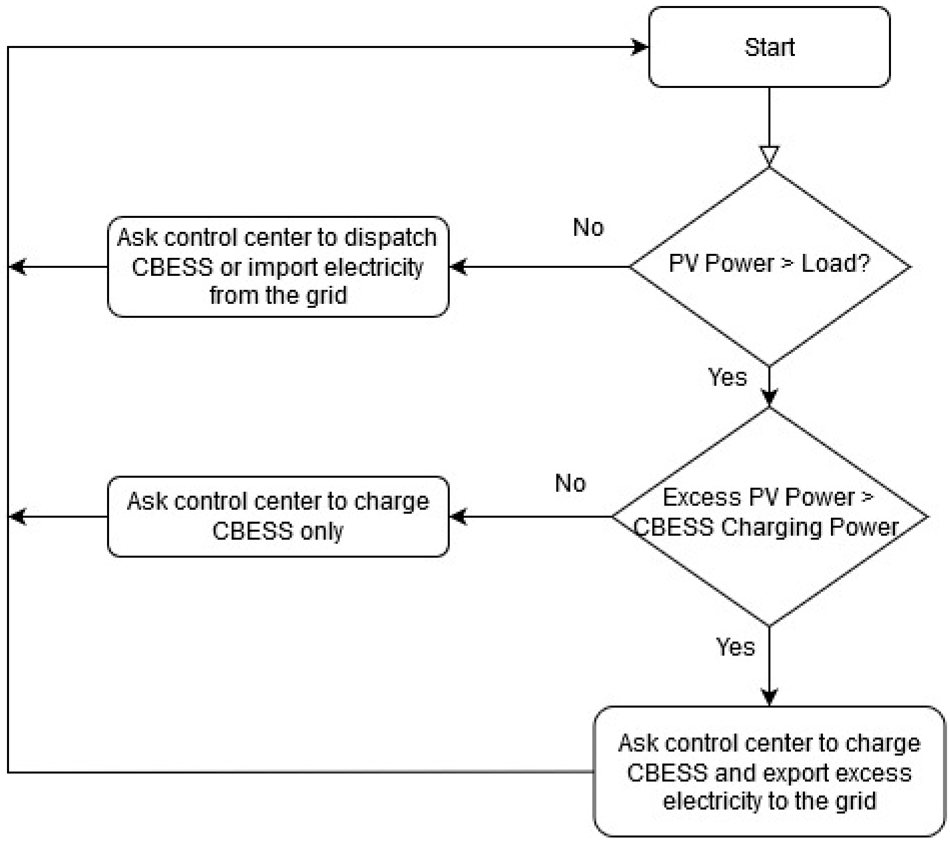

Figure A1. Flowchart for export and import from and to the grid.

Appendix C

Energies 2020, 13, x FOR PEER REVIEW 24 of 28

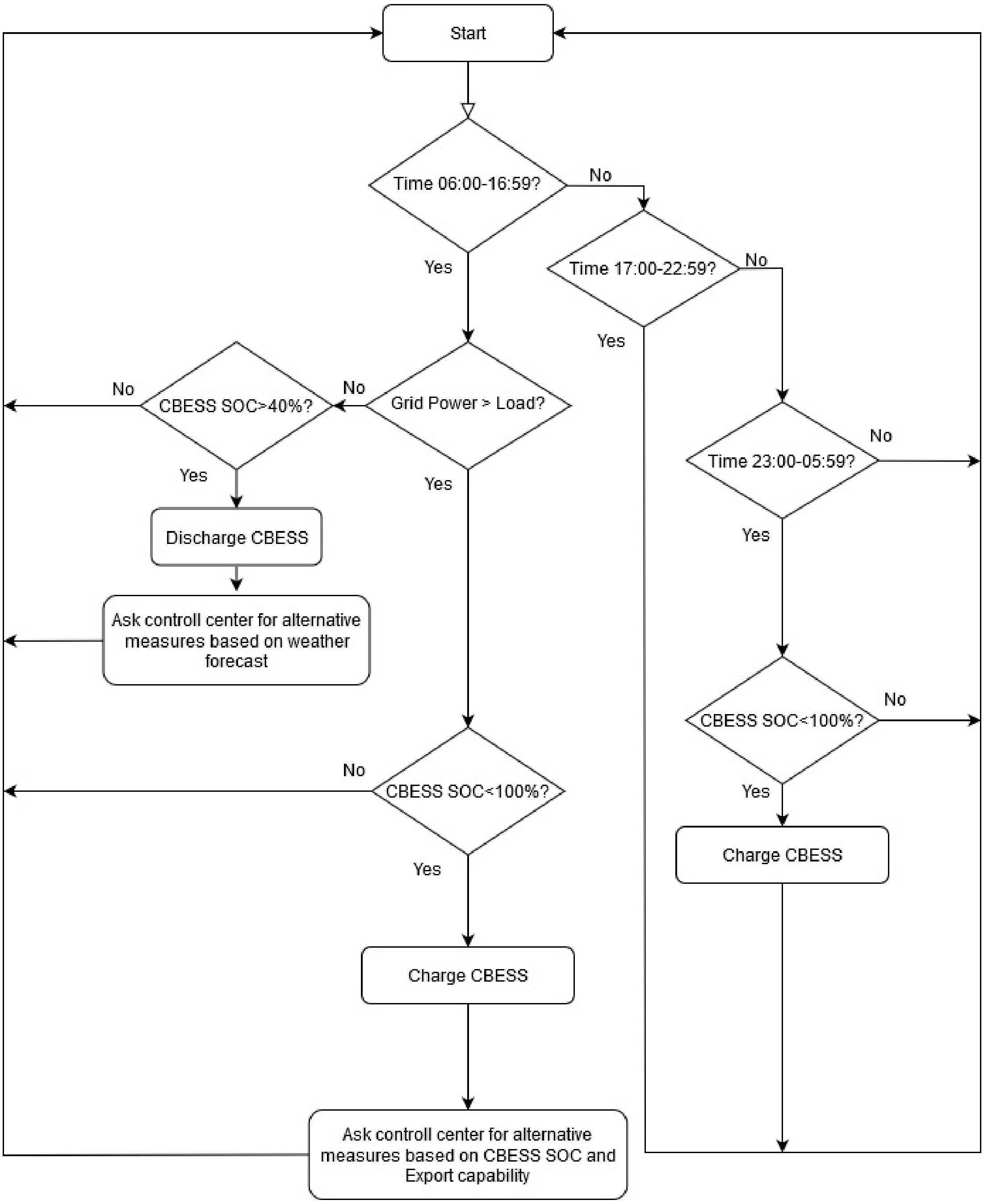

Figure A2. Flowchart of the CBESS control strategy.

Figure A2. Flowchart of the CBESS control strategy.

References

References

1. Kim, D.K.; Yoneoka, S.; Banatwala, A.Z.; Kim, Y.-T. *Handbook on Battery Energy Storage System*; Asian Development Bank: Manila, Philippines, 2018. [CrossRef]
2. Zsiborács, H.; Baranyai, N.H.; Vincze, A.; Zentkó, L.; Birkner, Z.; Máté, K.; Pintér, G. Intermittent Renewable Energy Sources: The Role of Energy Storage in the European Power System of 2040. *Electronics* **2019**, *8*, 729. [CrossRef]

1. Kim, D.K.; Yoneoka, S.; Banatwala, A.Z.; Kim, Y.-T. *Handbook on Battery Energy Storage System*; Asian Development Bank: Manila, Philippines, 2018; doi:http://dx.doi.org/10.22617/TCS189791-2.
2. Zsiborács, H.; Baranyai, N.H.; Vincze, A.; Zentkó, L.; Birkner, Z.; Máté, K.; Pintér, G. Intermittent Renewable Energy Sources: The Role of Energy Storage in the European Power System of 2040. *Electronics* **2019**, *8*, 729, doi:10.3390/electronics8070729.

3. Mongird, K.; Fotedar, V.; Viswanathan, V.; Koritarov, V.; Balducci, P.; Hadjerioua, B.; Alam, J. Energy Storage Energy Storage Technolgy and Cost Characterization Report. Available online: https://www.energy.gov/sites/prod/files/2019/07/f65/Storage%20Cost%20and%20Performance%20Characterization%20Report_Final.pdf (accessed on 3 September 2020).

3. Mongird, K.; Fotedar, V.; Viswanathan, V.; Koritarov, V.; Balducci, P.; Hadjerioua, B.; Alam, J. Energy Storage Energy Storage Technolgy and Cost Characterization Report. Available online: https://www.energy.gov/sites/prod/files/2019/07/f65/Storage%20Cost%20and%20Performance%20Characterization%20Report_Final.pdf (accessed on 3 September 2020).
4. Division, B.P. Power System Master Plan 2016. In *Power Division, Ministry of Power, Energy and Mineral Resouces*; Government of Bangladesh: Dhaka, Bangladesh, 2016.
5. ESMAP. Energy Storage Partnership (ESP). 2019. Available online: https://www.energy.gov/sites/prod/files/\T1\textquotedblleft2019/07/f65/Storage%20Cost%20a\T1\textquotedblrightd%20Performance%20Characterization%20Report_Final.pdf (accessed on 16 November 2020).
6. Frangoul, A. Fully-Electric Tuk-Tuks are Changing the Way People Get Around . Available online: https://www.cnbc.com/2018/08/10/fully-electric-tuk-tuks-are-changing-the-way-people-get-around.html (accessed on 30 March 2020).
7. del Bello, L. Delhi's Inventive Answer to the Electric Car: The Rise of the Electric Three-Wheeler could Help to Reduce India's Emissions and Improve a'r Quality, but how can this Niche Vehicle Compete on Delhi's Busy Streets? Available online: https://\T1\textquoterightww.bbc.com/future/article/20200304-the-electric-vehicles-cutting-delhis-ai\T1\textquoteright-pollution-problem (accessed on 30 March 2020).
8. Shandilya, N.; Saini, V.; Ghorpade, A.R. E-RICKSHAW DEPLOYMENT IN INDIAN CITIES-Handbook: Supporting Sustainable Mobility under Smart City Mission. Available online: https://shaktifoundation.in/wp-content/uploads/2019/07/Handbook-ERickshaw-deployment-in-Indian-Cities.pdf (accessed on 3 December 2019).
9. Ward, J.; Upadhyay, A. India's Rickshaws Outnumber China's Electric Vehicles—Bloomberg: There are more E-Rickshaws in India than Battery-Powered Passenger Car' in China. Available online: https://www.bloomberg.com/news/features/2018-10-25/india-s-rickshaws-outnumber-china-s-electric-vehicles (accessed on 22 February 2020).
10. Mehra, P. E-Rickshaw is the Low Hanging Fruit but a few Sour Spots Remain: E-Rickshaw is the Low Hanging Fruit but a Few Sour Spots Remain. 14 January 2020. Available online: https://www.thehindubusinessline.com/specials/clean-tech/e-rickshaw-is-the-low-hanging-fruit-\T1\textquotedblrightut-a-few-sour-spots-remain/article30568018.ece (accessed on 4 June 2020).
11. Rian, M.Z.; Rahman, M.A.N.; Rahman, M. (Eds.) Study on Power Consumption and Social Aspects of Battery Operated Auto-Rickshaw. In Proceedings of the International Conference on Mechanical, Industrial and Energy Engineering, Khulna, Bangladesh, 26–27 December 2014.
12. Roy, P.K. Frequent power outages plague parts of rural Bangladesh. *The Financial Express*. 9 September 2018. Available online: https://www.thefinancialexpress.co.bd/views/frequent-power-outages-plague-parts-of\T1\textquotedblrightrural-bangladesh-1536508811 (accessed on 31 March 2020).
13. The World Bank. Bangladesh Meets Clean Energy Demands with New Power Plant. Available online: https://www.worldbank.org/en/news/feature/2019/11/21/bangladesh-meets-clean-energy-demands-with-new-power-plant (accessed on 4 August 2020).
14. Hasan, M. Bangladeshi battery busting boundaries: 25 local companies now exporting to 70 countries. *Dhaka Tribune*. 9 December 2019. Available online: https://www.dhakatribune.com/business/2019/09/12/bangladeshi-battery-busting-boundaries-2-local-companies-now-exporting-to-70-countries (accessed on 3 June 2020).
15. ANI. Indiatimes Lead-Acid Battery Market will Grow Explosively with EVs, Says Deepak Ojha, MD, Waldies—ET Auto. 19 July 2020. Available online: https://\T1\textquotedblleftauto.economictimes.indiatimes.com/news/industry/lead-acid-battery-market-will-grow-expl\T1\textquotedblrightsively-with-evs-says-deepak-ojha-md-waldies/70296216 (accessed on 25 March 2020).
16. Pure Earth. Toxic Sites Identification Program in Bangladesh. Available online: https://www.pureearth.org/wp-content/uploads/2018/12/Bangladesh-TSIP-Report-UNIDO.pdf (accessed on 21 September 2020).
17. Singh, P.; Gandhiok, J. Delhi: How your green ride is turning air grey | Delhi News—Times of India. *Time Times of India*. 26 August 2019. Available online: https:/\T1\textquotedblleftimesofindia.indiatimes.com/city/delhi/how-your-green-ride-is-turni\T1\textquotedblrightg-the-air-grey/articleshow/70832937.cms (accessed on 4 Feburary 2020).
18. Harding, S.; Kandlikar, M. Explaining the rapid emergence of battery-rickshaws in New Delhi: Supply-demand, regulation and political mobilisation. *World Dev. Perspect.* **2017**, *7*, 22–27. [CrossRef]

19. Priye, S.; Manoj, M. Passengers' peceptions of safety in paratransit in the context of three-wheeled electric rickshaws in urban India. *Saf. Sci.* **2020**, *124*, 104591. [CrossRef]
20. Philip, L. Hero Electric E rickshaw: Unorganised Players with Cost Edge Lead the E-Rickshaw Race. Available online: https://economictimes.indiatimes.com/industry/auto/auto-news/unorganised-players-with-cost-edge-lead-the-e-rickshaw-race/articleshow/71788181.cms (accessed on 24 Feburary 2020).
21. Delgado-Sanchez, J.-M.; Lillo-Bravo, I. Influence of Degradation Processes in Lead–Acid Batteries on the Technoeconomic Analysis of Photovoltaic Systems. *Energies* **2020**, *13*, 4075. [CrossRef]
22. Quora Crowdsourced Answer. What are the Causes of E-Rickshaw Battery Failing within 6 Months? Which is the Best Battery for an E-Rickshaw?—Quora. Available online: https://www.quora.com/What-are-the-causes-of-E-rickshaw-battery-failing-within-6-months-Which-is-the-best-battery-for-an-E-rickshaw (accessed on 4 August 2020).
23. BPDB. Annual Report 2018–2019. Dhaka, Bangladesh, 2019. Available online: https://bpdb.gov.bd/bpdb_new/index.php/site/annual_reports (accessed on 23 June 2020).
24. BPDB. Power Generation Units (Fuel Type Wise). Available online: https://www.bpdb.gov.bd/bpdb_new/index.php/site/power_generation_unit (accessed on 21 September 2020).
25. SREDA. RE Generation Mix | National Database of Renewable Energy. Available online: http://www.renewableenergy.gov.bd/ (accessed on 21 September 2020).
26. Energy and Power. EP TALKS: Rooftop Solar Future in Bangladesh. Available online: https://www.facebook.com/watch/?v=759834161232362 (accessed on 24 Octorber 2020).
27. Islam, S. Bangladesh Outlines Plan for Up to 40 GW of Renewables in 2041. Available online: https://www.pv-magazine.com/2020/10/20/bangladesh-outlines-plan-for-up-to-40-gw-of-renewables-in-2041/ (accessed on 25 Octorber 2020).
28. Choi, W.Y.; Kook, K.S.; Yu, G.R. Control Strategy of BESS for Providing Both Virtual Inertia and Primary Frequency Response in the Korean Power System. *Energies* **2019**, *12*, 4060. [CrossRef]
29. Fusero, M.; Tuckey, A.; Rosini, A.; Serra, P.; Procopio, R.; Bonfiglio, A. A Comprehensive Inverter-BESS Primary Control for AC Microgrids. *Energies* **2019**, *12*, 3810. [CrossRef]
30. Fitzgerald, G.; Mandel, J.; Morris, J. The Economics of Battery Energy Storage: How multi-use, customer-sited batteries deliver the most services and value to customers and the grid: Rocky Mountain Institute. 2015. Available online: https://rmi.org/insight/economics-battery-energy-storage/ (accessed on 12 January 2020).
31. Stein, K.; Tun, M.; Musser, K.; Rocheleau, R. Evaluation of a 1 MW, 250 kW-hr Battery Energy Storage System for Grid Services for the Island of Hawaii. *Energies* **2018**, *11*, 3367. [CrossRef]
32. Vernay, A.-L.; Sebi, C. Energy communities and their ecosystems: A comparison of France and the Netherlands. *Technol. Forecast. Soc. Chang.* **2020**, *158*. [CrossRef]
33. Tuerk, A.; Neumann, C.; Dorian, F.; Leen, P. Emerging Business Models for Community Batteries in the EU: Story Highlight April 2019. Available online: http://horizon2020-story.eu/wp-content/uploads/STORY-highlight-Community-batteries_10.04.2019.pdf (accessed on 4 January 2020).
34. Koirala, B.P.; van Oost, E.; van der Windt, H. Community energy storage: A responsible innovation towards a sustainable energy system? *Appl. Energy* **2018**, *231*, 570–585. [CrossRef]
35. ME-Solshar. What We Do—ME Solshare: What We Do. Available online: https://www.me-solshare.com/what-we-do/ (accessed on 4 January 2020).
36. The Lost Annals of Transport. GeVeCo—The Lost Annals of Transport. Available online: https://lostannalsoftransport.wordpress.com/tag/geveco/ (accessed on 26 Octorber 2020).
37. EV Battery-Swapping Finds New Life in China. Available online: https://news.cgtn.com/news/2020-08-16/EV-battery-swapping-finds-new-life-in-China-SWZQhFZoEE/index.html (accessed on 26 Octorber 2020).
38. Neubauer, A.P.J. A Techno-Economic Analysis of BEV Service Providers Offering Battery Swapping Services. National Renewable Energy Laboratory: Ann Arbor, MI, USA, 2013. Available online: https://www.nrel.gov/docs/fy13osti/57502.pdf (accessed on 27 August 2020).
39. Zhong, L.; Pei, M. Optimal Design for a Shared Swap Charging System Considering the Electric Vehicle Battery Charging Rate. *Energies* **2020**, *13*, 1213. [CrossRef]
40. Fang, X.; Misra, S.; Xue, G.; Yang, D. Smart Grid—The New and Improved Power Grid: A Survey. *IEEE Commun. Surv. Tutor.* **2012**, *14*, 944–980. [CrossRef]
41. Mortaz, E.; Valenzuela, J. Microgrid energy scheduling using storage from electric vehicles. *Electr. Power Syst. Res.* **2017**, *143*, 554–562. [CrossRef]

42. Mathiesen, B.V.; Lund, H.; Connolly, D.; Wenzel, H.; Østergaard, P.A.; Möller, B.; Nielsen, S.; Ridjan, I.; Karnøe, P.; Sperling, K.; et al. Smart Energy Systems for coherent 100% renewable energy and transport solutions. *Appl. Energy* **2015**, *145*, 139–154. [CrossRef]
43. Dominic, P.; Artur, P.; Ivan, J.; Jamie, L.; Meredith, B.; Oliver, J.; Chiara, A.; Roland, S.; Roos, V.; Evy, B.; et al. *Electric Mobility & Development: An Engagement Paper from the World Bank and An Engagement Paper from the World Bank and the International Association of Public Transport*; The World Bank Group: Washington, DC, USA, 2018. Available online: http://documents.worldbank.org/curated/en/193791543856434540/Electric-Mobility-and-Development-An-Engagement-Paper-from-the-World-Bank-and-the-International-Association-of-Public-Transport (accessed on 16 July 2020).
44. Mathiesen, B.V.; Lund, H. Comparative analyses of seven technologies to facilitate the integration of fluctuating renewable energy sources. *Appl. Energy* **2009**, 3. [CrossRef]
45. Pigott, A. EVs on the Grid—Challenges and Opportunities. Available online: https://www.smart-energy.com/industry-sectors/electric-vehicles/evs-on-the-grid-challenges-and-opportunities/ (accessed on 4 January 2020).
46. Noel, L.; de Rubens, G.Z.; Kester, J.; Sovacool, B.K. *Vehicle-to-Grid*; Springer: Cham, Switzerland, 2019.
47. HOMER. Welcome to HOMER. Available online: https://www.homerenergy.com/products/pro/docs/latest/index.html (accessed on 3 April 2020).
48. Micangeli, A.; Del Citto, R.; Kiva, I.N.; Santori, S.G.; Gambino, V.; Kiplagat, J.; Viganò, D.; Fioriti, D.; Poli, D. Energy Production Analysis and Optimization of Mini-Grid in Remote Areas: The Case Study of Habaswein, Kenya. *Energies* **2017**, *10*, 2041. [CrossRef]
49. Lilienthal, P.; Lambert, T.; Gilman, P. Computer Modeling of Renewable Power Systems. In *Encyclopedia of Energy*; Elsevier, Academic Press: Amsterdam, The Netherlands, 2004; pp. 633–647.
50. Lambert, T.; Gilman, P.; Lilienthal, P. Micropower System Modeling with Homer. In *Integration of Alternative Sources of Energy*; Farret, F.A., Simões, M.G., Eds.; Wiley: Hoboken, NJ, USA, 2006; pp. 379–418.
51. Bhatia, M.; Angelou, N. Beyond Connections Energy Access Redefined. Available online: https://www.worldbank.org/content/dam/Worldbank/Topics/Energy%20and%20Extract/Beyond_Connections_Energy_Access_Redefined_Exec_ESMAP_2015.pdf (accessed on 4 February 2020).
52. Battery University. Charging Information for Lead Acid Batteries—Battery University. Available online: https://batteryuniversity.com/learn/article/charging_the_lead_acid_battery (accessed on 3 November 2020).
53. Rahimafrooz. Electric Vehicle and E-rickshaw—Rahimafrooz. Available online: http://www.rahimafrooz-batteries.com/electric-vehicle-and-e-rickshaw/ (accessed on 4 Octorber 2020).
54. Stenzel, P.; Baumann, M.; Fleer, J.; Zimmermann, B.; Weil, M. Database development and evaluation for techno-economic assessments of electrochemical energy storage systems. In Proceedings of the Energy Conference (ENERGYCON), 2014 IEEE International, Cavtat, Croatia, 13–16 May 2014; pp. 1334–1342.
55. Lairenlakpam, R.; Thakre, G.D.; Gupta, P.; Singh, Y.; Kumar, P. Effect of different drive modes on energy consumption of an electric auto rickshaw. In Proceedings of the 2017 IEEE Transportation Electrification Conference (ITEC-India), Pune, India, 13–15 December 2017; pp. 1–5.
56. BERC. BERC Electricity Tariff Order (Retail). Available online: http://www.berc.org.bd/site/notices/999da7ce-b204-4bcc-987c-49678efa9983/BERC-Electricity-Tariff-Order-Retail- (accessed on 23 May 2020).
57. Reno, M.J.; Lave, M.; Quiroz, J.E.; Broderick, R.J. (Eds.) PV ramp rate smoothing using energy storage to mitigate increased voltage regulator tapping. In Proceedings of the 2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC), Portland, OR, USA, 5–10 June 2016.
58. Manhart, A.; Hilbert, I.; Magalini, F. *End-of-Life Management of Batteries in the Off-Grid Solar Sector: How to Deal with Hazardous Battery Waste from Solar Power Projects in Developing Countries?* Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH: Eschborn, Germany, 2018. Available online: https://www.giz.de/de/downloads/giz2018-en-waste-solar-guide.pdf (accessed on 11 April 2020).
59. IFC. *The Dirty Footprint of the Broken Grid: The Impacts of Fossil Fuel Back-Up Generators in Developing Countries*; International Finance Corporation: Washington DC, USA, 2019. Available online: https://www.ifc.org/wps/wcm/connect/industry_ext_content/ifc_external_corporate_site/financial+institutions/resources/dirty-footprint-of-broken-grid (accessed on 11 April 2020).
60. Seetharaman; Moorthy, K.; Patwa, N.; Saravanan; Gupta, Y. Breaking barriers in deployment of renewable energy. *Heliyon* **2019**, *5*, e01166. [CrossRef] [PubMed]

61. Sarker, M.R.; Pandzic, H.; Ortega-Vazquez, M.A. Electric vehicle battery swapping station: Business case and optimization model. In Proceedings of the 2013 International Conference on Connected Vehicles and Expo (ICCVE): Electric Vehicle Battery Swapping Station: Business Case and Optimization Model, Las Vegas, NV, USA, 2–6 December 2013; pp. 289–294.
62. Sarker, M.R.; Pandzic, H.; Ortega-Vazquez, M.A. Optimal Operation and Services Scheduling for an Electric Vehicle Battery Swapping Station. *IEEE Trans. Power Syst.* **2015**, *30*, 901–910. [CrossRef]

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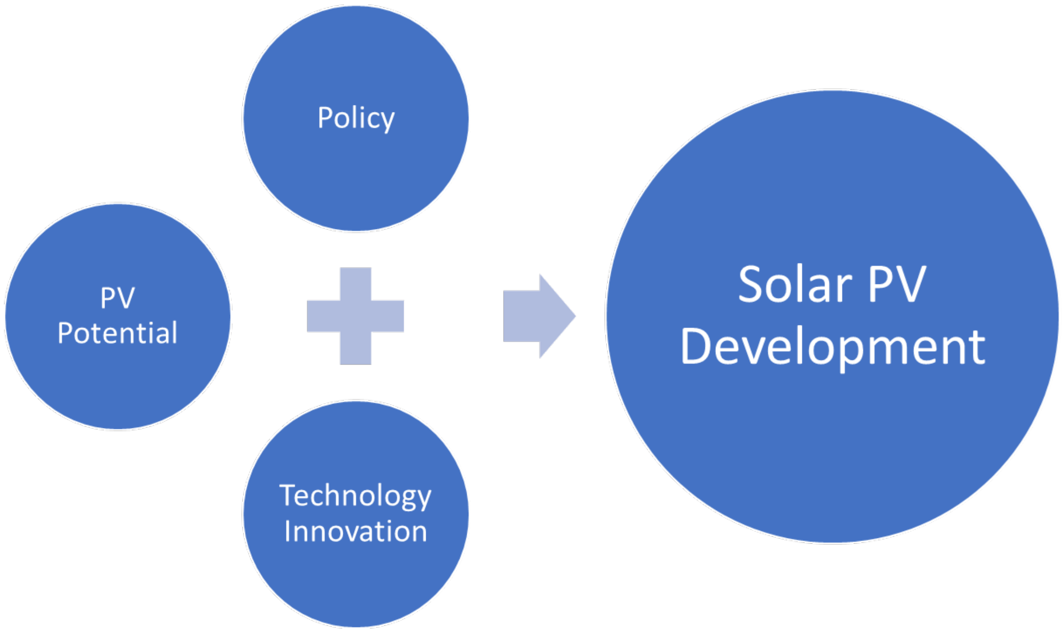
Chapter 5 Synthesis



5.1 Discussion

The overall goal of this dissertation is to contribute to the sustainable energy transition in Bangladesh by addressing distinct challenges and utilising country-specific opportunities in Bangladesh. To contribute to the goal, the author undertakes this research with the hypothesis, **"Synergising land use, policy, and technological innovation with local opportunities can create a pathway to unlock solar energy potential for a sustainable energy transition in Bangladesh."** The author articulates three research studies to support this hypothesis. In this chapter, it synthesises the findings from these three studies, presented in Chapters 2, 3 and 4.

5.2 The nexus between solar PV systems, virtual net-metering and electric rickshaws charging stations

The sustainable energy transition in Bangladesh is critical to achieving the country's climate targets, particularly through solar PV technology, due to the lack of indigenous fossil and other proven RE resources. However, land use constraints, impaired by rapid urbanisation, present significant challenges to materialising solar energy resources using traditional implementation of solar PV systems. In addition, lack of investment and grid integration issues intensify the challenge. In this dissertation, the nexus of three studies illustrates a potential pathway to address the challenges for solar PV deployment, articulating policy innovations and technical integration solutions. The following discussion creates a nexus between the research questions and findings to support the hypothesis and contribute to the research's overall goal.

Research Question 1: What is the implementable solar PV potential in Bangladesh according to different types of solar PV systems that can address the competing land use challenge?

Chapter 2 addresses this research question. The research presented in Chapter 2 on reassessing solar PV potential was motivated by the scarcity of space for solar systems due to increasing urbanisation, rapid land-use changes, and the need to preserve agricultural and forest lands. To answer this research question, this research undertakes an in-depth assessment of Bangladesh's geographic and technical solar PV potential. Using advanced geospatial modelling, the study evaluates various solar PV systems, including Rooftop PV (RPV), Ground-mounted PV (GPV), Floating PV (FPV), and Agrivoltaic (APV) systems. The research estimates a potential of approximately 30 GWp for RPV, 9 GWp for GPV, 5 GWp for FPV, and 81 GWp for APV. The potential was determined using strict land-use criteria, which resulted in a comparatively lower potential for typical ground-mounted systems but a higher potential for RPV and APV systems. Despite being a riverine country, the potential for floating PV was low due to the exclusion of water bodies with low depths and river currents. However, these figures emphasise the necessity and viability of diversifying solar PV deployment to avoid land use conflicts. The study thus discourages sole use of lands for solar PV installation and advocates for the promotion of dual land-use approaches, such as rooftop, floating and agrivoltaic PV systems, to overcome land scarcity while contributing to the national renewable energy targets. Considering the cost and technology maturity, the study emphasises the widespread implementation of rooftop potential across the country and across different sectors such as residential, commercial, industrial, government and social. Furthermore, according to population dynamics and forecasts, the potential of rooftop PV is expected to increase due to higher settlement requirements. However, for this potential to be realised across different sectors, suitable policies are essential to enable widespread adoption and increase participation in investment in solar PV systems. At the same time, it is also essential to address the variability issue of increased solar PV in the grid.

Research Question 2: What policy can help increase participation in adopting and investing in solar PV to implement the potential and address the land or space availability constraints by leveraging the widespread adoption of smart electric meters?

The research presented in Chapter 3 addresses this question. This study was inspired by the success of Bangladesh's Solar Home System Programme and the widespread adoption of smart prepaid electricity meters, which created the opportunity for policy instruments like Virtual Net Metering. To facilitate the widespread adoption of solar PV, this research explores the role of policy innovation through Virtual Net-Metering. The research showed how VNM can enable households and businesses, particularly those in multi-family or multi-storey buildings with limited space for solar PV, to invest in remote solar PV installations or share rooftop PV systems. Additionally, VNM is technically more inclusive as it removes the 3-phase requirement barrier for the traditional net-metering policy. This inclusive policy mechanism provides a financial incentive for citizens to engage in the energy transition, with the potential for significant savings in electricity costs. However, the economic feasibility of VNM showed very little benefit to the residential sector as a significant number of households enjoy subsidised grid electricity through energy progressive block tariffs. Considering the current electricity price, commercial consumers could reduce their electricity bills by over 50% through VNM, with a payback period of less than six years. Similarly, households with higher energy demand can also benefit from VNM policies, as they also pay higher electricity bills. The research recommended policy measures such as the Renewable Portfolio Standard (RPS) to engage commercial sectors in renewable energy investment and called for more economic incentives to promote PV system adoption. To encourage the widespread adoption of solar PV and to materialise rooftop PV potential, Bangladesh can utilise its experience from the Solar Home System Programme to suitable support mechanisms, such as business models, incentives and supply chains. However, in addition to the policy to encourage participation, it is necessary to improve grid infrastructure to address the grid integration challenges for the expected PV system capacity required to facilitate the sustainable energy transition in Bangladesh.

Research Question 3: How can Bangladesh address the VRE integration challenge by leveraging the growing adaptation of electric mobility, such as electric three-wheelers?

Upon identifying PV system potential and a suitable policy to increase PV deployment, the research presented in Chapter 4 answers this technical question. The research presented in this chapter was driven by the widespread adoption of electric rickshaws in the country and the quest for developing a sustainable solution. The integration of solar PV into the grid presents technical challenges, particularly given the variable nature of renewable energy. Chapter 4 outlined a pathway to address this challenge by leveraging a locally available opportunity: electric rickshaws (e-rickshaws) or electric three-wheelers. The study proposed the utilisation of battery swapping and charging stations (BSCS) for e-rickshaws as community battery energy storage systems (CBESS). Such systems could store excess solar energy and release it during periods of peak demand, thus reducing reliance on the national grid. To validate this concept, a case study was performed with distributed rooftop solar systems and a BSCS operated as CBESS. The results not only showed an increased share of renewable energy in the local grid but also showed how the community can benefit from locally installed solar PV systems. This innovative approach addresses the solar PV integration in the grid and offers an energy storage solution to increase local resource utilisation. Although the research focused on lead acid batteries considering established local manufacturing industries, the concepts presented in the study can be used with other battery technologies such as lithium-ion.

In summary, the nexus (as shown in Figure 5.1) of findings from all three research studies provides a strong argument for the research hypothesis: "**Synergising land use, policy, and technological**

innovation with local opportunities can create a pathway to unlock solar energy potential for a sustainable energy transition in Bangladesh." The geographic, technical and economic assessment of PV potential, coupled with policy mechanisms such as VNM and innovative energy storage solutions like CBESS, offers a coherent pathway for overcoming the barriers to solar PV adoption. By integrating these approaches, Bangladesh can accelerate its transition to sustainable energy, enhancing both environmental sustainability and socio-economic resilience. The following discussion continues with the multi-faceted implications of the research.

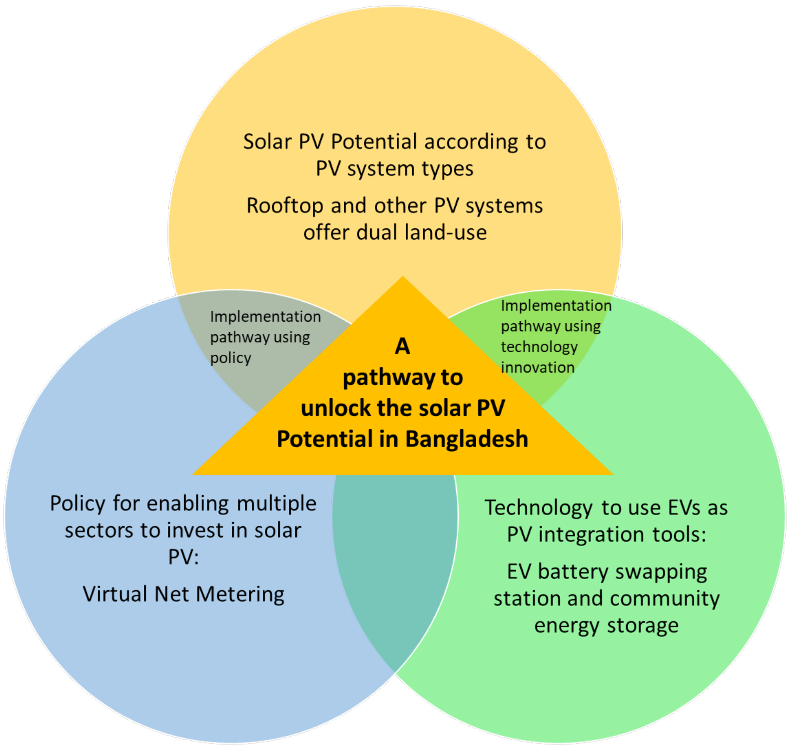


Figure 5.1 The nexus between 3 research questions and results for creating a pathway to unlock solar PV deployment in Bangladesh

5.3 Implication of the research in facilitating Bangladesh's sustainable energy transition

Including the Bangladesh government, several studies have modelled the country's energy system with scenarios involving high penetration of renewable energy, particularly solar PV, as summarised in Table 1.1 (Section 1.5, Chapter 1). These studies estimate solar PV capacity ranging from 6 GW to 127 GW, depending on the scenario and target year. While these analyses provide insights into overall energy system requirements and renewable energy capacities needed to achieve scenario targets, they largely neglect the implementation aspects, considering country-specific challenges and opportunities.

This dissertation addresses these gaps by offering a detailed assessment of solar PV potential, identifying implementable capacity, and proposing strategies that integrate policy and technical innovations. These findings not only facilitate the realisation of capacity scenarios from previous studies but also offer valuable insights for future research. Furthermore, the dissertation advocates for revising the role of solar PV in Bangladesh's Integrated Energy and Power Master Plan (IEPMP) 2023 based on its conclusions.

5.4 Implication for policy advocacy

This research advocates for amending existing policies affecting renewable energy development and formulating new policies to facilitate sustainable energy transition in Bangladesh, such as:

5.4.1 Implication for land use policy

Although Bangladesh has a relatively strict land use policy aimed at protecting and preserving agricultural lands, a gap exists between policy and practice in the development of utility-scale solar PV plants. Chapter 2 examined the current practices of solar power plant development in Bangladesh and revealed a significant reliance on agricultural lands for these projects. The analysis showed that 6 out of 10 solar PV plants were established on croplands, highlighting the extensive use of agricultural land in a country already constrained by limited land availability. This finding directly contradicts the land use policy outlined by the Sustainable and Renewable Energy Development Authority (SREDA).

The current policy framework does not adequately safeguard private agricultural lands from being sold to power plant developers. Given the long-term implications of losing agricultural lands and the potential for land use conflicts, the government must explore alternative policies to promote dual land use. This research decomposed solar PV potential based on system types while applying strict land use criteria to identify suitable locations for each type. Policymakers can leverage the land use approach adopted in this research to design and implement policies that better align with the sustainable development of solar PV systems in Bangladesh.

5.4.2 Implication for Renewable Portfolio Standard, Mandates and Obligation Policy

This research can support the introduction of policies such as renewable energy portfolio standards, mandates, and obligations through the concept of virtual net metering (VNM), as discussed in Chapter 3. With the rapid growth of the commercial and industrial sectors in Bangladesh, it is vital to actively involve these sectors in the country's sustainable energy transition. However, commercial entities often operate in shared spaces within multi-storey buildings, facing challenges in implementing solar PV systems due to limited space and the lack of rooftop ownership.

VNM offers a viable solution to these challenges by enabling the implementation of solar PV systems through rented rooftops, allowing businesses to generate and consume renewable energy. This research demonstrated that VNM can provide electricity at a lower cost than grid electricity in Bangladesh. Therefore, policymakers should consider integrating VNM provisions into the existing net-metering policy while introducing renewable energy portfolio standards, mandates, and obligations, particularly for large commercial and industrial consumers as well as high energy-consuming residential users.

The solar PV potential assessment presented in Chapter 2 can further support the identification of suitable sites for remote solar PV generation to facilitate the implementation of VNM and subsequently introduce renewable energy portfolio standards, mandates, and obligations. Such policies have the potential to reduce reliance on large-scale investors for renewable energy projects, promoting a more decentralised investment approach to Bangladesh's energy transition.

5.5 Implication for developing energy communities

The implications of this research can be extended to support the formation of energy communities in both urban and rural areas. The VNM concept introduced in Chapter 3 enables the shared use of rooftops or spaces for developing collective solar PV systems. In densely populated urban areas of Bangladesh, VNM can facilitate the creation of smaller communities where tenants, such as residential, commercial, and industrial users, can collaboratively build and share rooftop PV systems.

In rural areas, common spaces such as front yards or backyards of settlement clusters can be utilised to develop shared solar PV systems, promoting access to renewable energy among community members. However, further investigation is required to establish appropriate support mechanisms, including policies and financial frameworks, to enable and sustain the formation of such energy communities effectively.

5.6 Implication for developing microgrid, local energy system, and virtual power plant

Chapter 4 introduced a local energy system concept featuring a microgrid with a community battery energy storage system (CBESS) that utilises a battery swapping and charging station. Rural and semi-urban areas in Bangladesh frequently experience brownouts due to insufficient energy supply from the grid, driving reliance on fossil fuel backup generators and redundant systems. The proposed CBESS can significantly enhance the reliability of local grids, thereby reducing dependency on secondary or redundant energy supply systems.

The implementation of microgrids presents a viable pathway for improving power system reliability by engaging various local and regional stakeholders. Planning smart energy systems is crucial for advancing the decarbonisation of the energy sector. The conceptual CBESS proposed in this research can serve as a central component in realising such smart energy systems in rural areas. Furthermore, these smart energy systems have the potential to create a nexus across different sectors, including transportation, agriculture, and the productive use of electricity, fostering a holistic approach to sustainable development. Furthermore, the study also introduced the concept of a Rural Virtual Power Plant (RVPP) to address the lack of capacity in the implementation of a local energy system. An RVPP, established by local utilities or independent aggregators, can address challenges like limited local expertise and technology awareness in rural renewable energy investment. RVPPs optimise local grid energy management, benefiting stakeholders and promoting productive energy use, such as powering rice husking, crushing mills, milk processing, and cottage industries with renewable energy through smart contracts and meters.

5.7 Implication for promoting green energy for electric vehicles

Chapter 3 demonstrated how the proposed VNM topologies can facilitate the adoption of electric vehicles (EVs) across various consumer categories in Bangladesh. The results indicate that VNM offers greater benefits to consumer groups that pay higher electricity tariffs. Consequently, high energy-consuming residential users, commercial entities, and small industries could maximise their advantages by transitioning from fossil fuel vehicles to EVs or considering EVs for their next vehicle purchase.

Additionally, countries such as India, Nepal, Thailand, Vietnam, and Bangladesh are witnessing a rapid rise in the penetration of electric three-wheelers. However, charging stations in these regions often lack sufficient space to generate adequate energy for charging vehicles. Remote solar PV plants integrated with VNM can address this challenge by supporting the growing energy demand and enabling greener transportation solutions through electric vehicles.

5.8 Implication for sustainable battery management for electric 3-wheelers.

Chapter 4 addressed several challenges and proposed potential opportunities for electric rickshaws and their role in Bangladesh's renewable energy. It identified that battery management has become a critical issue due to the widespread use of e-rickshaws. Poor management practices result in a short lifespan for lead-acid batteries, leading to uncontrolled disposal and unsafe recycling practices. Establishing regulated battery swapping and charging stations could centralise battery procurement and recycling processes. Additionally, the research indicated that multiple services could be combined with the CBESS model through battery swapping stations, creating business opportunities, particularly in rural areas. A conceptual business model was also presented, outlining stackable ventures such as Rural Virtual Power Plants (RVPP), energy arbitrage, grid services, and VRE integration.

5.9 The core message

The distinct role of solar PV in local and global energy transition is undeniable. At the same time, adopting solar PV is challenging for many nations, especially those with high population density and poor economies like Bangladesh. For these nations, unlocking solar PV potential for a sustainable energy transition requires a synergistic approach, combining land-use strategies, policy frameworks, and integration solutions that leverage country-specific local opportunities and innovation.

This dissertation demonstrated that despite high population density and land-use constraints, Bangladesh holds significant potential for solar PV implementation. Innovation and value stacking are essential for realising this potential. Drawing on its experience with the Solar Home System Programme, Bangladesh can leverage assets such as over 5 million smart meters to implement innovative policies and the widespread adoption and use of electric rickshaws to promote and integrate renewable energy.

5.10 Scientific contributions

This dissertation makes a significant contribution to the literature by conducting multidisciplinary research that spans geospatial, technical, economic, social, and environmental domains. It addresses methodological and empirical research gaps through innovative approaches and key findings presented across its chapters.

In **Chapter 2**, the research develops multi-criteria-based binary geospatial models for four distinct types of solar PV systems. It introduces Agrivoltaics in seasonally inundated lands (APV-SIL) as a novel variant within the Agrivoltaic domain, specifically designed for low-lying areas. The models and findings generate valuable quantitative and qualitative data on Bangladesh's solar PV potential, supporting energy system modelling and enabling informed decision-making. Additionally, the research identifies system-specific solar PV potentials across the country, providing critical insights for district-level solar capacity planning by government agencies and power utilities. The study also proposes land use strategies to address constraints related to limited land availability, ensuring more effective solar PV deployment. Overall, the chapter demonstrates how solar potential can be categorised by specific system types to enhance decision-making and planning.

In **Chapter 3**, the dissertation highlights the potential of policy instruments, such as virtual net metering (VNM), to address space constraints and three-phase connection issues, thereby increasing public participation in renewable energy adoption. The research customises the socket parity method to identify suitable consumers for VNM and prosumer aggregation concepts. It also employs the net present cost (NPC) method to evaluate comparative cost-saving benefits between grid electricity and VNM-generated electricity. Furthermore, a combined model integrating the socket parity and NPC methods is developed to assess the national-level economic feasibility of VNM-based prosumer aggregation. Through this work, the research demonstrates how the widespread adoption of smart prepaid electricity meters can be leveraged to create innovative policies that support renewable energy deployment.

In **Chapter 4**, the research examines the role of electric rickshaws as an emerging energy use case in facilitating the integration of variable renewable energy into the grid. It develops an innovative energy system model using HOMER Pro software, addressing gaps in the existing literature (Google Scholar 2024). A unique battery control strategy is proposed to support the development of community energy storage systems. Additionally, the study introduces a next-day time-shift battery management system, which ensures adequate energy availability for electric rickshaws while extending battery lifespan by reducing cycle usage. Overall, this chapter demonstrates how innovative approaches can transform challenges into opportunities, paving the way for sustainable solutions.

Figure 5.2 below illustrates the impact of the research presented in Chapters 2, 3, and 4. According to the Google Scholar (2024) citation index, the research is gaining recognition primarily in the international context, highlighting its significance in addressing key gaps in the literature.

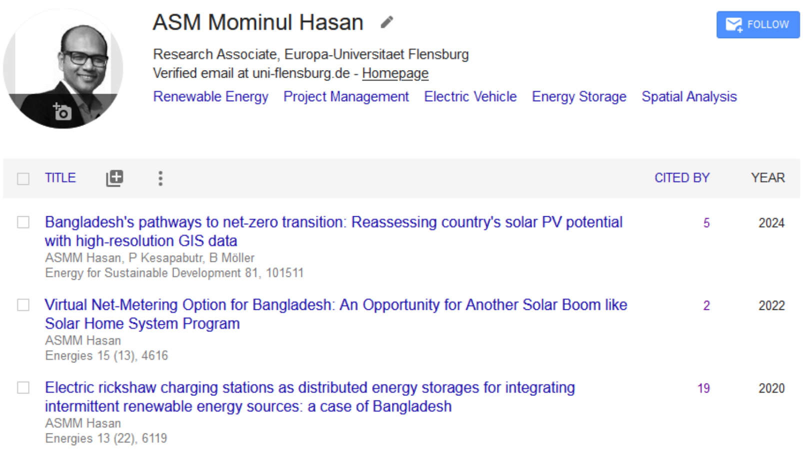


Figure 5.2: Impact of the research performed during this doctoral research period

Source: (Google Scholar 2024)

5.11 Limitations

The research performed for this dissertation is investigative and explorative techno-economic desktop studies, using primarily secondary data from different credible sources. However, the research lacks insights and perceptions from stakeholders such as policymakers, electricity consumers, building owners, and electric rickshaw owners, which remained out of the scope during the study.

In Chapter 2, state-of-the-art spatial and non-spatial datasets were utilised in this research, with OpenStreetMap's building footprint data serving as the primary source for estimating rooftop PV (RPV) potential. However, several limitations were identified. First, potential inaccuracies could arise from human errors in drawing building footprints and from the absence of specific building data, such as typology, age, and usage, which might affect the precision of RPV estimates. It was noted that incorporating high-resolution Digital Surface Model (DSM) or LiDAR data could have improved the RPV model's accuracy by allowing for more precise simulation of shadow effects. Local substation capacity was omitted from consideration to reduce complexity, although this factor may influence the feasibility of localised PV deployment.

While the bathymetry data used is considered advanced, it is not up-to-date, which could limit insights into the feasibility of FPV systems on inland water bodies. For APV systems, the lack of crop yield data constrained the ability to estimate the Land Equivalent Ratio (LER), limiting the understanding of potential integration with agricultural practices. Future research could address these limitations to refine solar PV potential assessments and provide more accurate guidance for renewable energy planning.

In Chapter 3, the cost-recovery method was employed to calculate energy wheeling costs for VNM, which may not fully reflect the actual costs associated with VNM. Average energy consumption and electricity tariff data by consumer category from various utilities were used to calculate the benefits of VNM, but consumer perspectives and willingness to invest in VNM systems were not directly surveyed. Given that energy generation costs during non-solar periods can be high, increased VNM adoption may raise concerns about fairness among consumers.

In Chapter 4, although a one-day time shift offers greater benefits for the energy system, it doubles the initial costs, posing a significant limitation to implementing this approach. The simulated system assumes unrestricted export of excess energy to neighbouring communities or other areas through the grid; however, grid constraints may impede both the export and import of power. Additionally, with a one-day time shift, it is assumed that achieving an 8-year lifespan for lead-acid batteries would be challenging, given the micro-cycling required for renewable energy integration.

5.12 Outlook

This research establishes key building blocks for Bangladesh's energy transition and complements existing studies on the country's energy system modelling. However, developing a new energy system model remains a critical next step to directly simulate the VNM policy and the proposed community battery energy storage system using electric rickshaw batteries. Currently, electricity demand in Bangladesh peaks in the evening, but this pattern is expected to shift to the daytime with impending economic transitions. It is, therefore, crucial to estimate how much of the identified solar PV potential can be realised in light of future demand trends and grid capacity. Such estimations are essential for avoiding issues like the "duck curve," which could destabilise the grid. A comprehensive analysis of future demand patterns, grid and substation capacity, and renewable energy integration is vital to ensuring a stable and sustainable energy transition.

Future studies are encouraged to investigate advanced, cost-reflective wheeling methods to enhance the VNM policy. Field studies could also provide valuable insights into consumer attitudes toward renewable energy investments, generating data to better inform policy recommendations.

Moreover, an accurate estimation of the number of electric rickshaws in Bangladesh is necessary. Field studies examining the perceptions of drivers and charging station owners about using charging infrastructure for renewable energy integration could offer a realistic evaluation of this concept's feasibility.

While this research focuses on electric rickshaws as an emerging energy use case in Bangladesh, identifying additional use cases, especially daytime and flexible loads, is equally important. Expanding the scope to include these areas would enable the full utilisation of the identified solar PV potential.

Bibliography

Ahmed, Robel; Rahman, Anisur; Paul, Durjoy Kumar; Ahmed, Mim Mashrur (2024): Exploring biomass resources and conversion technologies in Bangladesh: Current status, challenges, and future prospects. In *Bioresource Technology Reports* 28, p. 101998. DOI: 10.1016/j.biteb.2024.101998.

Alam, Majbaul; Bhattacharyya, Subhes (2017): Are the off-grid customers ready to pay for electricity from the decentralized renewable hybrid mini-grids? A study of willingness to pay in rural Bangladesh. In *Energy* 139, pp. 433–446. DOI: 10.1016/j.energy.2017.07.125.

BPDB (2024): Annual Report 2022-2023. Bangladesh Power Development Board. Available online at https://www.bpdb.gov.bd.

Breyer, Christian; Bogdanov, Dmitrii; Gulagi, Ashish; Aghahosseini, Arman; Barbosa, Larissa S.N.S.; Koskinen, Otto et al. (2017): On the role of solar photovoltaics in global energy transition scenarios. In *Prog. Photovolt: Res. Appl.* 25 (8), pp. 727–745. DOI: 10.1002/pip.2885.

Buckley, Tim; Nicholas, Simon; Ahmed, Sara J. (2016): Bangladesh Electricity Transition: A Diverse, Secure and Deflationary Way Foreward. Institute for Energy Economics and Financial Analysis. Available online at https://ieefa.org/wp-content/uploads/2016/11/Bangladesh-Electricity-Transition_-NOVEMBER-2016.pdf, checked on 3/24/2022.

Cabraal, Anil; Ward, William A.; Bogach, V. Susan; Jain, Amint (2021): LIVING IN THE LIGHT: THE BANGLADESH SOLAR HOME SYSTEMS STORY. The World Bank. Available online at https://documents1.worldbank.org/curated/en/153291616567928411/pdf/Living-in-the-Light-The-Bangladesh-Solar-Home-Systems-Story.pdf, checked on 9/25/2022.

Das, Anjana; Halder, Arideep; Mazumder, Rahul; Saini, Vinay Kumar; Parikh, Jyoti; Parikh, Kirit S. (2018): Bangladesh power supply scenarios on renewables and electricity import. In *Energy* 155, pp. 651–667. DOI: 10.1016/j.energy.2018.04.169.

Das, N. K.; Chakrabartty, J.; Dey, Mrinmoy; Gupta, A. SenK.; Matin, M. A. (2020): Present energy scenario and future energy mix of Bangladesh. In *Energy Strategy Reviews* 32, p. 100576. DOI: 10.1016/j.esr.2020.100576.

Debnath, Kumar Biswajit; Mourshed, Monjur (2024): Although feasible, falling renewables costs might not benefit Bangladesh's energy sector's decarbonisation: Is this another 'debt-fossil fuel production trap'? In *Energy for Sustainable Development* 79, p. 101416. DOI: 10.1016/j.esd.2024.101416.

Finance Division (2023): BANGLADESH ECONOMIC REVIEW 2023. Finance Division, Ministry of Finance, Government of the People's Republic of Bangladesh. Available online at https://mof.portal.gov.bd/site/page/28ba57f5-59ff-4426-970a-bf014242179e/Bangladesh-Economic-Review-2023, checked on 7/1/2023.

Fraunhofer ISE (2024): Photovoltaics Report 2024. Fraunhofer ISE; SE Projects GmbH. Available online at https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html, checked on 8/1/2024.

GHSL-Global Human Settlement Layer (2018): Country Fact Sheets based on the Degree of Urbanisation: Bangladesh. Testing the Degree of Urbanisation at the global level. European Commission. Available online at https://ghsl.jrc.ec.europa.eu/CFS.php, checked on 3/25/2023.

Goggins, Gary; Rau, Henrike; Moran, Paul; Fahy, Frances; Goggins, Jamie (2022): The role of culture in advancing sustainable energy policy and practice. In *Energy Policy* 167, p. 113055. DOI: 10.1016/j.enpol.2022.113055.

Google Scholar (2024): ASM Mominul Hasan. Available online at https://scholar.google.com/citations?hl=en&user=9Mk8CdMAAAAJ&view_op=list_works&sortby=pubdate, updated on 12/15/2024, checked on 12/15/2024.

Gulagi, Ashish; Ram, Manish; Solomon, A. A.; Khan, Musharof; Breyer, Christian (2020): Current energy policies and possible transition scenarios adopting renewable energy: A case study for Bangladesh. In *Renewable Energy* 155 (2), pp. 899–920. DOI: 10.1016/j.renene.2020.03.119.

GWEC (2024): Global Wind Report 2024. Global Wind Energy Council (GWEC). Available online at https://gwec.net/global-wind-report-2024/.

Hassan, Anisha; Kirchhoff, Hannes; Khan, Madiha Akter; Groh, Sebastian (2024): The Rickshaw VPP. A Discussion Basis White Paper for Bangladesh's Light Electric Vehicle-Based Virtual-Power-Plant. Solshare Ltd. Available online at https://solshare.com/wp-content/uploads/2024/09/SOLshare-Rickshaw-VPP-White-Paper_May-2024.pdf, checked on 5/8/2024.

Hassan Shetol, M.; Moklesur Rahman, M.; Sarder, Ratneshwar; Ismail Hossain, M.; Kabir Riday, F. (2019): Present status of Bangladesh gas fields and future development: A review. In *Journal of Natural Gas Geoscience* 4 (6), pp. 347–354. DOI: 10.1016/j.jnggs.2019.10.005.

Hellqvist, Laura; Heubaum, Harald (2023): Setting the sun on off-grid solar?: policy lessons from the Bangladesh solar home systems (SHS) programme. In *Climate Policy* 23 (1), pp. 88–95. DOI: 10.1080/14693062.2022.2056118.

Hossain, Md Lokman; Shapna, Khusnur Jahan; Li, Jianfeng (2023a): Solar energy brightens lives and strengthens the resilience of geographically challenged communities in Bangladesh. In *Energy for Sustainable Development* 74, pp. 79–90. DOI: 10.1016/j.esd.2023.03.016.

Hossain, Shah Mohazzem; Biswas, Sagor; Raihan Uddin, Md (2023b): Sustainable energy transition in Bangladesh: Challenges and pathways for the future. In *Engineering Reports* 6 (1), Article e12752. DOI: 10.1002/eng2.12752.

IEA (2021): Net Zero by 2050. A Roadmap for the Global Energy Sector. International Energy Agency, IEA. Paris. Available online at https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf.

IEA (2023): COP28: Tracking the Energy Outcomes – Topics - IEA. Supporting and reporting global climate progress. International Energy Agency. Available online at https://www.iea.org/topics/cop28-tracking-the-energy-outcomes, updated on 8/1/2024, checked on 8/1/2024.

IEA (2024a): Data and statistics - Bangladesh. International Energy Agency, IEA. Available online at https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?country=WORLD&fuel=Energy%20supply&indicator=TESbySource, updated on 12/6/2024, checked on 12/6/2024.

IEA (2024b): Energy Statistics Data Browser. International Energy Agency. Available online at https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser, checked on 4/1/2024.

IESD (2023): Study on Grid Stability in Bangladesh. Institute of Energy and Sustainable Development (IESD). Available online at https://www.eeas.europa.eu/sites/default/files/documents/2023/EUD%20Grid%20Final%20Report_V3.pdf, checked on 6/25/2024.

IRENA (2019): Global energy transformation: A roadmap to 2050 (2019 edition). International Renewable Energy Agency (IRENA) (978-92-9260-121-8). Available online at https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Apr/IRENA_Global_Energy_Transformation_2019.pdf.

IRENA (2020): Renewable Energy and Jobs – Annual Review 2020. International Renewable Energy Agency (IRENA). Abu Dhabi. Available online at https://www.irena.org/publications/2020/Sep/Renewable-Energy-and-Jobs-Annual-Review-2020.

IRENA (2024): Renewable Energy Statistics 2024. International Renewable Energy Agency (IRENA). Available online at https://www.irena.org/Publications/2024/Jul/Renewable-energy-statistics-2024.

Islam, A.K.M. Sadrul; Islam, Mazharul (2005): Status of renewable energy technologies in Bangladesh.

Kirchhoff, Hannes; Strunz, Kai (2024): Peer-to-Peer Microgrids for 100% Renewable Swarm Electrification: Scalable, Sustainable, Self-Serviceable, Safe, and Stable Design. In *IEEE J. Emerg. Sel. Top. Ind. Electron.* 5 (2), pp. 318–335. DOI: 10.1109/JESTIE.2024.3363667.

Moazzem, K. G.; Preoty, H. M.; Mallick, M. A. (2022): Policy Instruments to Promote Renewable Energy in Bangladesh. CPD Working Paper 148. Centre for Policy Dialogue (CPD). Dhaka. Available online at https://cpd.org.bd/resources/2023/08/Policy-Instruments-to-Promote-Renewable-Energy-in-Bangladesh.pdf, checked on 3/22/2024.

Mondal, Alam Hossain; Klein, Dieter (2011): Impacts of solar home systems on social development in rural Bangladesh. In *Energy for Sustainable Development* 15 (1), pp. 17–20. DOI: 10.1016/j.esd.2010.11.004.
Mondal, Md. Alam Hossain; Denich, Manfred (2010): Assessment of renewable energy resources potential for electricity generation in Bangladesh. In *Renewable and Sustainable Energy Reviews* 14 (8), pp. 2401–2413. DOI: 10.1016/j.rser.2010.05.006.
Mondal, Md. Alam Hossain; Denich, Manfred; Mezher, Toufic (2014): Deployment of renewable energy technologies in Bangladesh: Long-term policy implications in power sector. In *Energy Strategy Reviews* 2 (3-4), pp. 307–312. DOI: 10.1016/j.esr.2012.11.006.
MPEMR (2023): Integrated Energy and Power Master Plan (IEPMP) 2023. With assistance of Japan International Cooperation Agency (JICA), The Institute of Energy Economics, Japan (IEEJ). Government of the People’s Republic of Bangladesh. Dhaka, Bangladesh. Available online at https://powerdivision.portal.gov.bd/sites/default/files/files/powerdivision.portal.gov.bd/npfblock/IEPMP_Report_2023.pdf, checked on 1/1/2024.
Nandi, Sanjoy Kumar; Hoque, Mohammad Nasirul; Ghosh, Himangshu Ranjan; Chowdhury, Riku (2013): Assessment of Wind and Solar Energy Resources in Bangladesh. In *Arab J Sci Eng* 38 (11), pp. 3113–3123. DOI: 10.1007/s13369-012-0429-5.
Newcombe, Alex; Ackom, Emmanuel Kofi (2017): Sustainable solar home systems model: Applying lessons from Bangladesh to Myanmar's rural poor. In *Energy for Sustainable Development* 38, pp. 21–33. DOI: 10.1016/j.esd.2017.03.002.
NREL-USAID (2018): Assessing the Wind Energy Potential in Bangladesh. Enabling Wind Energy Development with Data Products. National Renewable Energy Laboratory (NREL); USAID. Available online at https://www.nrel.gov/docs/fy18osti/71077.pdf, checked on 2/25/2024.
Nurunnahar, Syeda; Shariful Islam, Md; Rahman, Mahbubur (2022): Electric vehicles in Bangladesh: Impact on the environment, mobility, and the economy of an impending ban. In *Public Health Challenges* 1 (4), Article e43. DOI: 10.1002/puh2.43.
OCHA (2024): Welcome - Humanitarian Data Exchange. United Nations. Available online at https://data.humdata.org/, updated on 12/23/2024, checked on 12/23/2024.
Power Division, Bangladesh (2016): Power System Master Plan 2016. With assistance of JICA, Tokyo Electric Power Services Co., Ltd., Tokyo Electric Power Company Holdings, Inc. Power Division, Ministry of Power, Energy and Mineral Resouces, Government of Bangladesh. Dhaka.
Sajjad, Mojibul; Rasul, Mohammad G. (2015): Prospect of Underground Coal Gasification in Bangladesh. In *Procedia Engineering* 105, pp. 537–548. DOI: 10.1016/j.proeng.2015.05.087.
Shafiqul, Alam (2024): Streamline power sector to reduce overcapacity, financial burden. In *The Business Standard*, 1/29/2024 (Online). Available online at https://www.tbsnews.net/supplement/streamline-power-sector-reduce-overcapacity-financial-burden-783150, checked on 5/4/2024.
Sharif, Islam; Mithila, Marufa (2013): Rural Electrification using PV: the Success Story of Bangladesh. In *Energy Procedia* 33, pp. 343–354. DOI: 10.1016/j.egypro.2013.05.075.
Shiraishi, Kenji; Shirley, Rebekah G.; Kammen, Daniel M. (2019): Geospatial multi-criteria analysis for identifying high priority clean energy investment opportunities: A case study on land-use conflict in Bangladesh. In *Applied Energy* 235, pp. 1457–1467. DOI: 10.1016/j.apenergy.2018.10.123.
SREDA (2024): National Database of Renewable Energy, SREDA. Sustainable and Renewable Energy Development Authority (SREDA). Dhaka, Bangladesh. Available online at http://www.renewableenergy.gov.bd/index.php?id=1&i=1, updated on 1/15/2024, checked on 1/15/2024.
Statista (2024): Global cumulative installed solar PV capacity 2023 | Statista. Statista Ltd. Available online at https://www.statista.com/statistics/280220/global-cumulative-installed-solar-pv-capacity/, updated on 12/24/2024, checked on 12/24/2024.
Teske, S.; Morris, T.; Nagrath, K. (2019): 100% RENEWABLE ENERGY FOR BANGLADESH-FINAL DRAFT. Access to renewable energy for all within one generation. INSTITUTE FOR SUSTAINABLE FUTURES. Sydney.

The Financial Express (4/2/2024): Three-wheelers consume 5pc of country's electricity. Dhaka. The Financial Express. Available online at https://thefinancialexpress.com.bd/national/three-wheelers-consume-5pc-of-countrys-electricity, checked on 9/22/2024.

The World Bank (2023): World Bank Open Data. The World Bank. Available online at https://data.worldbank.org/, checked on 7/1/2023.

UNFCCC (2023): COP28 Agreement Signals "Beginning of the End" of the Fossil Fuel Era | UNFCCC. UNFCCC. Available online at https://unfccc.int/news/cop28-agreement-signals-beginning-of-the-end-of-the-fossil-fuel-era, updated on 8/13/2024, checked on 8/13/2024.

WEF (2024): Fostering Effective Energy Transition. World Economic Forum. Available online at https://www.weforum.org/publications/fostering-effective-energy-transition-2024/, checked on 7/29/2024.

WorldPop (2018): Global 100m BSGM outputs.

Yu, Haoxuan; Wen, Bodong; Zahidi, Izni; Chow, Ming Fai; Liang, Dongfang; Madsen, Dag Øivind (2024): The critical role of energy transition in addressing climate change at COP28. In *Results in Engineering* 22, p. 102324. DOI: 10.1016/j.rineng.2024.102324.

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Zusammenfassung

Der weltweite Wandel hin zu nachhaltiger Energie stellt dicht besiedelte, ressourcenbeschränkte Länder wie Bangladesch vor besondere Herausforderungen, wenn es darum geht, ein angemessenes Gleichgewicht zwischen nachhaltiger Energie und Entwicklung herzustellen. Da sich der Energiebedarf Bangladeschs aufgrund des Bevölkerungswachstums, der wirtschaftlichen Entwicklung und der Industrialisierung bis 2050 voraussichtlich verdreifachen wird, ist das Land nach wie vor stark von einheimischen und importierten fossilen Brennstoffen abhängig, während erneuerbare Energien weniger als 5 % des Energiemixes für die Stromerzeugung ausmachen. Obwohl die weit verbreitete Einführung von Solar Home Systems (SHS) den Zugang zu Energie erheblich verbessert hat, hat Bangladesch mehrere wichtige Meilensteine seiner Ziele im Bereich der erneuerbaren Energien nicht erreicht. Unter den erneuerbaren Energieressourcen erweist sich die Solarenergie, insbesondere die Photovoltaik (PV), aufgrund ihrer Verfügbarkeit als die praktischere Lösung zur Erreichung der EE-Ziele. Allerdings stehen Herausforderungen wie Landknappheit, finanzielle Zwänge und eine unzureichende Netzinfrastruktur einer breiten Einführung im Wege. Um Wege zur Erschließung des Potenzials der Photovoltaik für die nachhaltige Energiewende in Bangladesch zu finden, werden in dieser Dissertation drei miteinander verbundene Forschungsarbeiten durchgeführt, die sich auf die Bewertung der Ressourcen, die Politik und die technologische Innovation konzentrieren und lokale Möglichkeiten als Katalysatoren nutzen. Die Analysen verwenden einen multidisziplinären Ansatz, der geographische Analysen, wirtschaftliche Machbarkeitsstudien und die Modellierung von Energiesystemen umfasst. In der Ressourcenanalyse wurde ein PV-Potenzial von über 100 GW ermittelt, wobei PV-Dachanlagen (RPV) die wirtschaftlichste Lösung darstellen (36-70 USD/MWh). Sie zeigt, dass Bangladesch die Ziele für die Installation von PV-Anlagen durch die Einführung von Aufdachanlagen erreichen kann, und empfiehlt die Beibehaltung der doppelten Nutzung von Land bei der Entwicklung von PV-Anlagen auf dem Boden. Die Politikstudie hebt das Potenzial von Virtual Net-Metering (VNM) als skalierbares politisches Instrument hervor, um die weit verbreitete Einführung von netzgekoppelten PV-Anlagen zu fördern, insbesondere um das RPV-Potenzial zu nutzen und den Erfolg des SHS-Programms zu wiederholen. Sie zeigt auch das Potenzial von VNM, die Stromkosten um bis zu 50 % zu senken, und bietet eine umfassendere Beteiligung an Investitionen in erneuerbare Energien. Darüber hinaus zeigt die technologische Innovationsforschung den Einsatz von elektrischen Rikscha-Ladestationen als dezentrale Energiespeicher, um intermittierende EE-Erzeuger zu integrieren und Wege für verschiedene andere Möglichkeiten zu eröffnen, wie etwa virtuelle Kraftwerke in ländlichen Gebieten. Zusammenfassend lässt sich sagen, dass diese Dissertation gangbare Wege für den Einsatz von PV-Solaranlagen in Bangladesch aufzeigt und dabei die Synergie zwischen Flächennutzung, innovativer Politik und technologischen Innovationen betont. Sie bietet politischen Entscheidungsträgern und Interessenvertretern Lösungen, die auf lokal entwickelten Möglichkeiten beruhen, und trägt zum globalen Diskurs über die Einführung erneuerbarer Energien in ressourcenbeschränkten, dicht besiedelten Ländern bei, die vor ähnlichen Herausforderungen stehen.

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About the author

Mominul Hasan was born in an unelectrified village in north Bangladesh in 1987 and completed primary education there. After his primary education, he moved to Dhaka with his family and went to high school there. In 2023, he started studying at Bogra Polytechnic Institute for a Diploma in Engineering in Electrical Technology and earned the degree in 2006. After that, he graduated with an electrical and electronic engineering degree from United International University (UIU) in Dhaka in 2012, and his village was electrified in 2013. Following his bachelor's degree, he spent nearly 4 years at the Centre for Energy Research at UIU, contributing to the research, development and implementation of various solar photovoltaic projects across Bangladesh. In April 2015, Mominul joined Solshare, an innovative energy start-up in Bangladesh, where he worked until December 2015. During this short tenure, he made a notable contribution to the start-up, implementing several projects, including the first peer-to-peer grid. Mominul moved to Germany in 2016 to pursue a Master of Engineering in Energy and Environmental Management (EEM) at the Europa-Universitaet Flensburg (EUF) with a DAAD scholarship. After completing his M. Eng., he began to work for the EEM department at EUF in September 2017 and officially started his doctoral research in 2018.