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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].

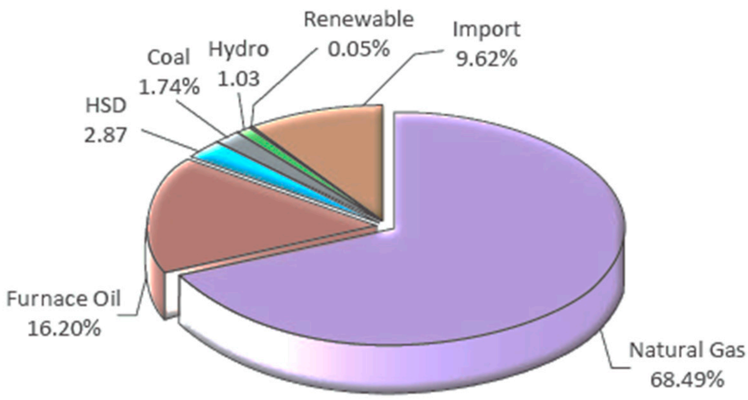

Figure 1. Grid energy generation mix of Bangladesh in financial year 2018–2019. Total generation was 70.53 GWh, which includes imports from India [23].

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.

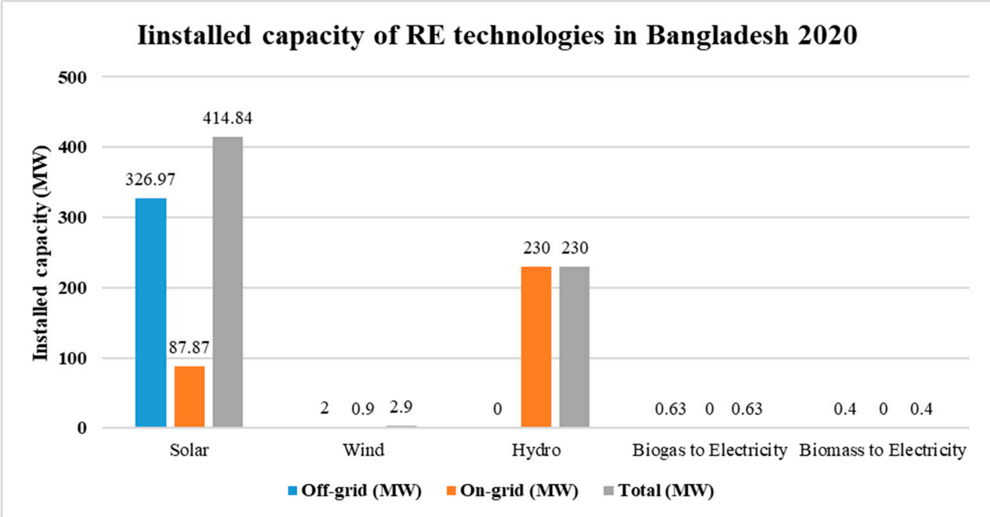

Figure 2. Installed capacity of RE technologies for electricity generation in Bangladesh as of 2020 [25].

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.

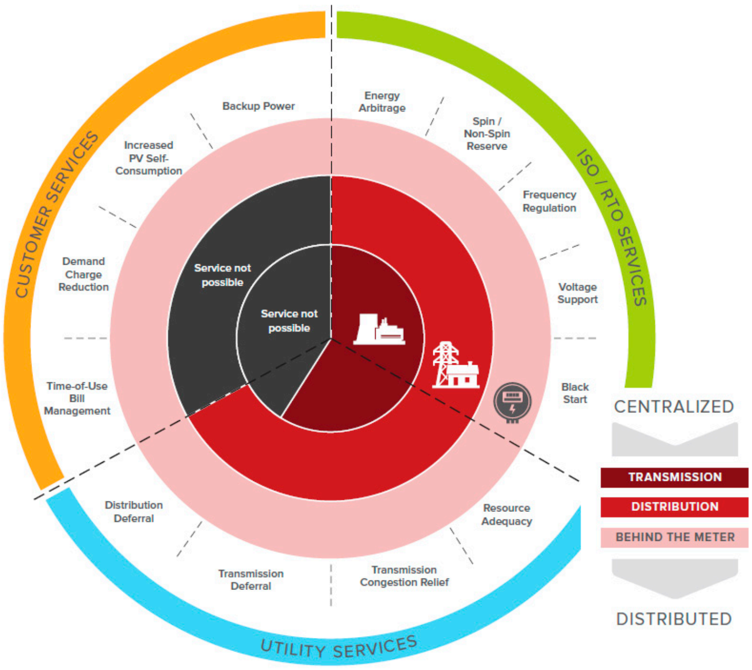

Figure 3. Illustration of 13 services offered by BESS to three main stakeholders: (1) Utility, (2) Customer, (3) Independent System Operator, ISO or Regional Transmission Organizers, RTO. Source: Fitzgerald et al. 2015 [30].

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.

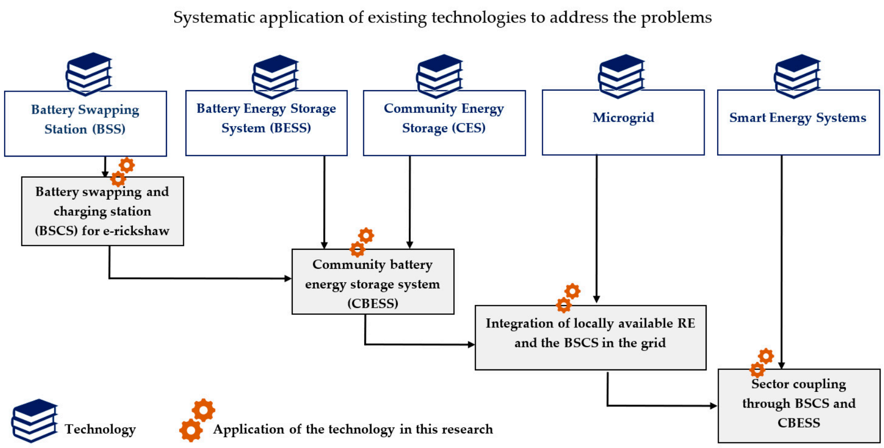

Figure 4. Application of existing technologies in this research to address the problems.

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	

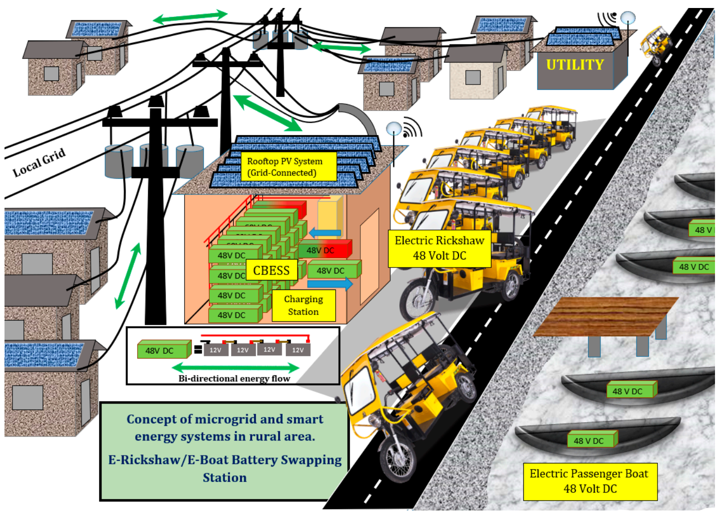

Figure 5. The concept of rural smart energy systems using a BSCS for e-rickshaws. Major components include e-rickshaw or similar transports, distributed/rooftop solar PV, local grid, local utility, and auxiliary battery sets as community battery energy storage system (author's illustration).

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.

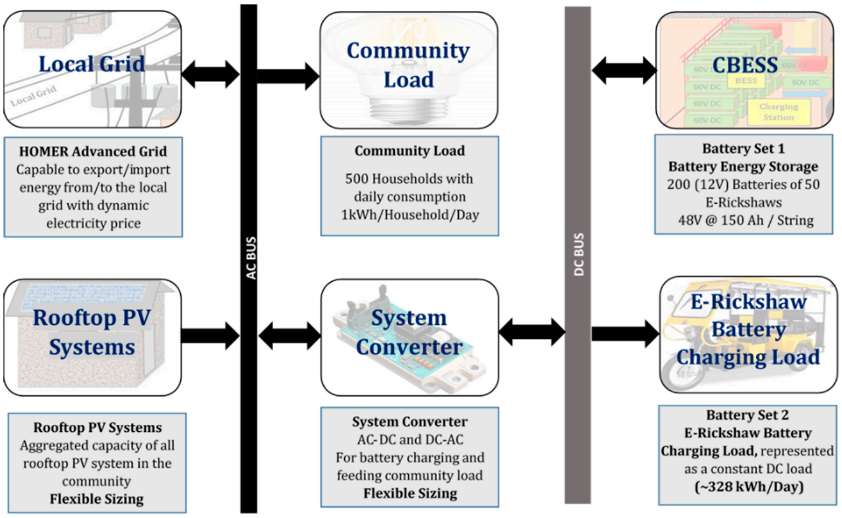

Figure 6. Architecture of the system for HOMER Pro software (author's illustration).

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.

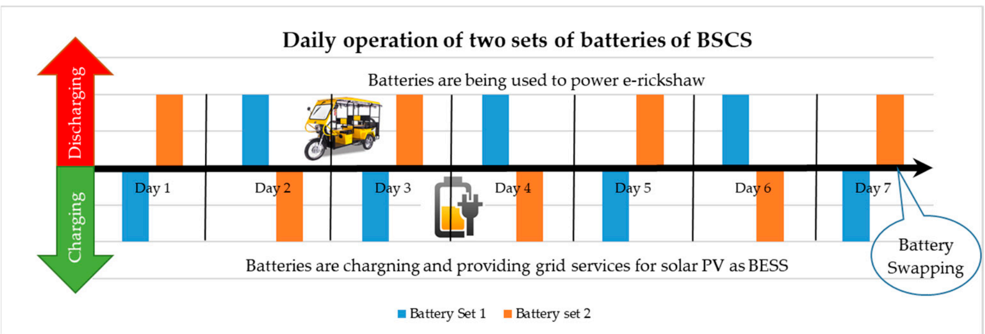

Figure 7. Daily operation of two sets of batteries.

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.

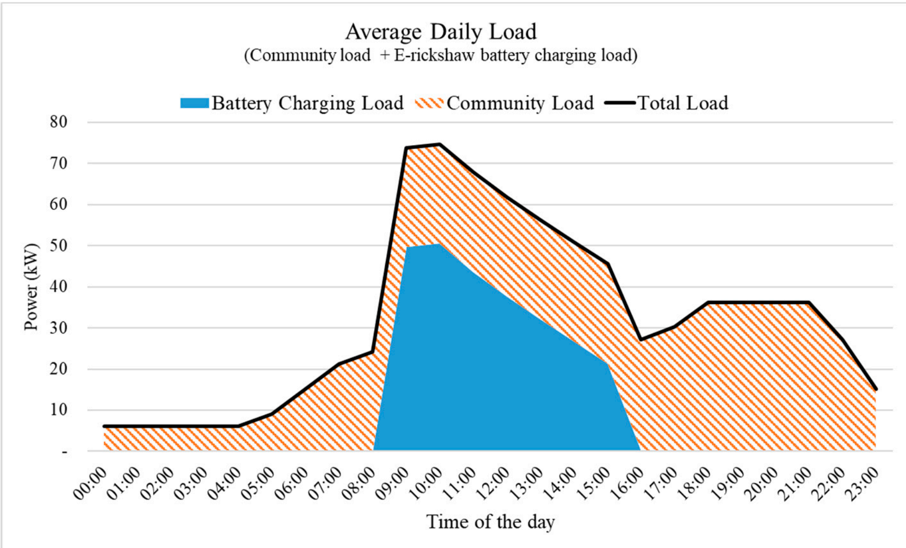

Figure 8. Average daily total load of the system. The total is the sum of community load and e-rickshaw battery charging load. The annual demand was calculated to be 256,595 kWh.

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.

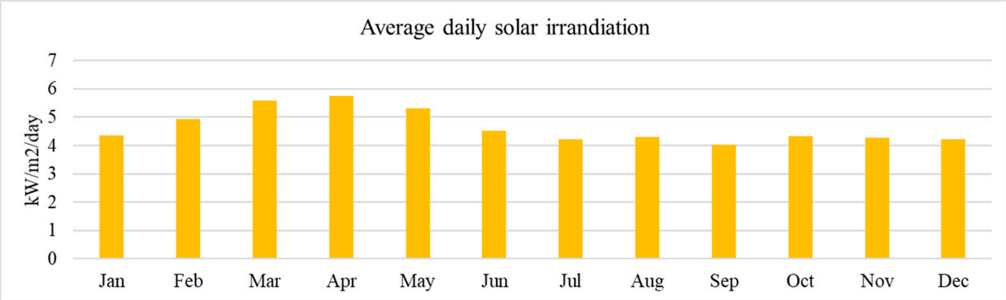

Figure 9. Monthly average daily solar irradiation for the assumed system location.

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.

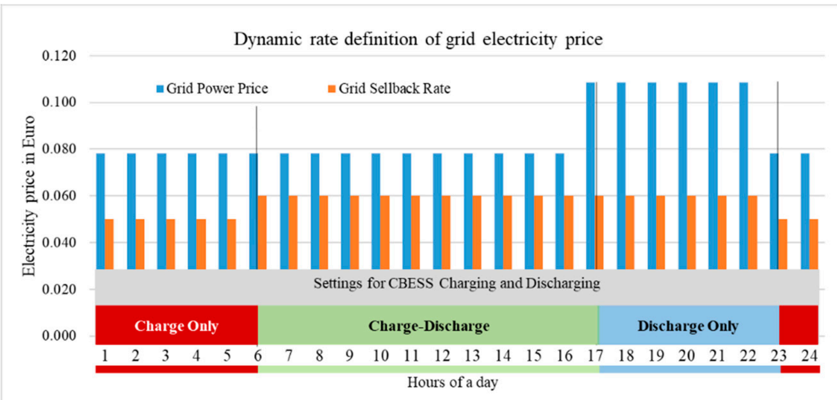

Figure 10. Dynamic rate definition of grid electricity price (power price and sellback rate) and conditions for CBESS dispatch.

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.

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

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.

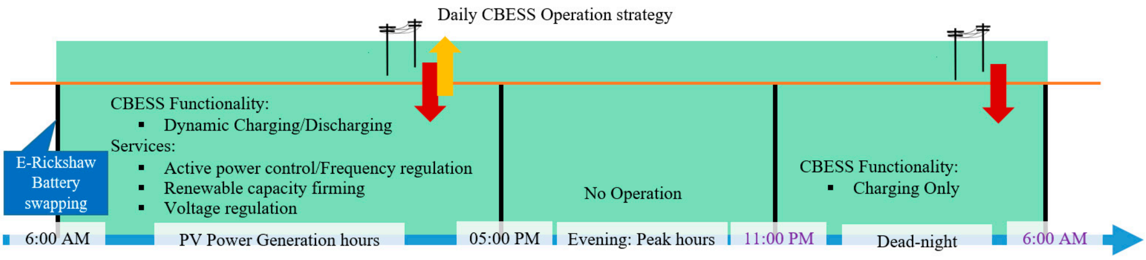

Figure 11. Time-based daily operational strategy of CBESS. Batteries are charged mainly during the day at the same time it provides grid services.

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	256,595	93
2	RE 74.8% +Grid	235	74.8		
3	RE 87.2% + Grid	469	87.2		
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.

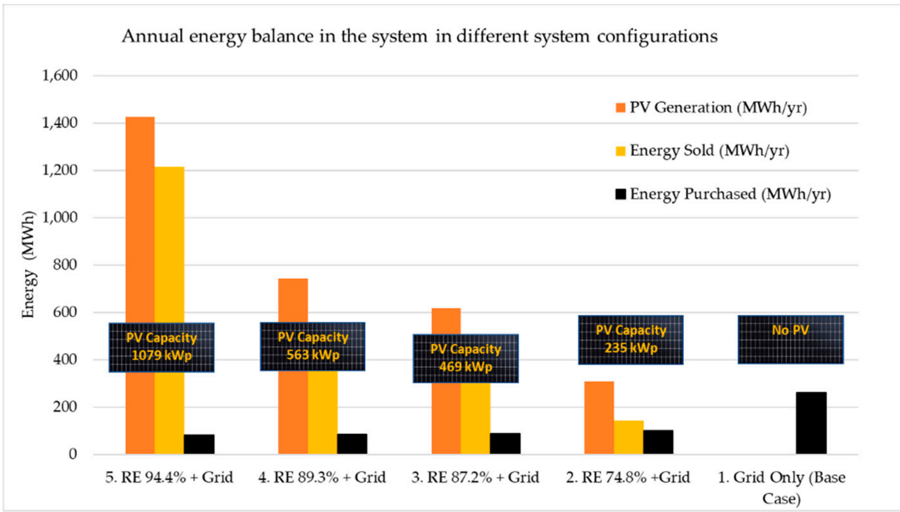

Figure 12. Annual energy balance in the systems in different system configurations.

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.

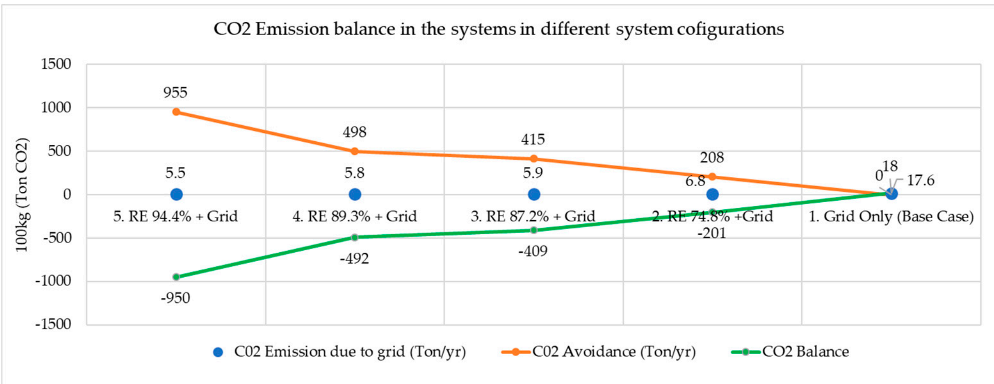

Figure 13. CO_2 emission balance in the systems. The balance was calculated considering grid emission factor of Bangladesh, which is 670 g/kWh.

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].

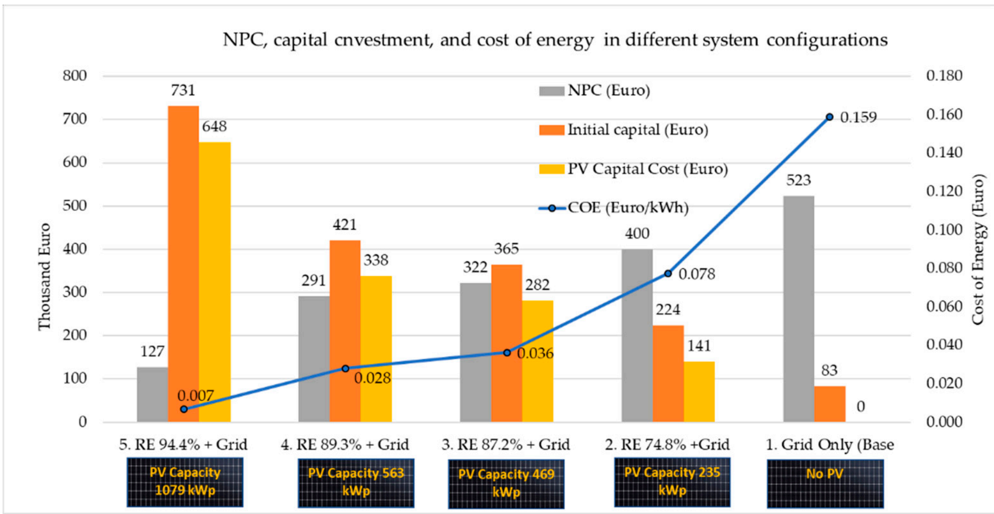

Figure 14. Net present cost (NPC), capital investment and cost of energy (COE) in different system configuration. Right axis shows the cost of energy while the left axis shows NPC (grey bars), capital investment for the whole system (orange bar) and PV capital cost (yellow bar).

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.

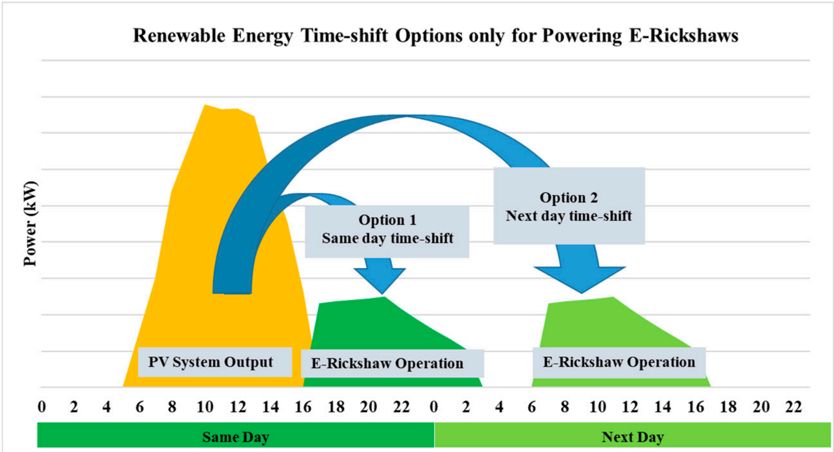

Figure 15. Renewable energy time-shift options for powering e-rickshaws. Option 1 offers same day time-shift and Option 2 offers next day time shift.

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.

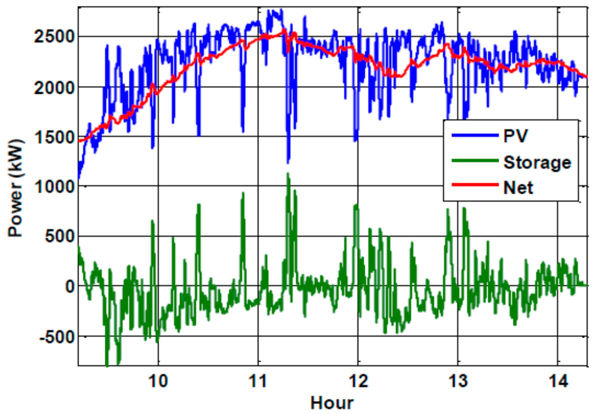

Figure 16. Example of solar PV output/ramp rate smoothing using battery energy storage on a cloudy day between 9:00–15:00 in California [57]. Blue line shows the fluctuating output of a PV system. Red line shows desired output of a PV system against its variability. The green line shows charging and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

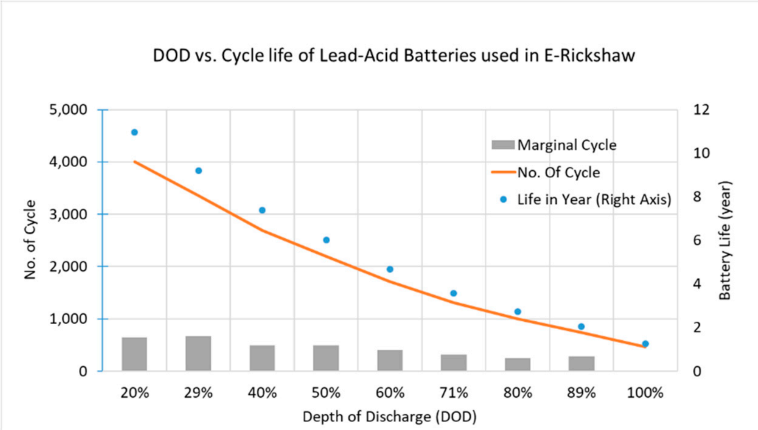

Figure 17. Depth of discharge vs cycle life (orange line) and equivalent life expectancy (blue dots) of LABs used in e-rickshaws. The grey bars show marginal cycles for every 10% additional DOD [53].

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.

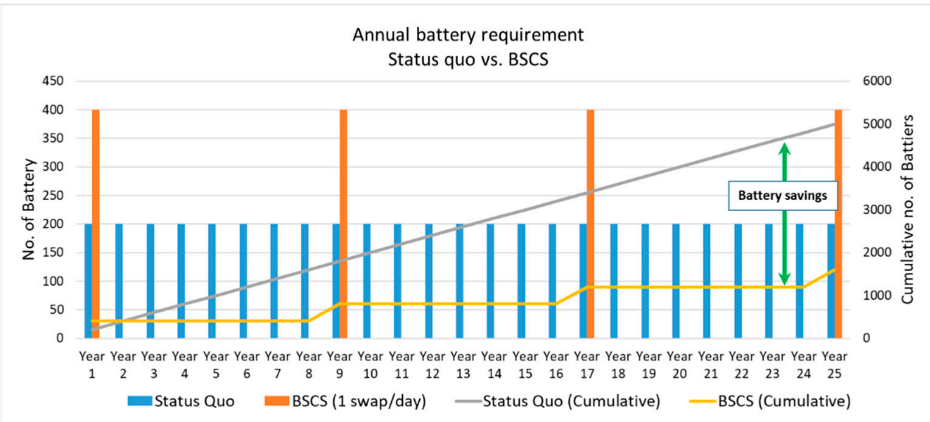

Figure 18. Annual battery requirements for 50 e-rickshaws. The blue bars represent status quo, which is no swapping and no battery management and considering 1-year lifetime. Orange bar represents battery requirements for BSCS with one swap a day with battery management to maintain 60% DOD. Battery lifetime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

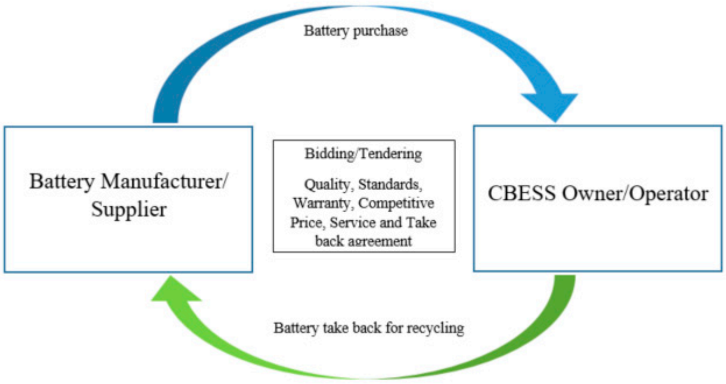

Figure 19. E-rickshaw battery value chain for BSCS option.

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.

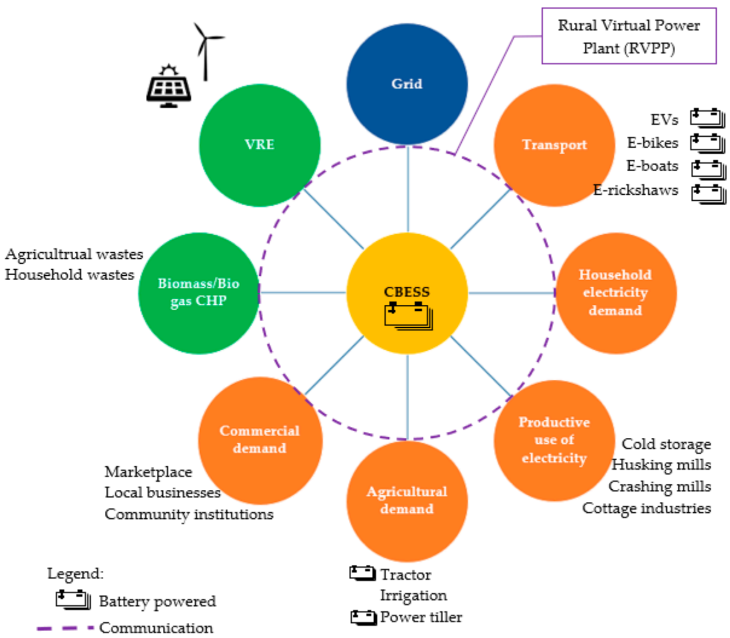

Figure 20. Concept of smart energy systems in rural areas considering the BSCS/CBESS as a central component.

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 ($_{\text{Pbatt}}$)

$$P_{batt,dmax,kbm} = \frac{-kcQ_{max} + kQ_1e^{-k\Delta t} + Qkc\left(1 - e^{-k\Delta t}\right)}{1 - e^{-k\Delta t} + c(k\Delta t - 1 + e^{-k\Delta t})} \tag{A2}$$

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 ($_{\text{Pbatt}}$)

$$P_{batt,cmax,kbm} = \frac{kQ_1e^{-k\Delta t} + Qkc\left(1 - e^{-k\Delta t}\right)}{1 - e^{-k\Delta t} + c(k\Delta t - 1 + e^{-k\Delta t})} \tag{A4}$$

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

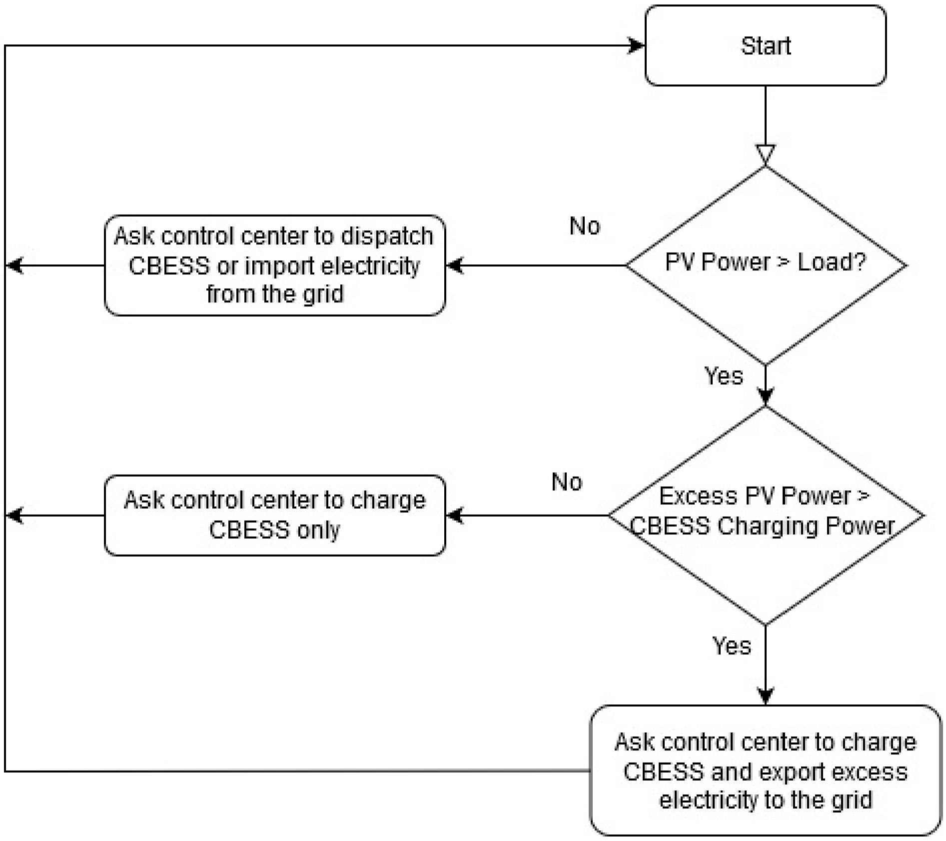

Figure A1. Flowchart for export and import from and to the grid.

Appendix C

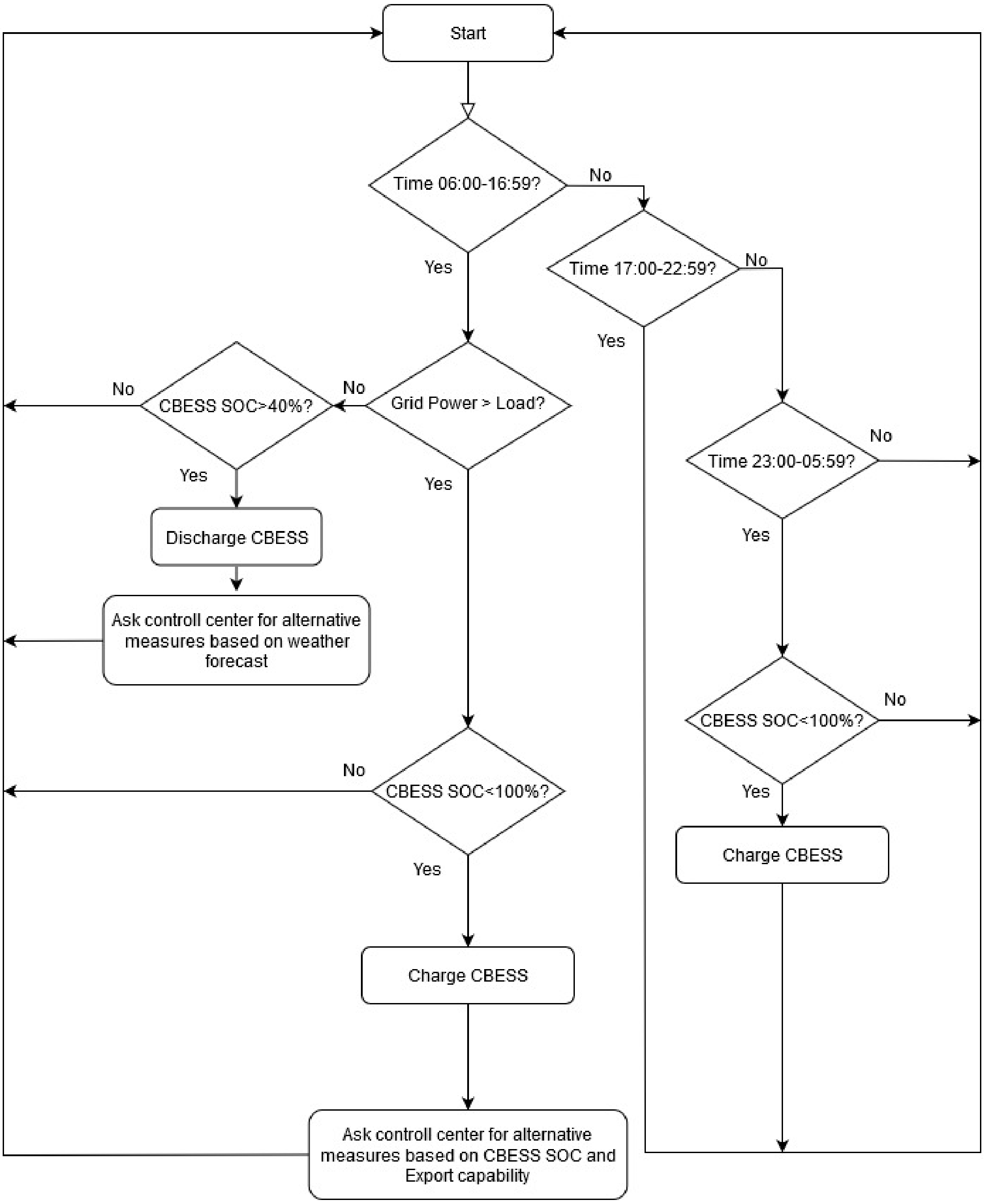

Figure A2. Flowchart of the CBESS control strategy.

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