Battery-operated auto rickshaws

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What is the evidence that battery-operated auto rickshaws in south Asia can run profitably on solar power?

- **In converting 3-wheelers/auto-rickshaws from petrol/CNG to battery operated, what policy conditions have supported or impeded this shift?**
- **What market incentives were found to be effective?**
- **How else can auto-rickshaws be electrified? How can renewable energy use support the charging of electric vehicles?**
- **What technologies have been proven effective, what battery technology is best?**

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1. Summary

This rapid evidence review collates available evidence on whether battery-operated auto rickshaws in south Asia can run profitably on solar power. The evidence on this subject is nascent, context specific and influenced by a number of factors. Given the complexity of subject matter, a broad approach to addressing this query is adopted. This draws on a range of literature on the subject including: discussions of the nature of auto rickshaw vehicle fleets, technical papers exploring the design of battery powered auto rickshaws and case studies of the deployment of battery powered vehicles (including where they draw on renewable energy sources). This review draws on a diffuse literature, key papers include:

- Das et al., (2020) who reflect on the diverse nature of the auto rickshaw fleet and the multiple functions such vehicles serve in south Asia. Of interest is the extent to which battery operated (or e-rickshaws) serve in different functions.
- Grütter & Kim, (2019) who explore e-mobility options for Asian countries, presenting a series of case studies exploring the deployment of battery powered auto rickshaws.
- SUM4ALL (2022) who discuss electromobility and its synergies with developing renewable electricity infrastructure. Of interest is their identification of five business models and exploration of benefits and limitations of these.
- Hasan (2020) who explores the potential for e-rickshaws in contributing to improved energy management (and importantly, the integration of renewable energy).

The report is structured as follows:

- Section two provides an overview of contextual factors that influence the viability of electric rickshaws and of their use of solar energy. This includes background details of the nature of rickshaw vehicle fleets, challenges and opportunities associated with battery powered rickshaws and importantly potential business models.
- Section three provides an overview of contexts where battery powered rickshaws have been deployed and whether these deployments have been successful. This includes a reference to whether renewable energy is utilised to power fleets.
- Section four and five provide some broad reflections on sub questions posed including conversion of three-wheelers to battery and which battery technologies and charging approaches have been deemed as successful.

Commentors widely agree that a well-functioning transport sector is considered vital for a country’s sustainable development with many countries identifying electrification of vehicle fleets and the use of renewable energy for charging as a solution. This review highlights that evidence regarding the subject is limited, mixed and variable. In particular, evidence regarding the role of electric vehicles powered by solar power and its impact is challenging to gather, given limited uptake of solar power use by e-rickshaws and the absence of systematically collected data. A number of broad factors are viewed to influence whether battery-operated auto rickshaws can run profitably on solar power:

- It is widely held that in a relatively short period, e-rickshaws have grown significantly in number, though there are data-related challenges in estimating the historical penetration of electric rickshaws.
- Relative to electric cars, electric two- and three-wheelers are considered to be more amenable to being manufactured in many LICS and MICS, are easier to maintain, take up less road space, are easier to charge, and are more affordable.
- Three-wheeler fleets are used for a variety of different purposes, and their operating parameters, such as travel pattern, load type, etc, vary. Consequently, the fuel or charging requirements of these fleets may differ.
- Markets in LICS and MICS often lack clear guidelines for the deployment of e-rickshaws and their administration and maintenance. Electric units deployed are often of low quality, equipped with lead batteries with a short life span and with environmental disposal problems, and vehicle convenience is not the same with gasoline or diesel or compressed natural gas (CNG) units in terms of power, driving range, and speed.
- Important problems such as maintenance and replacement components, public charging infrastructure facilities, and improved battery technology are highlighted as impediments to the successful deployment of e-rickshaws at scale.
- Road transport and renewable electricity sectors provide considerable opportunity for capturing synergies that can decarbonise and improve access to electricity and transportation. Improving business models and financial investments in both sectors need suitable integrated policy measures, funding mechanisms and governance structures to succeed, especially in LMICs with unstable grid infrastructure and limited access to finance.

Overall, the existing literature on whether battery-operated auto rickshaws in south Asia can run profitably on solar power has important gaps. The limited evidence and variation of impacts found in available studies across the global south may partly be explained by differences in energy grid composition, existing policies (including financial and non-financial incentives), and geographic characteristics. Despite these challenges nascent positive findings have been identified, though these will require further exploration, pilot testing and evaluation:

- Commercial adoption of e-vehicles for passenger and goods transport has been found to be cost-competitive. Pilot programmes indicate that electric two and three wheelers have reasonably low total costs of ownership when used in commercial fleet operations. Evidence regarding the role of solar power electric three wheelers is limited.
- Smart integration of energy storage systems with renewables such as solar and wind can increase grid flexibility, minimise fixed demand charges, and make business propositions more attractive by supplying consumers with low carbon, reliable, and affordable energy.
- EV fleets could play a role as distributed energy storage systems, thereby helping to increase the share of renewables. Second-life batteries from EVs can also play an important role for storing the fluctuating supply of energy from renewable sources

The literature reviewed in this review makes no reference to gender or disability.

2. Context

A well-functioning transport sector is considered vital for a country's sustainable development. However, transport systems can negatively impact the environment through emissions and pollutants, contributing to poor air quality and leading to ill health. Grütter and Kim (2019: x) highlight that in 2015, the transport sector emitted around 7.5 billion tons of carbon dioxide (CO_2) representing 18% of all man-made CO_2 emissions. The International Energy Agency projects 50% higher transport emissions by 2060 (Grütter & Kim, 2019: x).

In response to the above, many countries have identified electrification of vehicle fleets and the use of renewable energy for charging as a solution. The majority of Nationally Determined Contributions to address climate change identify transport as a mitigation priority and a number of countries in Asia have made electric mobility (e-mobility) pledges with these considered as an important pillar to the achieving decarbonisation (Grütter & Kim, 2019: x).

Auto-rickshaws

The composition of vehicle fleets varies widely across countries. Some countries, primarily low- and middle-income (LICS and MICS) countries in Asia, depend primarily on two- or three-wheeled vehicles for 60-80% of their total passenger vehicle-kilometres (World Bank, 2023: 24). Three-wheeled vehicles (commonly referred to as auto Rickshaws) are an important intermediate para-transit mode of transportation operating in urban centres in many south Asian countries (Das et al., 2020: 7). This sector consists of auto-rickshaws operating on compressed natural gas (CNG), diesel and batteries (Mishra et al., 2022: 23). E-rickshaws, powered by conventional lead-acid batteries, have become a common and convenient mobility option in a number of settings (Kumar & Quaddus, 2020: 930).

Das et al., (2020: 16-17) outline that three-wheeler fleets are used for a variety of different purposes, and their operating parameters, such as travel pattern, load type, etc, vary. Consequently, the fuel or charging requirements of these fleets may also differ. Das et al (2020: 16-17) provide a detailed overview of the nature of auto rickshaw fleets and the role of e-rickshaws in different aspects of this. Whilst reflecting on India, this overview is broadly consistent with fleet operations in other South Asian countries and may have important ramifications for which elements of the fleet can be converted to solar.

Passenger segment: This segment involves three-wheeler-based transportation of passengers from one point to another.

Para-transit fleet: This category caters to the intermediate mobility demand of the public in an urban area. The services of this fleet can be hailed on the street or via mobile applications. It operates in the following ways:

- *Single node operation*: The starting point (node) for a three-wheeler is fixed and is also the point of return after making one or more trip(s). The travel demand usually extends beyond the local area and is intra-city in nature.

The auto rickshaws hailed from auto rickshaw stands and halt-and-go points in Indian cities fall into the above sub-category. E-rickshaws are rarely used in such a mode of operation, due to their slower speeds and lower driving ranges.

- *Double node-buffer zone operation*: Here, a three-wheeler's movement revolves around two nodes, i.e. starting point and ultimate destination (often the last resting place, pre-set by the driver). Users of the three-wheeler's service follow similar two-node movement.

Here also, e-rickshaws have a limited use compared to traditional auto rickshaws, due to their slower speeds and lower driving ranges.

- *Fixed route operation*: In this case, the three-wheeler follows a fixed route between two or more points, and passengers using its services board and deboard along the designated route. The terminals of the fixed routes usually operate as three-wheeler stands.

This mode of operation is prevalent in the Indian cities of Amritsar, Bhubaneswar, Ranchi, and Kochi, where bus- and metro based public transport options have to compete with three-wheelers. The three-wheelers are mostly auto rickshaws, rather than e-rickshaws in such settings.

Feeder transport fleet: This fleet serves public transit operations in urban areas. In order to facilitate last-mile and first-mile connectivity for public transport routes, feeder transport fleets are deployed at different transit nodes/ stations, based on the travel demand/ footfalls.

Mobility service providers augment first-and last-mile connectivity (for example in Delhi between metro stations), by ferrying passengers to and from various points. The vehicles do not necessarily operate along fixed routes. In this mode of operation, e-rickshaws are frequently used.

Goods segment: For this segment, the operations entail the transportation of goods from one point to another.

Courier fleet: This fleet supports courier delivery services in a city. The delivery may result from an e-commerce transaction, intra-city cargo transport, or traditional mail coming from outside the city. The operation is based on a hub-and-spoke model, wherein the goods are stored at different levels of warehousing hubs (and nodal delivery centres) and transported along different levels of "spokes" (roads).

Grocery delivery fleet: Three-wheeler fleets that are used to deliver groceries, perishables, and related household items in an area fall into this category. Grocery delivery fleets transport goods between local businesses and local households (or third-party vendors) and typically cover a number of neighbourhoods. In case a delivery location falls beyond the catchment area of one fleet and its associated businesses, another fleet of the same service provider covers that location, along with the relevant local businesses. The delivery usually happens in pre-fixed time slots, as per the convenience of the consumers.

Three-wheeler fleets are used for different purposes, and their operating parameters, such as travel pattern, load type, etc, vary. Consequently, the charging requirements of these fleets may also differ.

Electric rickshaws

Though there are data-related challenges in estimating the historical penetration of auto rickshaws (Das et al., 2020: 7), it is widely held that in a relatively short period, e-rickshaws have grown significantly in number. For example, they currently comprise 83% of the Indian electric vehicle (EV) market (as of 2020) (Mishra et al., 2022). Kumar & Quaddus (2020: 931) summarising a number of older estimates (from between 2014-2016) highlight that there are more than 100,000 e-rickshaws operating in Delhi, 67,753 in Dhaka and 60,000 in Karachi.

Electrification of two- and three-wheelers has been identified as “low hanging fruit” for clean mobility in a number of contexts. For example, in India NITI Aayog[1] highlight that based on the market readiness, cost competitiveness, ease of charging, and emission reduction potential electrification of two- and three-wheelers should be a priority (NITI Aayog & Rocky Mountain Institute, 2017). India’s main program for electrifying vehicles has set aside 23% of its funds to support two-wheel rickshaw electrification and 29% for three-wheelers (Das et al., 2020: 7).

Relative to electric cars, electric two- and three-wheelers are considered to be more amenable to being manufactured in many LICS and MICS, are easier to maintain, take up less road space, are easier to charge, and are more affordable to a larger share of the population. E-rickshaws can thus fill niches in local transportation systems given how short most urban trips are (World Bank, 2023: 87).

Despite this, markets in LICS and MICS often lack clear guidelines for the deployment of e-rickshaws and their administration and maintenance (Mishra et al., 2022). Electric units deployed are often of low quality, equipped with lead batteries with a very short life span and with environmental disposal problems, and vehicle convenience is not the same with gasoline or diesel or CNG units in terms of power, driving range, and speed. While the low purchase price of such electric units makes them an attractive option (see Mishra et al., 2022: 27), users need to invest in new batteries after circa one year (Grütter & Kim, 2019: 75). For the analysis of environmental impact of auto versus e-rickshaws, Mishra et al (2022: 27) calculated vehicle kilometre travelled.

Important problems such as maintenance and replacement components, public charging infrastructure facilities, and improved battery technology are highlighted as impediments to the successful deployment of e-rickshaws at scale. A non-exhaustive list of challenges is explored below.

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[1] the apex public policy think tank of the Government of India, and the nodal agency tasked with catalysing economic development

Challenges

Electricity grid capacity

The market for e-rickshaws in developing countries is thriving without proper planning to meet the growing transportation demand. The deployment of e-rickshaw also lacks appropriate legislation. Because of unplanned growth, it puts on an additional burden on the existing energy infrastructure. 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 places additional strain on the system (Hasan, 2020).

Running 100% EVs places stress on the grid in terms of both electricity production and demand. EV charging can have a sizable impact on the loads applied to the grid at certain times and locations. The rise in the number of EVs can be accommodated by power generation facilities as long as the vehicles are charged off-peak or where renewable sources of energy are integrated (though renewable sources may be variable) (Grütter & Kim, 2019). Faster charging during peak demand, however, can have a significant impact. The extent to which EVs will impact the electricity networks will depend greatly on technologies and charging modes used, with the bulk of charging expected to occur in low-voltage distribution grids in residential or commercial areas (Grütter & Kim, 2019: x).

The transition to 100% renewable energy and EV fleets creates significant challenges for the electricity grids. EV charging infrastructure is being rapidly deployed globally. The global stock of EV chargers grew by almost 40% from 5.2 million in 2018 to about 7.3 million in 2019. Of the total stock however, 6.5 million chargers were private chargers (NITI Aayog, 2023: 8). NITI Aayog (2023) note that the continued development of EV charging infrastructure and its integration will depend on the policy and regulatory framework, which must also consider the prospective repercussions of the added EV load in the network, such as increased peak demand and congestion in the distribution grid. More broadly, while e-rickshaws are praised for their low carbon emissions, their operators are accused of being responsible for the huge unofficial electricity consumption that is exerting pressure on the inadequate electricity supply.

While EVs pose a challenge to managing the power system, their controllable and flexible characteristics present an opportunity to provide Vehicle-to-everything (V2X) services. In India, NITI Ayog reflect on three key challenges to supporting renewable EV charging (NITI Aayog, 2023: 12):

- Required policies and regulatory frameworks to enable the efficient deployment and integration of charging infrastructure.
- Required technologies and management of the potential impacts of the additional EV load in the power network.
- Mode of offering grid flexibility services from EVs, and how they can be unlocked.

To overcome this situation, researchers have proposed that solar panel technology could be used to recharge the e-rickshaw batteries (see for example Sulepeth & Kalashetty, 2018 and Solshare, 2023). As solar and wind are variable resources, so the amount of energy generated by them fluctuates with the weather conditions. For higher spells of wind and solar generation EVs can be charged at their maximum rated speeds, however, for lower supply scenarios the charging speed may reduce temporarily (NITI Aayog, 2023: 6) The NITI Aayog review of e-vehicle charging infrastructure and distribution grid makes only fleeting reference to the role of solar and typically draws on examples from the global north when references are made.

Considering energy issues, the Government of Bangladesh has implement taken initiatives to promote solar photovoltaic (PV)-powered charging stations. However, Hasan (2020) comment that (at the time of writing) only fourteen charging stations have been built, which have an aggregated capacity of less than 300 kW. These charging stations are built off-grid and offer plug-in charging options, which is time consuming and does not add any other value. Despite the above challenges, Hasan (2020) suggests that modern technologies can significantly improve the charging of e-rickshaws from technical and economic points of view.

Informality

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 or research (Hasan, 2020).

In south Asia, informal e-rickshaw operation can contribute to the development of economically viable, citizen-oriented and environmentally friendly transport systems. Although informal e-rickshaw operation is important, significant gaps are apparent in the literature in relation to e-rickshaw sustainability issues and policies, and the development of a methodology grounded in a robust theoretical base (Khan & Quaddus, 2020: 930). Given this informality, developing and enforcing regulations can be challenging. It is also challenging to accurately estimate numbers of e-rickshaws in operation.

Lack of regulation

The absence of e-vehicle registration and operators' driving licences and fitness certificates can pose challenges (Kumar & Quaddus, 2020: 933). Kumar and Quaddus (2020) reflect that inter-vehicle and intra-vehicle conflict on urban streets due to lack of fixed routes and e-rickshaws' cheaper fares. Due to the lack of regulation of e-rickshaw operation and perceptions of excessive numbers of e-rickshaws, some have criticised e-rickshaws for creating traffic jams on urban roads (Kumar & Quaddus, 2020: 933).

Limited international standards

Electric two- and three-wheelers are distinct in design from the other classes of EVs both in terms of their powertrain and battery related aspects. There are limited international standards governing their design and as such, there is no standardisation of charging practices worldwide for these vehicles (Das et al., 2020). The regional charging standards in prominent EV markets such as the US, Europe, and China are mostly associated with electric four-wheeled vehicles. In contrast, India has two standards for EV charging that are applicable to low voltage four-, three- and two-wheeled vehicles. Das et al. (2020) reflect that the Indian market presents an opportunity to develop effective home-grown charging solutions that draw on renewable energy sources but that this will require the generation of specific standards and regulations.

Design issues

The majority of studies have focused largely on the design of a new model of e-rickshaw by employing its entire weight as the essential criterion. With a more intelligent and efficient design, the battery-powered three-wheeler is meant to perform on level with or better than a conventional vehicle (Sethi et al., 2023). More design testing is required to explore the extent to which solar powered e-rickshaws can function at an equivalent level to other auto rickshaws and in which sections of the vehicle fleet they are best suited.

Battery technologies

According to the Indian government's strategy on electric vehicles, an increasing number of manufacturers are producing e-rickshaws for short-distance commuters. However, the producers typically employ Lithium- ion (Li-ion) battery packs or lead-acid batteries.

Lead-acid batteries are the commonly used energy carriers for e-rickshaws in south Asia. in India, the market is expected to reach $7.6 billion by 2030. Bangladesh alone hosts over twenty five lead-acid batteries manufacturers (Hasan, 2020).

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 of e-rickshaws in many contexts. In Bangladesh, despite some recognised recycling facilities, most used batteries are poorly managed and end up in scrap material businesses (Hasan, 2020).

In contrast to conventional lead-acid batteries, lithium-ion (Li-ion) batteries offer the advantages of quick charging, greater depth of discharge, and much lower maintenance costs (Sethi et al., 2023). The depth of discharge (DoD)[2] of a lithium-ion battery often exceeds that of a lead-acid battery by around 80%. However, Li-ion batteries have some drawbacks, such as memory issues and limited life spans (Sethi et al., 2023).

Lithium iron phosphate batteries ($LiFePO_4$ or LFP batteries) are also increasingly used in e-vehicles because of their low cost, high safety, low toxicity, long cycle life and other factors. $LiFePO_4$ or LFP batteries can run for 2,000 cycles (charging-discharging), whereas the Li-ion battery charging cycle is only about half as long. Some of the advantages of $LiFePO_4$ battery over Li-Ion battery are (Sethi et al., 2023: 327).

- Charging time is less.
- Rate of discharge is better.
- Overall maintenance is less
- Most broadly life of battery is more, which depends upon the number of deep recycle (charging cycle).

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[2] A battery's depth of discharge (DoD) indicates the percentage of the battery that has been discharged relative to the overall capacity of the battery.

Developing adequate policies to manage the transition of battery technologies is required, particularly in terms of battery technology management

Battery management

The management of batteries (e.g. swapping and disposal) involves several environmental and safety concerns. Commentators such as Upadhyay (2022) have recommended that end of life management of batteries be handled in a systematic way to reduce adverse health, safety and environmental impacts.

A practical method for recycling batteries and other energy storage components from EVs is viewed as essential for the successful implementation of this transportation technology. Disposal of EV batteries is likely to be costly and detracts from the environmental benefits of a zero-emission vehicle.

A blog by Upadhyay (2022) reflects on the informal economy that has emerged in south Asia in response to the emergence of e-vehicles. He notes that a large and thriving informal economy in South Asia around the disposal of lead acid batteries. Between 2013-14 and 2016-17, official data reveals a 1,000% rise in tonnes of batteries sold in India. In 2017-18, 1.2 million tonnes of batteries entered India’s recycling industry, 90% of which were processed informally (Upadhyay, 2022). The Batteries (Handling and Management) Rules 2001, amended to improve implementation in 2010, is the primary regulation in India on the use and disposal of lead acid batteries (Upadhyay, 2022). It makes manufacturers, assemblers and dealers responsible for ensuring the collection of used batteries from buyers and sending them to registered recyclers. However, a 2017-18 status review report of the rules published by the government’s own Central Pollution Control Board observed that (as reported by Upadhyay, 2022) “state pollution boards had been grossly inadequate in reporting inventories of appropriate stakeholders and compliance reports”. Manufacturing with lead as well as recovery of lead from waste is prohibited in India’s capital by the Delhi Master Plan 2021. This has led to illegal recycling units shifting to nearby towns such as Murad Nagar (Upadhyay, 2022).

Infrastructure

The ability to electrify road transport in LMICs is determined by the power sector’s capacity to provide reliable electricity at an affordable cost. With access to electricity as well as sufficient and reliable supply still being a concern in many LMICs, integrated planning and the joint development of both sectors becomes important.

The planning of charging facilities for electric two- and three-wheelers requires an examination of the nuances of the EV ecosystem. There is a need to understand how various players involved in e-two and electric three wheeler commercial operations, such as the vehicle manufacturers, fleet operators, and charging service providers, are managing charging requirements and how and when deploying renewable energy is feasible (see tables 2-6 and SUM4ALL, 2022: 14).

Despite these concerns, e-mobility, as a productive load, is also a new business case for the electricity sector. It gives utilities and independent power producers the opportunity to serve a new demand that can act as a base load and strengthen the financial viability of investments in grid expansion and additional generation capacity (SUM4ALL, 2022: 15). Land scarcity and grid constraints are the major hindrances for implementing expanded solar energy technology use in countries like Bangladesh (Hasan, 2020)

Opportunities

Transport electrification and renewables

Road transport and renewable electricity sectors provide considerable opportunity for capturing synergies that can decarbonise and improve access to electricity and transportation. Improving business models and financial investments in both sectors need suitable integrated policy measures, funding mechanisms and governance structures to succeed, especially in LMICs with unstable grid infrastructure and limited access to finance (SUM4ALL, 2022: 11).

SUM4ALL flag actions required across the stakeholder spectrum drive utilisation of renewables in e-mobility charging as follows:

- **Governments**: Drive renewable electricity and EV demand and supply with a clear vision and a road map toward long-term commitments.
- **Power utilities**: Add renewable electricity to production capabilities and support solar rooftops and smart charging solutions for customers, encouraging the use of renewable electricity for EV charging.
- **Manufacturers**: Build affordable and locally suitable, high quality EVs integrating renewable electricity through efficient and clean supply chains.
- **Operators**: Establish valued, scalable business models that can solve the affordability and productivity challenge.
- **Financiers**: Provide easy access to low-cost financing and scalable financing instruments.
- **Renewable electricity developers**: Grow the mix with customers to optimise electricity costs and network efficiency through grid integration.
- **Power exchanges**: Support favourable infrastructure and price mechanisms to allow round the clock renewable electricity and EV integration.

Commercial adoption of e-vehicles for passenger and goods transport has been found to be cost-competitive (Das et al., 2020: 9). Pilot programmes indicated that electric two and three wheelers have reasonably low total costs of ownership when used in commercial fleet operations. Evidence regarding the role of solar power electric three wheelers is limited.

SUM4ALL (2022: 17) comment that it is also an opportunity for the electricity sector to participate in the industry with new business models along the EV value chain. For example, EV manufacturers can deploy renewable electricity at their facilities, operators, and service providers at charging stations, among others. Further to this SUM4ALL (2022: 17) comment that the smart integration of energy storage systems with renewables such as solar and wind can increase grid flexibility, minimise fixed demand charges, and make business propositions more attractive by supplying consumers with low carbon, reliable, and affordable energy.

In a similar vein, Grütter & Kim (2019: xi) comment that increasing renewable energy penetration rates requires sufficient energy storage systems due to unpredictability of renewable sources (e.g., wind and solar). EV fleets could play a role as distributed energy storage systems, thereby helping to increase the share of renewables. Second-life batteries from EVs can also play an important role for storing the fluctuating supply of energy from renewable sources (Grütter & Kim, 2019: xi).

Business model

SUM4ALL (2022: 19) identify five different business models for e-mobility and renewable electricity integration, these are listed below including an overview of benefits, limitations, and recommendations. These each require further interrogation in the contexts in which they are applied and testing of their viability in real world contexts and at scale.

Table 1: Captive fleet charging with re-integration for public transport e-buses, ride hailing taxis (two-, three- and four-wheeler), and freight vehicles

GROWTH RATIONALE	The shift to public transport bus systems is increasing with a drive for operational and financial efficiency and to increase fleet size with a transition to e-buses. Also, the ride-hailing freight services market is growing and making an economic case for electrification. Public transport e-buses, ride-hailing taxis, and freight vehicles having access to a dedicated depot in strategic city locations with ample spaces would provide an easy charging opportunity with renewable electricity integration. As the push for freight electrification grows, warehouses make the most sense for charging points, considering the typical logistics profile of hub-and-spoke or point-to-point models, and vehicle layovers of ~5–6 hours during loading and unloading. Charging fleets with large battery capacities (for buses, trucks) demands more energy, which makes a case for integration with renewable electricity to reduce grid load. Big rooftops as well as ground space in depots and warehouses provide opportunities for renewable electricity integration for charging. Given the size of fleets and the required high megawatt-level charging loads, especially in case of e-buses, captive renewable electricity—produced for an entity's own consumption—alone may not be sufficient; additional supply from grid-connected installations, eventually off-site and with rights to use the grid for remote consumption may be needed, requiring open energy access.
BENEFITS	Reducing load on the grid during peak hours using renewable electricity with Battery Energy Storage Systems for charging, thereby reducing the grid investment costs required to manage peak demand. Reduce impact on the grid by reducing harmonics and voltage instability and thereby reduce losses in the system. e-bus or e-truck batteries provide good stationary renewable energy power backup storage (as BESS) at lower costs given higher daily distance runs and battery utilisation, thereby undergoing faster replacement.

LIMITATIONS	High investment costs when using batteries to store renewable energy to charge fleets overnight. Scheduling fleets to match charging patterns and renewable energy generation requires suitable locations to install renewable electricity on site or remote access to grids.	
SUITABILITY TO LMICS	e-buses provide higher GHG abatement per passenger-kilometre compared to other vehicle segments. Hence, they are often a high priority for LMICs to extend fiscal incentives and low cost financing from development finance institutions and climate funds. Already a high share of private operators is managing intracity and intercity bus systems in LMIC cities, and the right initial support can bring investments in e-buses. Apart from e-buses, ride-hailing taxis or fleets, and freight are also a prominent use case for renewable electricity integration for captive fleet charging.	
RECOMMENDATIONS	Government Support deployment of fleet electrification through fiscal and non-fiscal incentives. Provide additional incentives for charging captive fleets by renewable energy. Support solar leasing (a business model where the client has the photovoltaic unit installed on site, yet the unit remains in the provider's possession) to reduce capital expenditure for the client. Allow renewable electricity units to transmit power through the grid to an off taker (open access).	Fleet Operator Open fleet charging location for private users (may be for some hours of the day) to add profit to the business.

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Table 2: Green public EV charging integration with RE and BEES (including kerbside charging)

GROWTH RATIONALE	Public charging stations (PCSs) give visibility and confidence to EV users. Increasingly, more PCSs are getting integrated into existing matured commercial locations. These locations typically have space for renewable electricity integration. With many users resorting to home or office charging, rising PCS use, including kerbside charging, are moving toward quick opportunity or top-up charging. Real estate space at PCSs and prevailing high electricity commercial tariffs makes a business case for renewable electricity integration. Depending on space availability

<table>
<tr><td></td><td colspan="2">at the site, 100% renewable electricity can be supported with a mix of onsite and remote generation with open access to the electricity grid or the right to trade in produced renewable electricity for deferred consumption.
Renewable electricity plus BESS combined with a grid makes PCSs greener. It also reduces electricity and demand charges. This, further integrated with smart chargers, will allow PCS operators to align pricing signals with utilities given time of use or time of day tariffs and to drive EV charging users' behavioural change.
BESS using repurposed batteries from EVs could further make its deployment with renewable electricity more economical.</td></tr>
<tr><td>BENEFITS</td><td colspan="2">Provides better grid stability and reliability by supporting peak load shaving, thereby reducing required grid investments in equipment like inverters.
BESS at PCS will provide the necessary back-up power system at the time of grid failure/ outages and act as an ancillary support to the grid.</td></tr>
<tr><td>LIMITATIONS</td><td colspan="2">Requires land or space for deployment, which is a constraint in urban areas.
Need for smart charging solutions to better manage multiple EV charging demands, which also calls for high investments.
Low utilisation of PCSs affects the business economics.</td></tr>
<tr><td>SUITABILITY TO LMICS</td><td colspan="2">Most LMICs are in the early stage of EV adoption and have low and scattered demand at PCSs, posing a viability challenge for private investments without high capital subsidies.
Typically, the real estate cost in urban cities is high in LMICs, meaning that PCSs incline more toward fast charging than long-time parking and slower charging.
High voltage and high-power lines typically cost more in electricity infrastructure setup costs. As well, electricity commercial tariffs in LMICs are usually higher. The high sanctioned load for PCSs and lower utilisation results in high monthly charges.</td></tr>
<tr><td>RECOMMENDATIONS</td><td>Government
Provide capital subsidy to set-up PCSs and kerb-side chargers.
Plan to make grids smart through deployment of smart meters and pre-paid meters to monitor and manage renewable electricity generation and EV charging.
Provide discounted tariffs to PCS deploying renewable electricity.</td><td>Operators
Deploy smart solutions to manage uncontrolled EV charging at PCS.</td></tr>
</table>

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Table 3: Utilises as integrated renewable electricity and EV charging as-a-service provider for homes and offices

GROWTH RATIONALE	The economics of renewable electricity and EV are becoming attractive for end users and their fast proliferation high grid impact. Progressive utilities have started facilitating customers improving energy efficiency, behavioural or automated demand response (i.e., devices which connect during low demand disconnect during high demand) through time of use or demand charging, and solar rooftop generation. In many countries there is a growing trend of providing solar rooftop (SRT) as-a-service (long-term power purchase agreements or PPAs) to residential and commercial customers as a RESCO (renewable electricity service company) model. Private utilities are playing increasing roles in extending this service to customers. Many utilities in developed countries are extending the charging-as-a-service (CaaS) model to customers; they are extending investment or rebates or offering both, and optimising national cost on public charging infrastructure. During high renewable electricity output hours, EV charging shifts - for relatively low power electric 2 wheelers and e-cars at home and offices - through appropriate times of use and smart charging can optimise further end user economics and also utility costs for grid expansion. LMICs tend to have a high share of inverter and battery power backup systems at homes and offices. These storage assets can be leveraged to charge from captive solar rooftops and then support EV charging later in the day or night. Increasing new power backup systems would allow high loads (air conditioners, EVs) to be run through renewable electricity. In LMIC rural areas, where rooftops are weak, the deployment of solar panels over utility poles and pooling the power can be used for charging EVs.	
BENEFITS	Managed and controlled charging can reduce impact of EV charging on the grid.	
LIMITATIONS	High investment required by utilities to deploy smart technological solutions to monitor real-time integration of renewable electricity and EVs.	
SUITABILITY TO LMICS	Many LMICs struggle with electricity availability challenges, and most public utilities are unable to bring enough investments in grid upgrades. The economics of solar rooftop systems that are connected to the grid are increasingly favourable to end users and there is rising adoption. The right fiscal incentives for solar rooftop investment and favourable net metering policy can bring mass distributed renewable electricity adoption and democratised investment in grid generation capacity. Slow alternating current (AC) charging at homes and offices is the most-used type of EV (2 wheelers and cars) charging worldwide (more than public charging), offering additional load and revenue opportunity to utilities. Utilities in LMICs can take on a higher renewable mix (via renewable purchase obligations or RPOs) and EV targets in their customer base. They can also leverage external investments in solar rooftops and EVs to their advantage through innovative tariff and settling mechanisms (like ToU/ToD/net metering) and driving appropriate demand responses, including EV charging, during renewable electricity rich time and avoiding bunching of grid peaks.	
RECOMMENDATIONS	Government	Utility/Operator

	Mandate utilities by setting targets for renewable electricity deployments in the country Incentivise users to use solar rooftops for charging EVs over exporting electricity to the grid.	Provide solar rooftops to customers eligible for subsidies, which the government can support with a one-time subsidy; for example, in the agricultural sector, and provide further incentives for maintenance. Reduce the power purchase rate of feed-in-tariffs for consumers to encourage the use of generated renewable electricity power in-house rather than exporting.

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Table 4: Battery swapping for light EV charging

GROWTH RATIONALE	Battery swapping allows users to charge (swap the battery) quickly. Battery swapping charging stations are solely allocated to batteries that will be used in swapping. This allows renewable electricity integration, including captive systems; fuel stations could be key locations to host battery swapping.
BENEFITS	Is attractive for vehicle operators as swapping does not require the same amount of time as charging. In commercial fleets, it can increase fleet utilisation, improve logistics and delivery timelines, and save time. Allows separation of batteries and EVs ownership, thereby reducing the upfront cost of EVs for the end user. Provides an attractive business model for new energy operators through improved battery life, grid responsive charging, and renewable electricity integration. Reduces investments in charging networks and centralises electricity consumption. Allows the use of batteries as storage (in a managed manner) and the ability to put power back into the grid. Addresses space constraints in urban areas as multiple batteries can be stacked, using less space than parking for charging.
LIMITATIONS	High investment cost, high degree of technical requirements, and high inventory of batteries. Battery swapping stations demand high energy from the grid to keep the batteries charged round the clock. Need for standardisation of batteries (with different technologies) for interoperability without hampering technology upgradation. Battery swapping fits best for commercial and fleet-operated electric 2-wheelers, 3-wheelers, light 4-wheelers (particularly commercial vehicles) which run a high daily distance and have certainty in the routes to allow optimising the network of battery swapping stations.

	Many LMICs have a dominant vehicle share of 2-wheelers, 3-wheelers, and light 4-wheeler commercial vehicles, with increasing fleet adoption in these segments. The Asia-Pacific region dominates battery swapping applications in 2-wheelers, 3-wheelers, and light commercial vehicle segments, namely China, Japan, India, Indonesia, the Philippines, and others.	
RECOMMENDATIONS	Government Provision of capital subsidy and access to space at preferential rates to set up battery swapping stations and the extension of additional subsidies for integrating with renewable electricity. Define interoperability standards to ensure safety and compatibility of battery packs. Allow higher foreign direct investment in this segment to attract global investors when setting up battery swapping systems. Provide a single point of contact for clearances and approvals for battery swapping projects. Allow usage of waste lands, provide spaces or offer both to set up such battery swapping stations.	Operators Provide additional discounted rental/ leasing rates when using battery swapping with renewable electricity. Use identical (singular type) of battery for swapping in multiples based on application. Automate the process of battery swapping system for faster turnaround.

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Table 5: Distributed Renewable Electricity-Based Mini- or Micro-Grid Powering Rural Areas and EVs

GROWTH RATIONALE	Distributed renewable electricity-based mini or micro-grids are a solution for supplying electricity all day to many communities without adequate grid service. The financial viability of most mini or micro-grids requires strategies to increase electricity sales. Mini/micro-grids' need demand loads that can be time shifted to periods when renewable electricity is available, otherwise balancing the demand-supply will require substantial storage facilities. EVs with large on-board energy storage can provide a base load to distributed renewable electricity mini or micro-grids and potentially help mini/micro-grid operators improve their business cases and expand energy services. Distributed renewable electricity based mini/micro-grids can potentially be used as EV charging stations, like a battery swapping station that charges batteries during renewable electricity generation and then leases out these batteries to the EV drivers during operations. This would allow drivers to top up their EVs.

	Distributed renewable electricity based mini/micro-grids can use sources like solar, biogas, or even hybrid sources of energy.	
BENEFITS	Provides access to affordable/reliable electricity/transport in underserved areas. Reduces loss and wastage of farm produce due to increased access to transport. Provides a base load to Mini grids improving the business cases for the operator and reducing costs for the end user. Encourages rural entrepreneurship in providing renewable electricity to productive applications, like EVs for transport services, grain milling, rice hulling, cold storage, sewing machines, and food processing. Ensures safety by providing power during night using battery storage. Supports education by providing access to transportation to schools/colleges. Ensures seamless delivery of essential services such as healthcare, education (online learning), and internet connectivity, which have become vital owing to pandemic-like situations.	
LIMITATIONS	High investment costs for deploying Mini grids and lack of financing support. Requires regular local maintenance support (skilling) to keep mini grid workings for e-mobility applications.	
SUITABILITY TO LMICS	Access to both affordable and reliable electricity and transportation continues to be a challenge in LMICs. 238 million households will need to gain electricity access in Su bSaharan Africa, Asia, and island nations by 2030 to achieve universal access. Diesel generator sets are used as an energy source, which is a highly polluting technology (including in island countries). Distributed renewable electricity based mini grids offer an opportunity to power remote rural areas of LMICs. Mini grids can serve almost half of the total rural population—an estimated 111 million households. Transport facilities are also limited in remote areas, and the modes of transport that exist are primarily 2-wheelers, 3-wheelers, and light 4-wheeler commercial vehicles. Hence this model will fit primarily for electric 2- and 3-wheelers but can be extended to light commercial vehicles depending on the size of the mini grid.	
RECOMMENDATIONS	Government Mandate that mini grids be considered part of formal energy planning processes and help support them with financial resources and incentives where required. Support community-based mini grid projects as part of national rural electrification programs and poverty reduction efforts. Provide financial and fiscal incentives to encourage mini grid development and keep electricity tariffs affordable. Fiscal incentives include customs waivers	Mini grid operator (private/ power utility Encourage and incentivize charging of EVs during off-peak hours to help improve mini grid economics. Support the deployment of EVs through rental models and create alternate livelihood

	and tax breaks for investors. Financial incentives include grants, low-interest loans, and loan guarantees. Provide incentives to independent power producers to sell surplus power from mini grids to the national grid. Encourage small power producers with innovative business models to use mini grids to electrify rural communities and use them for charging EVs.	opportunities for rural entrepreneurs.

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3. Impacts of e-rickshaw utilisation

Considering the potential of solar power e-rickshaws is context specific. Grütter & Kim, (2019: xi), reflecting on the Asian countries with the largest greenhouse gas reduction when using EVs, note that it is those with a high share of renewable electricity production such as Armenia, Bhutan, Georgia, the Kyrgyz Republic, the Lao People's Democratic Republic, Nepal, and Tajikistan, while countries with a high carbon factor in electricity production such as India, Indonesia, Kazakhstan, Mongolia, and Turkmenistan will only result in limited GHG reductions by deploying EVs (Grütter & Kim, 2019: xi).

In what follows, a number of south Asian case studies, identified by Grütter & Kim (2019) and discussing the potential impact of three-wheeler EVs (including those powered by renewable sources of energy is provided).

Case studies

Nepal (Grütter & Kim, 2019: 68-69)

Nepal has a zero-grid factor as all its electricity production is based on renewables. Kathmandu's air pollution problems and high fuel prices create a favourable condition for the promotion of EVs. Nepal has developed various incentives schemes to promote EVs.

Electric three-wheelers were introduced in Kathmandu in 1993 with a United States Agency for International Development (USAID) financed project converting diesel 3-wheelers into e-rickshaws (Safa Tempos or e-Safas). In 2000, circa 600 electric three-wheelers plied the streets of Kathmandu, while more than 4,000 fossil fuel three-wheelers were operational.

Safa Tempos were assembled in Kathmandu with parts from India and the US and can transport up to 12 passengers with a drive range of 55 km and a battery life span of eighteen months using deep-cycle lead-acid batteries. Each vehicle has at least two sets of batteries and approximately forty battery charging and exchange stations were located at convenient points along main routes. The government does not charge any value-added tax and only 1% custom duty for the import of EV components and EVs do not have to pay the annual vehicle tax. The ban on diesel rickshaws in 1999 gave a decisive push toward e-rickshaws, with numbers increasing from 200 units prior to the ban to 600 units a year after the ban. After 2000, no new e-rickshaws were purchased as the government allowed for the import of petrol- and LPG-powered rickshaws as well as diesel microbuses with very similar reduced customs tariffs given to EVs. The government thereafter banned the entry of new three-wheelers, including the e-Safas, to Kathmandu.

E-pedicabs in a modern design were initiated by the Asian Development Bank and were trialled in Lumbini and Kathmandu in 2017. In contrast to motorised rickshaws, bicycle rickshaws are used for last-mile connectivity, transport a maximum of two passengers, and are confined to certain routes, e.g., in Kathmandu, around a tourist area. While electrified pedal rickshaws have been in use in Asian countries, there are differences between these motorised e-rickshaws introduced in Kathmandu and existing e-pedicabs:

- Modern, lightweight design of e-pedicabs with special customer features such as an on-board tablet device.
- E-pedicabs can be pedal-assisted while e-assisted rickshaws are too heavy and chain-runs are often impeded due to frame modifications, i.e., if the battery is empty, e-pedicabs can still operate while conventional battery-assisted pedal rickshaws cannot.
- Use of lithium-ion batteries instead of heavy, short-lived lead acid batteries, which have a high environmental cost when disposed.

Impact: Annual GHG reductions for the 600 e-Safas are around 2,200 tons of carbon dioxide (tCO_2e) tank-to-wheel (TTW) to 2,700 tCO_2e (WTW) or around 4 tCO_2e per vehicle per annum.

The commercial viability of e-rickshaws was linked to the ban on diesel units and financial benefits not available to fossil fuel units. Total costs of operation, including capital expenditure (CAPEX) and operational expenditure (OPEX), are around 30% higher for e-Safas than for diesel microbuses. An evaluation of social costs and benefits shows that e-rickshaws are economically more profitable than fossil fuel units, i.e., there is a case for subsidising EVs.

E-pedicabs consume around 0.5 kWh per day of electricity which would allow for full charging, e.g., through a 250-watt photovoltaic system. The CAPEX of an e-pedicab is currently around $2,500, making it financially nonviable compared to a bicycle rickshaw or a motorised unit.

Success factors and critical elements: A major critical factor in the rise and fall of e-rickshaws in Nepal was inconsistent government policy and opposition from interest groups of fossil fuel vehicle owners, which had very close links to the government. Conventional diesel three-wheelers were banned in 2000, but at the same time subsidies were given to microbuses to replace them and LPG three-wheelers were allowed (with LPG subsidised by the government). Also, allegations of battery pollution undermined the image of e-Safas. Batteries were also deteriorating faster than expected, occurring after a year. The government then banned all three-wheelers, including electric units alleging oversupply of vehicles and favouring diesel microbuses.

The potential for e-pedicabs is related to last-mile connectivity in urban centres with limited access to motorised vehicles. For other applications, e-pedicabs compete with e-rickshaws, which have more power, higher speed, and can carry more passengers and cargo.

Bangladesh (Dhaka) (Grütter & Kim, 2019: 80-)

Bangladesh has no policies or incentives toward EVs (at the time of writing), except its target for the electrification of services. However, there are an estimated 600,000 electric three-wheelers operating in the country, of which around half are assumed to be battery-assisted pedal-rickshaws and the rest e-rickshaws.

In 2014, GHG emissions in Dhaka due to passenger transport ranged from 2.3 million tCO2e tank-to-wheel (TTW) to 2.9 million tCO_2e well-to-wheel (WTW), of which around 10% are caused by motorised rickshaws which have a share of around 15% of motorised trips.

Table 6: Environmental Impact of Electric Vehicles in Bangladesh

Criteria	Situation	Comment
GHG impact of EVs	Electricity grid factor 0.64 $kgCO_2e/kWh$.	The grid factor has remained constant in the last 20 years with small annual variations. Based on vehicle type, the grid factor results in emission reductions by 40%–60% compared to fossil fuel vehicles.
Local pollution impact of EVs	Bangladesh has Euro 2 emission standards and pollution costs of $52,000 per ton of $PM_{2.5}$ and $370 per ton of NOx	The impact of an EV on local pollution levels is high compared to a conventional new vehicle due to the low vehicle emission standard applied in the country and relatively high pollution costs.

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Crica 500,000 cycle rickshaws and 50,000 CNG rickshaws operate in Dhaka. Currently, a large number of battery-assisted pedal rickshaws and e-rickshaws operate in the city. However, their usage has been restricted by the government due to concerns over design and safety of the vehicles, claims of low speed for main roads obstructing traffic, and especially due to illegal electric connections used by e-rickshaws creating stress on the grid, safety problems, and lack of payment.

Battery-assisted pedal rickshaws are confined to secondary roads while on main roads, only electric units operated by handicapped persons can be operated. Standard e-rickshaws can only be operated in confined areas while CNG units can be operated universally.

Higher-powered e-rickshaws can accommodate up to eight passengers and are only allowed in confined areas on secondary streets. In general, these use two battery sets of lead-acid batteries with a life span of 1–1.5 years. Drivers prefer the electric units compared to CNG-powered units as they can carry more passengers, have a lower initial purchase cost, and also lower operational costs. Drawbacks are regular battery replacement and limited usage.

E-rickshaws are financially attractive though batteries have to be replaced every year. If vehicles are used for more than 5–6 years, electric units tend to be more expensive than CNG units.

Table 7: Cost of Rickshaws in Dhaka

Parameter	Manual Rickshaw	Battery-Assisted Pedal Rickshaw	Electric Rickshaw	CNG
Features	Manually powered for two passengers	For two passengers, lead acid battery with six months to one year life span, battery replacement costs around $200, $0.60 electricity cost per day	For six–eight passengers; lead-acid battery with 1–1.5 years; can drive 100–120 km per day using $1.50 of electricity per day; battery replacement cost around $600; electricity consumption of around 0.13 kWh/km	For two–three passengers; same mileage as electric rickshaw; high price due to high tax levied on CNG-powered rickshaws
Cost	$300	$600	$1,800	$4,500

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Modern electric 3-wheelers have a large potential for GHG emissions reduction in Dhaka as substitutes for CNG units and for use for last-mile trips. Using electricity from the grid, replacing all CNG rickshaws and instead using e-rickshaws would result in a reduction of around 180,000 tCO_2e per annum; if electricity would be provided by renewable sources, reductions of 320,000 tCO_2e per annum could be achieved.

A recent top-level stakeholder meeting to address e-rickshaws convened by the Prime Minister of Bangladesh required e-rickshaws to get officially registered to ensure public safety and sought to resolve the issue of charging and electricity pilferage. Political interest to promote e-rickshaws and substitute pedal-rickshaws and CNG units is strong, but linked to a program which provides for safe designs of units, legal registration of units, and solution to the charging problem. A program addressing these issues (e.g., using e-rickshaws with battery swap systems and charging at swap stations with EV systems) would be an attractive option for Dhaka. It would not only have a significant impact on GHG reduction, but would also improve the livelihood of rickshaw drivers. It is important, however, that new e-rickshaw models are introduced which comply with safety standards, are based on lithium-ion batteries, and offered as a packaged solution with charging infrastructure powered by renewable energy sources to ensure political support.

India (Udaipur) (Grütter & Kim, 2019: 82-86)

In 2013, India unveiled the National Electric Mobility Mission Plan 2020 with the mission to make India a leader in the EV sector, targeting six-seven million EVs on the road by 2020. The Faster Adoption and Manufacturing of Electric-Vehicles program was launched for the period 2015–2017, extended until September 2018. But these short extension periods result in a lack of continuity and future clarity about financial incentives for EVs. As of mid-2018, financial incentives for EVs reached a maximum of $400 for scooters and motorcycles, $900 for 3-wheelers, $2,000 for cars, and up to $100,000 for buses.

Table 8: Environmental Impact of Electric Vehicles in India

Criteria	Situation	Comment
GHG impact of EVs	Electricity grid factor 0.82 kgCO_2e/kWh	EVs with this grid factor reduce by 10%–50% of GHG emissions, i.e., greening of the grid is important. The grid factor has improved on average annually by 1.5% over the last two decades; however, at this rate, India's grid will still be highly carbon intensive over the next 2 decades.
Local pollution impact of EVs	India has the vehicle emission standard BS IV (equivalent to Euro 4) and pollution costs of $32,000 per ton of $PM_{2.5}$ and $230 per ton of NOx	The impact of an EV on local pollution levels is relatively low compared to a conventional new vehicle complying with BS IV (equivalent to Euro 4).

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In 2016, the Prime Minister of India announced that all vehicles sold by 2030 will be electric. This target has been revised to about 30% of total vehicles. The Government of India also decided to go beyond a national EV policy and pursue action plans. Manufacturers voiced concerns over the lack of a clear policy road map, including a policy on charging infrastructure. While the national policy lacks clarity, various progressive states such as Karnataka have been rolling out EV guidelines and policies.

The Udaipur Municipal Corporation plans to transform its rickshaw fleet by introducing e-rickshaws and restricting the growth of diesel- and gasoline-based units. With assistance by the Capacities project funded by the Swiss Development Cooperation, a pilot project with 18 e-rickshaws from which the following data is derived.

Low-powered e-rickshaws with lead-acid batteries, used in most Indian cities, have significant disadvantages in carrying capacity, power, and speed, especially in hilly conditions such as in Udaipur. Higher-powered versions with lithium-ion batteries are available, albeit at higher cost. Lithium-ion batteries create less environmental problems and hazards with recycling, have a longer life span, and can be charged faster. Technical and environmental advantages therefore highlight that usage of e-rickshaws with lithium-ion batteries is preferable in contexts such as Udaipur.

Due to the high grid factor, the GHG reduction (WTW) is only 12% of e-rickshaws compared to diesel units, i.e., alternative sources of electricity production are important. The GHG impact can be significantly enhanced by using solar charging stations, a technology which can be combined well with e-rickshaws. This would increase the annual GHG reduction of a fleet of e-rickshaws in Udaipur from 850 tCO_2e to nearly 6,000 tCO_2, i.e., around 5% of the annual GHG emissions from the transport sector in Udaipur could be reduced.

In financial terms, e-rickshaws are excluded from subsidies making them slightly more expensive than diesel units; including the current government subsidy would make e-rickshaws at par or even slightly less expensive than diesel units. E-rickshaws, however, require battery replacement every two years, i.e., significant CAPEX investments which require financial planning by rickshaw owners or a system based on leased batteries.

Table 9: Diesel versus Electric Rickshaws in Udaipur

Parameter	Diesel Rickshaw	E-Rickshaw
GHG emissions per unit per annum	TTW: 0.97 tCO_2 WTW: 1.19 tCO_2	TTW: 0 tCO_2 WTW: 1.05 tCO_2
GHG reductions per annum fleet: 6,000 units	-	TTW: 5,800 tCO_2 WTW: 850 tCO_2
CAPEX per unit	$3,400	$4,900 including charger and two times battery replacement
OPEX per unit annually	$440	$250
Subsidy, Government of India	-	$650
Total Cost of Ownership per kilometre	$0.63/km	$0.61 per kilometre with subsidy $0.68 per kilometre excluding subsidy

Source: Grütter & Kim, 2019: 84 Reproduced under CC BY 3.0 IGO

The major barriers to widespread adoption of e-rickshaws in Udaipur include:

- Grid capacity is limited and authorities are concerned regarding additional peak load. This could be resolved through smart charging and battery swap offers, or charging with solar systems without putting an increased load on the grid.
- The driving range of current models is around 50 km without charge, which potentially limits the income of e-rickshaw drivers. This can be resolved by battery

swap systems and/or with fast chargers to reduce battery charging time (currently at 4 hours using 1 kilowatt chargers).

- Reliability of lithium-ion rickshaws is still low with full discharges experienced frequently. This is because majority of e-rickshaws in India are still using lead-acid batteries, with limited options and thereby experience with lithium-ion units.
- The low power of e-rickshaws results in slower driving speeds compared to conventional units. This contributes to the perception that slow-moving e-rickshaws increase traffic congestion. Higher-powered e-rickshaws can help overcome this problem but requires higher costs (increased vehicle and battery cost plus increased electricity usage).
- While subsidies are theoretically available, drivers in Delhi, for example, report that it is very difficult to access the subsidy fund and only 1% of the drivers actually obtained the incentive.

E-rickshaws used currently in India are basically low-cost, low-power lead-acid units with a short battery life span of six months to one year, with significant disadvantages in speed, power, load capacity, and driving range when compared to conventional units, while also creating potential health and environmental hazards with battery recycling. These are financially attractive enough to be taken up without further incentives by some rickshaw owners despite the technical disadvantages and environmental risks.

Higher-powered lithium-ion e-rickshaws, while not yet popular in India, can become an alternative and fare better against conventional rickshaws in power and load capacity, and also pose less environmental hazards concerning battery recycling. However, to have a significant GHG impact, these should be charged through renewable local energy sources, e.g., off-grid solar photovoltaic systems. To enhance driving range, battery swap systems or higher-powered fast chargers will be required. Also, the quality and after-sales service of these lithium-ion e-rickshaws need to be improved. In terms of costs, these can become a viable alternative with slightly higher total cost of ownership than conventional units — however, the charging structure required, including potentially a battery swapping scheme as well as high battery replacement costs and higher initial CAPEX, would very much favour a fleet approach based on, for example, leasing vehicles to owners. This would also allow for financing with lower interest rates as well as facilitate access to subsidy schemes for individual rickshaw owners. Aggregators could also help enforce improved after-sales service and higher quality products due to being high-volume buyers, who can push manufacturers toward providing high-quality units.

4. Conversion of three-wheelers to battery operated

The rise of e-rickshaws on urban streets and associated sustainability issues have encouraged greater consideration of these issues by urban designers in policy development processes. Concerns regarding the operation of battery powered rickshaws have prompted reaction from governments at various points. For example, Bangladesh planned to ban e-rickshaws due to significant of unofficial electricity consumption (at least 300 megawatts per day) in the early 2000s. Similarly, in India, a blanket ban on e-rickshaws by the Delhi High

Court was criticised and became an issue during the Assembly polls during a similar period (Kumar & Quaddus, 2020: 931).

Policies to support uptake and or conversion of three wheelers from petrol, diesel or CNG to battery are often grouped into price or financial incentives and non-price measures. In countries with high EV uptake, both measures have been taken (Grütter & Kim, 2019: xiii-xiv).

- Financial incentives are given for vehicles as well as charging infrastructure either as direct subsidies, fiscal incentives, or reduced energy costs.
- Non-price incentives depend very much on the country, and should be related to factors which influence purchase decisions of potential EV customers, including special lane access, parking perks, exemption from road and congestion charges, and exemption from driving and purchase restrictions.

National policies are typically targeted toward fiscal incentives. The largest impact from fiscal incentives is achieved if the EV purchase premium is reduced. Non-financial incentives are typically developed at the municipal level and result in cities having a decisive influence in the adoption of EVs. Policies that have been especially successful in this context include (Grütter & Kim, 2019: xiv):

- waivers on regulations that limit the availability of license plates,
- exemptions from access to restricted urban areas,
- exemptions from usage fees for road networks or parking fees,

Grütter and Kim (2019: xv) flag that in countries with a grid factor of over 0.8 $kgCO_2e/kWh$, greening the grid should be the first priority. The impact of EVs on GHG reduction in such countries will be small with high marginal abatement costs. Starting first with EVs or greening the grid in parallel to promotion of EVs is not considered an effective strategy since grid greening, in general, takes significant periods of time due to the long-life span of energy production units (Grütter & Kim, 2019: xv).

Grütter and Kim (2019: xv) also flag that incentives for lead-powered EVs should be phased out and battery recycling and re-usage policies should be put in place, obliging vehicle vendors to take back batteries and use them in secondary applications or recycle them.

Khan and Quaddus (2020) reflect that e-rickshaw operations should be legalised by the issuance of registration and operators’ driving licences and fitness. Further to this several studies advised that designated e-rickshaw parking places should be built to avoid traffic problems and support the establishment of battery charging stations.

5. Effective battery technologies and charging

Changes in battery electrochemistry has reduced the charging time and improved earnings of electric rickshaw drivers, however, the penetration of lithium-ion batteries is relatively low in the electric three-wheeler segment. Despite this, there is an increasing trend of retrofitting electric three-wheelers with lithium-ion batteries (Das et al., 2020: 23). It is important to note that in the case of electric three-wheelers battery capacity is typically determined by the vehicle application (Das et al., 2020: 24).

- e-rickshaws used in passenger transport have battery capacities between 2.8 kWh and 6.6 kWh.
- e-autos have a higher battery capacity, 3.8-7.4 kWh. The average difference in capacity between them is around 2 kWh.
- goods carrier e-carts have battery capacities between 4.2 kWh and 5.2 kWh.
- E-cargo goods carriers have batteries between 4.8 and 7 kWh. The average capacity difference between them is about 1.5 kWh.

Consideration of usage of electric rickshaws will therefore determine the type of battery used and the associated charging requirements. Electric two- and three wheelers are distinct in design from other classes of EVs in both their powertrain and battery related aspects. As noted above, there are limited international standards governing their design and as such, there is no standardisation of charging practices for these vehicles.

One option to support charging at pace and as discussed above is battery swapping schemes at nodal points. As e-rickshaws can have detachable batteries, which can be charged outside the EV battery swapping schemes may provide one means of supporting solar charging at fixed locations. Potential solutions to vehicle charging are presented below:

Battery Energy Storage System (BESS): BESS has been heralded as a significant catalyst for integrating renewable energy into the grid globally. 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 (Hasan, 2020). An aggregated form of the batteries of EVs at a single point can be considered a form of BESS.

Community Energy Storage (CES): Community energy storage (CES) is an existing concept to make communities self-sufficient in energy. In this network, energy generated by solar home systems (SHS) is stored in batteries at different households (Hasan, 2020). 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. This configuration can also be imagined with the concept with aggregated batteries of EVs/e-rickshaws at a single point (Hasan, 2020).

Battery Swapping Station (BSS): Battery swapping stations are becoming popular to avoid charging time for EVs. China has emerged at the forefront of this movement, offering battery swapping services to electric cars and motorcycles (Hasan, 2020). BSSs offer an energy service model rather than battery ownership, which minimises the risks of low battery lifetime to the vehicle owners. BSSs also offer less investment compared to distributed EV charging points (Hasan, 2020).

Microgrid and Smart Energy Systems: 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 (Hasan, 2020). The microgrid can also act as an electric vehicle aggregator to integrate EVs into power systems, and provide additional storage services.

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