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ELECTRIC VEHICLE RECYCLING POLICY STUDY FOR BHUTAN

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Development of Rules and Regulations for the Handling, Recycling and Disposal of Electric Vehicle Batteries

Special Report for the Government of Bhutan

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Rev 5

EXECUTIVE SUMMARY

Bhutan lacks petroleum resources, but has an abundance of hydroelectric power, thus moving towards electric propulsion is highly advantageous. In anticipation of the move towards electric vehicles, this study outlines electric vehicle battery handling and recycling guidelines. Given the relatively small size of the electric car fleet in Bhutan, even with aggressive expansion of the market share, it is unlikely that in-country electric vehicle battery recycling will be economically viable before the latter half of the 2030's. Even when end-of-life battery packs become available for recycling in quantity, given the relatively small vehicle population in Bhutan, only basic pack teardown and recycling is recommended, with the individual cells either used in secondary applications, or shipped to third party recycling centers outside of Bhutan.

Governmental Policy recommendations are made, following the best practices globally, and include such provisions as electric vehicle product labeling, battery pack labeling, and performance and durability standards as well as battery recycling requirements.

Finally, electric vehicle battery handling guidelines are presented, along with recommendations for training emergency responders in the hazards of electric vehicle batteries.

DISCLAIMER

TABLE OF CONTENTS

ABBREVIATIONS

Ah	Amp Hours
ASEAN	Association of South East Asian Nations
BMS	Battery Management System
CdS	Cadmium Sulfide type Battery
CO2	Carbon Dioxide
DNP	Department of National Properties
EV	Electric Vehicles
EOL	End Of Life
GEF	Global Environment Facility
GHG	Green House Gasses
GNHC	Gross National Happiness Commission
HV	High Voltage
IEA	International Energy Agency
IP	Ingress Protection
Kg	Kilograms
kW	Kilowatts
kWh	Kilowatt hours
LFP	Lithium-Iron-Phosphate type battery
Li	Lithium
LTO	Lithium-Titanate type battery
LMO	Lithium-Manganese-Spinel type battery
MoIC	Ministry of Information and Communications (of the government of Bhutan)
NBRC	National EV Battery Recycling Center
NCA	Lithium-Nickel-Cobalt-Aluminum type battery
NiMH	Nickel Metal Hydride type battery
NMC	Lithium-Nickel-Manganese-Cobalt type battery
PbA	Lead Acid type battery
PMU	Project Management Unit (of the government of Bhutan)
PPE	Personal Protection Equipment
RGOB	Royal Government of Bhutan
SCBA	Self Contained Breathing Apparatus
SOC	State Of Charge
SOH	State Of Health
UN	United Nations
UNDP	United Nations Development Program
UPS	Uninterruptable Power Supply
USD	United States Dollar

LIST OF FIGURES

1.0 INTRODUCTION

Given Bhutan's lack of petroleum resources, and abundance of hydroelectric power, it is evident that Bhutan will benefit greatly from shifting transportation away from combustion based propulsion to electric propulsion. One of the challenges to be faced with this new technology is the safe and environmentally appropriate handling of the batteries from Electric Vehicles (EVs) both during and after their use. To this end, together with our partners (UNDP, Ministry of Information and Communications (MoIC) and Project Management Unit (PMU)) we have developed policy and regulations for the handling, recycling and disposal of EV Batteries. This includes an assessment of the possibility of developing an in-country EV Battery recycling industry.

1.1 BACKGROUND

Vehicle population in Bhutan is rapidly growing with over 91% of the vehicles being privately owned. The "Light vehicle" is the largest sub-category with 71,827 vehicles (as of Dec 2020), accounting for 66.4% of the overall vehicle inventory. Out of the overall vehicle population there are only 77 EVs registered in the country. The annual growth rate of motor vehicles is 12-13% per annum leading to growing traffic congestion, air and noise pollution and increased GHG emissions from vehicles.

Since the transport sector is entirely reliant on imported fossil fuel, Bhutan has been experiencing a significant increase in fuel imports, increasing from US$ 10M (Nu 721M) in 2002 to about US14.6M (Nu 10.15 billion) in 2018 against hydro-electricity export revenue of US$ 160M (Nu 11.9 billion) in 2019. This not only exerts budgetary pressures on foreign exchange accounts and exposes the country to energy security risk but also represents a serious threat to Bhutan's commitment to remain carbon neutral - unless innovative low emission public transport systems are promoted to become the preferred choice for urban mobility.

Recognizing this, the Royal Government of Bhutan (RGOB) is committed to reducing fossil fuel dependency in the transport sector and shifting to alternate and indigenous resources. Use of excess hydropower being one such potential substitute together with improvements in vehicle fuel efficiency.

The RGOB is already making efforts to meet this aspiration to upgrade the public transport system. In addition to expanding its vehicle fleet for mass transit and improving the service delivery, it also aspires to capture the opportunity to make a technology leap and pilot Low Emission Vehicles (LEVs) such as hybrid and electric vehicles (EVs) in the country. Consequently, a number of studies have been commissioned with the aim of exploring options to promote more sustainable low emissions transport options such as electric, hybrid and non-motorised solutions for both the public and private transport sub-sectors.

The Gross National Happiness Commission (GNHC) Secretariat – the Operational Focal Point for Global Environment Facility (GEF) in Bhutan with technical support from UNDP formulated a project proposal that was approved by GEF in July 2018. While the GNHC was designated as the focal agency for the Electric Vehicle initiative in 2014, the responsibility was transferred to the Ministry of Information and Communications (MoIC) in June 2017 given its domain expertise and transport mandates. In order to effectively manage and implement the project, Project Management Unit (PMU) has been instituted under MoIC headed by a Project Manager under the supervision of Project Director and a multi-sectoral Project Board Chaired by the Secretary, MoIC.

The Project "Bhutan Sustainable Low Emission Urban Transport Systems" has now entered the implementation phase and a number of activities remain to be implemented. The objective of this on-going project is to promote low emission public transport systems as the preferred choice for urban mobility in Bhutan. The project will focus on the following outcomes intended to achieve the objective of the project:

Component 1: Policy support for the promotion of low emissions modes of transport

Component 2: Awareness and institutional capacity development

Component 3: Investments in Low Emissions Transport Systems and Support Services

The Social and Environmental Screening was done during the project implementation stage as per the GEF requirement. It was identified that the project could pose risks to community health and safety due to the transport, storage and the use/or disposal of hazardous or dangerous materials, mainly due to the batteries used by electric vehicles (cars).

This was also identified by the stakeholders as one of the major concerns for the project to consider by putting relevant and practical measures in place. For this purpose and considering the absence of local expertise, Focus Applied Technologies was contracted as an international consultant to assist the Royal Government of Bhutan.

2.0 PURPOSE OF THIS REPORT

This report explains the economics of Electric Vehicle battery recycling, reviews common governmental policies relating to Electric Vehicle batteries, presents battery handling guidelines, and proposes governmental policy for EV Battery Recycling, and Electric Vehicles and Batteries in general.

2.1 MATERIALS STUDIED FOR THIS REPORT

The bulk of the materials gathered for this study have come from published and on-line sources, a complete listing of which is to be found in the References section at the end. Google Earth has been used extensively for basic observation of vehicles mixes and road conditions in Bhutan (resulting in among other things that the usage of 2-wheelers in Bhutan is much lower than in the rest of SE Asia), as well as sizing estimates for battery recycling factories. In addition to these collected materials we have also leveraged off of the following:

Conference call on 26-Sept-2019 with Nawaraj Chhetri discussing the overall project objectives, and well as some general information including the following:

- Vehicle ownership is approximately 100,000 units and rapidly rising

- Existing EV fleet is quite small (<100 units), but there are several plans to increase this
- There is a pilot project to set up EV charging stations, and plans to expand the current system
- EVs are currently tax exempt
- EV's can be financed up to 70%, where as conventional vehicles can only be financed up to 30%
- There is great interest in assessing if an EV battery recycling facility would make sense in 5-10 years

Subsequently, we requested, and received vehicle registration statistics from Pema Chetsho, including a break down by vehicle type, and owner classification (Government, Private, Taxi, Diplomatic) with a summary of EV's.

Additionally, as Chairman of the Malaysian EV Standards Committee, as well as author of the ASEAN EV Standards (currently ongoing), we have access to a wide range of national standards pertaining to EV's as well.

Finally, on-site surveys were performed in Bhutan in November 2019 clarifying, among other things, the typical annual mileage of private vehicles, typical EV charger utilization, and investigating a high mileage electric taxi.

2.2 DELIVERABLES

The key deliverable of the project will be a final policy and regulations for disposal and recycling of EV batteries and feasibility report on establishment of batteries recycling Unit and re-use domestically, which needs to be technically cleared by the Technical Working Committee and endorsed by the Government and UNDP.

Deliverables of the assignment are separated into the following two items:

1) Submission of the Inception Report (Submitted 27-9-2019)
2) Final report (this document) with policy and regulations for battery disposal and a feasibility report for establishing a recycling Unit and re-use of batteries.

2.3 WORK FLOW

The Inception Note presented a detailed work plan for the assignment through desk review of documents such as Acts, Rules and Regulations, Regional and Global best practices, assessments, feasibility studies if undertaken in the past and available sources. The actual work will consist of:

Liaise with the Government counterparts, UNDP (CO and BRH) and relevant stakeholders

i. Consultations with all relevant stakeholders including UNDP, PMU in MoIC and GNHC for inputs
ii. Review the Prodoc and SESP
iii. Collect all the required data and information from relevant agencies

Policy and Regulations

- Review existing Acts, Rules and Regulations and other relevant documents
- Review the Global and Regional best management practices of EV batteries
- Recommend suitable policy and regulations;
- Submit a final report by working closely with the UNDP CO, PMU in MoIC and OFP

Initially we reviewed the existing rules and regulations of the Bhutan government relating to vehicles (Vehicle Type Approval, Standards, Registration), EV's, Batteries, Recycling and other related areas. This was performed via face-to-face meetings with the pertinent parties in Bhutan in order to get the latest policies, and discuss issues related with policies and enforcement. Subsequently a review was made of the existing policies. In parallel an extensive review was made of EV Batteries (chemistries, hazards and recyclability/disposal) as well as best practices of other countries in dealing with EV batteries. Additionally, during the initial visit we surveyed the industrial capabilities to determine if in-country recycling is a possibility for each of the various battery chemistries. This first visit was from 25-28th November 2019.

The next step was to draft the recommended policies, standards and regulations relating to EV Batteries, including: EV type classification, Battery Chemistry classification, Labeling and Tracking of batteries and suppliers (of both EV's and their batteries), and battery recycle, returning and scrapping procedures. These were based to some extent on the existing policies used by other countries, but were tailored for Bhutan's situation, from feedback from the relevant parties during the initial meeting.

Finally, based on anticipated volumes (extrapolated from vehicle purchase and population trends), the financial case for establishment of battery recycling center for the various chemistries is developed. Results indicate that lithium batteries will not be economically viable to attempt to recycle in Bhutan for the foreseeable future. Thus, the alternative disposal methods including repurposing the batteries for use in second life products, sales or shipment to external parties for recycling (ie. India or China) are considered.

Data for EV battery chemistries and recycling considerations were garnered via on-line research. Recycling plant cost came from both on-line sources, and a review of in-country expenses relating to plant construction and operation and conversations with existing EV Battery recyclers. Country specific policies were gathered from several ASEAN countries via our ASEAN network. Finally, the eventual policy development was largely based on feedback received from the various authorities interviewed in Bhutan, along with our experience in generating the same here in Malaysia.

2.4 TIMELINE

Review of background materials	September 20th – October 25th
Initial Interview in Bhutan:	November 25-28th
Policy Development:	Nov-Dec 2019
Final Report:	30 December 2020

3.0 ELECTRIC VEHICLE BATTERIES: GENERAL INFORMATION

An initial review shows the most common EV battery chemistries are Lead-Acid (PbA), Nickel-Metal-Hydride (NiMH), and Lithium-Ion as shown in the following figure below. PbA batteries dominate the smaller vehicles, while most modern electric cars are using one of the lithium chemistries, and NiMHs were common in hybrid vehicles from the 2000's. Clearly one factor that will be important is battery chemistry identification. This is commonly required in national EV regulations.

Battery Chemistry	Prevalence (2019)	Comments
Lead Acid (PbA)	Most common on small/low cost units (eg 2- & 3-wheelers)	Lead is a toxic substance Batteries are very heavy
Nickel-Cadmium (NiCd)	Not common in modern Electric Vehicles	Cadmium is a toxic substance "Memory" effect
Nickel Metal Hydride (NiMH)	Used on "2nd generation" EV's. Still common on hybrids	Good energy density but fairly inefficient
Lithium-Nickel-Cobalt-Aluminum (NCA)	Common on all but very low-end EVs*	Most Flammable
Lithium-Nickel-Manganese-Cobalt (NMC)	Common on all but very low-end EVs*	Most Flammable
Lithium-Manganese-Spinel (LMO)	Common on all but very low-end EVs*	Most Flammable
Lithium-Titanate (LTO)	Common on all but very low-end EVs*	Less Flammable
Lithium-Iron-Phosphate (LFP)	Common on all but very low-end EVs*	Less Flammable

Figure 1 Common Electric Vehicle Battery Chemistries. Star (*) indicates now or in the near future

Currently the cost of EV Batteries is approximately 190$/kWh for assembled packs, and around 145$/kWh for the individual batteries. Many are predicting that EV Battery cells will soon achieve the 100$/kWh threshold, perhaps as soon as 2020, and potentially half of that by 2025 (Hanley, 2018). EV Battery capacities are typically 30kWh to about 75kWh for non-luxury models, and up to about 100kWh for luxury models (EV Database 2019). Energy densities of the individual cells are at about 250Wh/kg, with short term targets of achieving 330 Wh/kg and longer-term targets of 500-1000Wh/kg. Thus, for a typical 30kWh pack the battery cell weight would be about 120kg, or perhaps 50-100% more for the whole pack. For comparison purposes the older Nissan Leaf's 24kWh battery pack weighs 295kg, only 144kg of which are the cells (Qnovo). This gives a net energy density of 81Wh/kg for the pack or 167Wh/kg for the cells. The Tesla model S pack gives 139Wh/kg for the pack, almost twice that that of the Nissan Leaf. Most EV cars have battery packs weighing 200 to 500kg (Berjoza 2017).

The ultimate life span of a battery pack depends on a number of factors including the individual owners' behaviors and environmental factors such as how hard they drain the battery, how frequently they re-charge the battery, how hot the battery gets. It also depends on battery and vehicle factors such as the maximum allowable depth of discharge, maximum attainable SOC (State Of Charge) during charge, thermal control of the cells in use, maximum current draw and re-charging current. This makes the longevity of a battery pack, usually expressed in charge-discharge cycles, difficult to estimate. Generally, an EV's battery is deemed to be at the end of its life when the batteries capacity (per charge) drops to 80% of the original capacity. Basically, if the vehicle initially achieves a range of 100km per charge, the batteries are deemed to be warn out when the per-charge range is reduced to 80km. The batteries can still be used, and often are, long after this point. It requires several years of actual use to determine exactly how long the batteries will last under real-life conditions, but the general assumption is that the vehicle should be capable of 5 to 10 years of operation before the batteries reach 80% capacity, with many manufacturers offering an 8 year warranty (Erwin 2019).

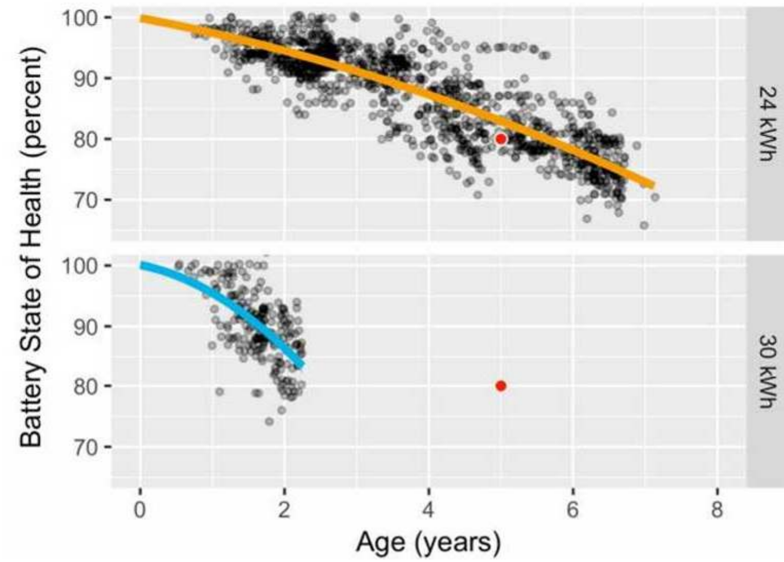

Figure 1 *State of Health of two different versions of the Nissan Leaf (Myall 2018).*

Figure 1 shows the State Of Health (SOH), which is the battery capacity divided by the original battery capacity, of various Nissan Leaf cars over a number of years. The 30kW packs can be seen to degrade much faster than the 24kW battery packs. The red dot indicates 80% SOH at 5 years (the design target).

A summary of typical automotive Electric Vehicle Battery Pack specifications is shown in Figure 2.

Typical Electric Car Battery Pack Specs			
Specification	**Low**	**High**	**Units**
Capacity	24	95	kWh
Weight	200	500	kg
Cost	4500	18000	USD
Energy Density	80	140	Wh/kg
Life Expectancy	500	1000	cycles
Life Expectancy	100	160	1000 km
Life Expectancy	5	10	years

Figure 2 *Typical Electric Car Battery Pack Specifications*

For our purposes the most important factor is the life expectancy in kilometers. Assuming divers of privately owned cars in Bhutan drive on average 10,000km per year, then most EV Battery packs should last between 10 and 16 years. It is likely that the batteries will not be instantly scrapped once their capacity drops to 80%, with some sources indicating battery use down to 70% is common. Thus, the scrapped batteries are unlikely to be available in less than 10 years from the original vehicle sales date, and may take up to 20 years to become available.

4.0 BHUTAN VEHICLE STATISTICS

Data received from MoIC indicates that there are currently (2020) at least 28 electric 2-wheelers and 130 electric 4-wheelers registered for road travel in Bhutan. Of the electric cars there are five different brands, Nissan Leaf being the most popular with 62% of the market, and the Mahindra Reva coming in second at 22%. This compares to about 65,000 privately owned cars, and approximately 10,000 privately owned 2-wheelers.

The economy has been growing at a rate of about 7.5% per year for the last ten years, with a commensurate increase in private vehicle sales, causing traffic congestion problems, Figure 3, especially in Thimphu (Gyeltshen 2019).

Figure 3 Traffic is becoming a problem in Thimphu

Taxis accumulate an average annual mileage of around 75,000 km (MoIC) while passenger cars were initially estimated to accumulate closer to 10,000 km (author's estimate based on geography). During the initial visit to Bhutan for the presentation of this study, a survey of private vehicles was undertaken with the author and personnel from MOIC, Figure 4. Together 40 vehicles were surveyed, and narrowed data down to privately owned petrol cars used for normal commuting. The annual mileage per car was thus determined to be approximately 10570km per year, very close to the original estimate of 10,000km/year.

Figure 4 Performing Private Car Survey in Thimphu

Assuming the battery packs last 100,000km Bhutan EV drivers can expect their batteries to retain at least 80% of their original capacity for around 10 years.

Electric Taxi Survey in Bhutan

Given the small number of electric taxis in Bhutan only one was surveyed, a Nissan Leaf with the 24kWh battery pack. The vehicle is 4 years old, and has 200,000km, for an annual mileage of 50k km/year (taxis in Bhutan typically have 40-80k km/year based on our/other studies). Additionally, the battery still has 7 bars out of 12 bars originally (ie. 7/12 of the original battery capacity), or only 58% capacity (SOH), Figure 5, however the owner does not plan to change the battery for another year or two, when the pack gets down below 50% capacity. Battery degradation is approximately 15% per 100k km, so a battery with 20% degradation (considered to be “End Of Life”) will have about 133k km. With drivers in Bhutan driving only 10k km per year this will take about 13 years, and, as with this driver, they will probably continue to use the battery well beyond this limit, perhaps closer to 20 years before scrapping the batteries.

Figure 5 Nissan Leaf Instrument Cluster from Electric Taxi in Bhutan

EV Taxi Instrument Panel indicating 199,327 kilometers. Battery Gage (right) Shows only 7 of 12 bars available (actual charge is at 1 bar indicating that the battery is near exhaustion during a single Paro-Thimpu-Paro trip)

4.1 BHUTAN ELECTRIC VEHICLE & BATTERY PACK PROJECTIONS

Taking the current population, and population growth rate, vehicle ownership and ownership growth rate, we can estimate the number of vehicles on the roads in Bhutan several years ahead. There are bound to be discrepancies between our projections and the actual numbers several years from now based on inaccuracies in our model, as well as unanticipated external factors such as wars, economic collapse, technological breakthroughs and the like. It is, however, important to attempt to estimate the EV fleet size, and age as these relate directly to the number of potentially recyclable batteries available in the future.

Taking the 2017 population of Bhutan to be 807,610 with an annual growth rate of 1.2% (World Bank), and assuming a constant population growth rate, we can predict a population of about 1 million in 2035. Assuming the automobile population grows at the current economic growth rate of 7.5%, starting with 105,000 vehicles in 2018, we can predict a total vehicle population of 359,000 vehicles in 2035, over three times the number currently on the roads. Car ownership is growing faster than the population rate, which would lead to the erroneous conclusion that around 2050 the number of cars would exceed the population. Instead as economies mature car ownership tends to saturate at approximately 0.7 automobiles per person (Dargay 2017). This actually results in more than one car per driver, understanding that the population will contain a large number of individuals incapable of holding driving permits due to age and other factors. According to our model we would expect the car ownership per person to saturate around 2046.

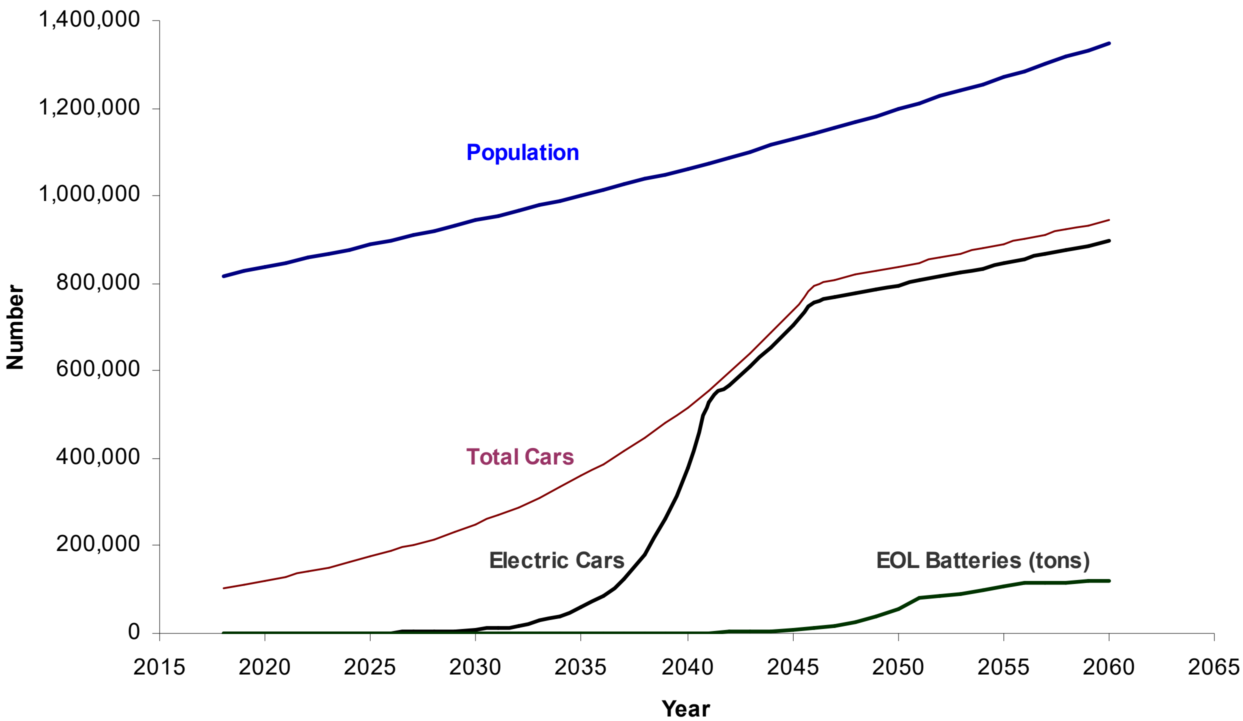

Figure 6 Projected population, car and EV population and recyclable EV batteries

A more difficult thing to predict is the number of Electric Vehicles in the total car population. This is harder to know as it is such a new technology that there are no firm trends yet established in Bhutan. The highest EV growth rates are in countries with aggressive electrification campaigns, such as Norway, resulting in an

EV population growth rate of 35% per year (IEA 2019). This is viewed as a highly optimistic number, only achievable if Bhutan were to enact similarly aggressive measures in promoting electrification of transport. The results of this “Best Case Scenario” are shown in Figure 6. While the fraction of cars which are Electric Vehicles appears to grow fairly slowly, the percentage of new cars being sold each year which are electric is actually projected to grow quite rapidly. In the projection shown above the percentage of new car sales in 2035 which are electric is about 73%, while the official EV road map calls for 70% of new cars to be electric by 2035 (Bagdia 2020).

As can be seen, the population is increasing at a steady rate, with the rate of increase in car ownership increasing significantly faster. Even with the optimistic growth rate of 35% electric vehicles are unlikely to become a significant fraction of the car population before 2030.

If we further assume that the Electric Vehicles have a life span of 10 years, and that each vehicle contains 150kg of batteries (individual cells) then we get the predicted tonnage of End Of Life (EOL) batteries available as shown in the line at the lower right of the figure. This again is an extremely optimistic projection as it assumes that all vehicles will have their battery packs removed at 10 years of age, and that 100% of these will be available for recycling. With these best-case assumptions, we will have 100,000 tons of batteries available in about 2054.

We have chosen to highlight this quantity (100,000 tons per year) of EOL batteries as this is the quantity where many of the recycling processes begin to make financial sense.

5.0 ELECTRICAL VEHICLE BATTERY RECYCLING

Lead-acid batteries (PbA) have historically been recycled in most markets due to the ease of recycling, and high cost of the material, leading to a recycling rate of almost 99% in the US. One of the keys in the high rate of recycling is that most battery sales outlets also accept returned batteries, and instantly discount the price of the new battery based on the returned one (WP 2019). The European Union has different target recycling rates for lead-acid, nickel-cadmium and other battery chemistries and have relatively high recycling rates accordingly (Tytgat 2013).

Lithium Ion batteries are a more recent innovation, and the recycling infrastructure has not yet been built up as substantially as for PbA batteries. Basically, the battery pack can be looked at as two separate systems: the individual cells, and the battery pack housing, wiring and Battery Management System (BMS) circuitry.

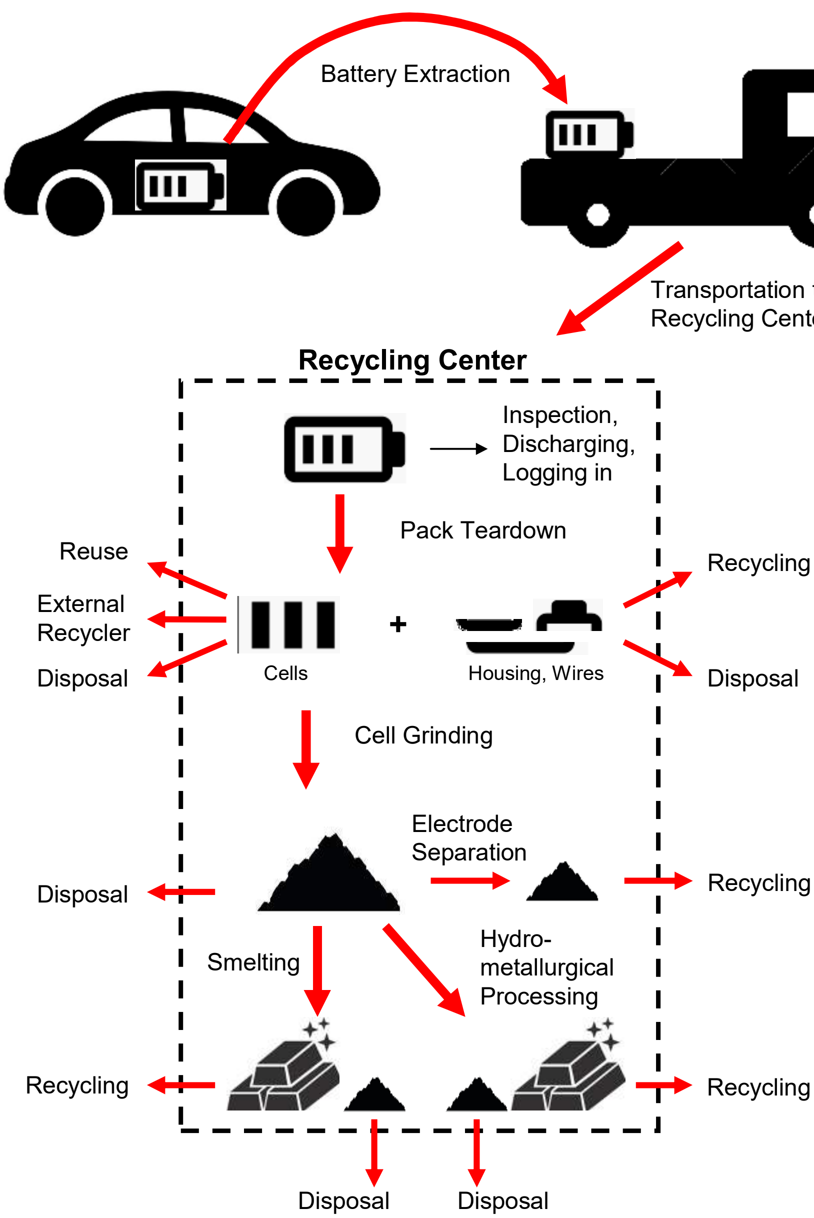

Figure 7 Potential Electric Vehicle Battery Recycling Pathways

The battery case is generally made out of plastics and aluminum, with smaller amounts of steel (mostly for fasteners) and a substantial amount of copper in the wiring. These materials may make up to about 40% of the total weight of the battery pack. Battery case teardown and recycling can be done on a relatively small scale, and according to some estimates, results in the lowest CO_2 pathway for battery recycling. However, the process is manual labor intensive as battery pack designs have not been standardized. Due to the potential electrical and fire hazards this work must be performed by trained technicians, rather than the unskilled workers associated with most bulk material recycling processes.

Once separated from the pack, the individual cells can then be reused to rebuild battery packs, used for other energy storage applications, recycled or disposed of. Recycling of the individual cells, however, is problematic due to the wide variation in materials used in them as well as differences in packaging. A number of studies cast doubt on the viability of economical recycling of Lithium batteries, except at very large scales (Elwert 2015, Reckmann 2016).

For recycling, the individual cells are generally ground to a powder from which the anode and cathode metals (generally copper and aluminum respectively) can be separated, and the remaining electrolyte materials can then be recycled either by thermal or chemical leaching processes.

It is possible to recycle some of the materials from the shredded cells, with laboratory studies showing a maximum 96% recovery rate for the main components Li and Co (Zhou 2010). A recent study, however, has shown that pyrometallurgical and/or hydrometallurgical recycling (breaking the batteries down to their elemental components) does not show significant carbon emissions advantages over basic materials recycling (where the positive electrode material can be reconditioned for use in new batteries) which requires only a fraction of the energy of the metallurgical processes, and yet can significantly reduce emissions (Ciez 2019). While the CO_2 impact of complete battery recycling in Bhutan may be offset by the predominant use of hydroelectric power, the economics of such a plant are likely to be disadvantageous for the foreseeable future, as shown below.

Pyrometallurgical processing requires heating the mixture to the melting point of the metals, and then separating the various metals from the resulting slag and processing them with further hydrometallurgical processes. Organic materials either burn, or are outgassed in the heating process. Hydrometalurgical processes involve dissolving the various materials in solvents for chemical extraction. This can yield good purity metals, and a substantial amount of liquid effluent.

5.1 LI-ION BATTERY PACKS – RECYCLABLE MATERIALS

As previously established typical battery EV battery packs weigh from 200-500kg, with the individual cells accounting for approximately 60% of this weight (Natkunarajhah 2015, Buchert 2011).

Batteries may contain around 10% Copper and 5% to 40% aluminum by weight. Currently many battery housings are made from Aluminum (for mechanical, thermal and weight reasons) however this is likely to be replaced by plastics in the future as battery thermal management improves.

Looking at the battery pack composition of a number of different chemistries we can get a range on the value of recyclable materials. We will analyze this at three different levels: The individual cells, the anode and cathode foil layers, and the pack housing. Figure 8 gives approximate materials break down by component (Buchert 2011) and materials cost (Gulia 2019).

Battery Cell	Material	**Aluminum**	**Cobalt**	**Copper**	**Graphite**	**Lithium**	**Nickel**	**Total**
Cost	USD/kg	1.79	32	5.7	1.8	13	15.7	
Low Content	g/kg	34.0	0.0	79.0	60.0	7.6	0.0	
High Content	g/kg	42.5	39.0	100.0	70.0	14.0	86.0	
High Value	USD/kg	0.06	0.00	0.45	0.11	0.10	0.00	0.72
Low Value	USD/kg	0.08	1.25	0.57	0.13	0.18	1.35	3.55
Anode/Cathode	Material	**Aluminum**		**Copper**				
Low Content	g/kg	34		60				
High Content	g/kg	40		70				
High Value	USD/kg	0.061		0.342				0.40
Low Value	USD/kg	0.072		0.399				0.47
Housing		**Aluminum**		**Copper**				
Low Content	USD/kg	17		13				
High Content	g/kg	21		38				
High Value	g/kg	0.030		0.074				0.10
Low Value	USD/kg	0.038		0.217				0.25
					Total All Components	**(Low)**	**USD**	**1.23**
						(High)	**USD**	**4.28**

Figure 8 EV Battery Component Materials and Value Breakdown

Assuming that the profitable case materials are only aluminum (from housing and heat sinks) and copper (from wiring) the case alone can yield 0.10 to 0.25 USD per kilo of recyclables. The electrodes are mostly copper and aluminum, and can vary from about 0.40 to 0.47 USD per kilo of cells. Finally the additional materials inside the battery, consisting of Aluminum, Cobalt, Copper, Graphite, Lithium and Nickel, may total to between 0.72 and 3.55 USD per kilo of cells.

To place this in perspective, we need to analyze a typical battery pack for the potential value of recyclable materials. For this analysis we assume the pack is around 40kWh and weighs 250kg, 150 kg for the cells, and another 100kg for the housing, wires and BMS.

Pack Weight	kg	250
Cells weight	kg	150
Housing Weight	kg	100
Housing Recyclables	USD/kg	0.175
Housing Yield	%	100
Housing Value	USD	17.5
Electrode Recyclables	USD/kg	0.435
Electrode Yield	%	95
Electrode Value	USD	62.0
Cell Recyclables	USD/kg	2.14
Cell Yield	%	80
Cell Value	USD	256.8
Total potential value	**USD**	**336.3**

Figure 9 EV Battery Pack Recyclables Value by Component

Taking the average value for each of the components analyzed above, with an assumed recyclable material yield, we can then calculate the value of each component of the battery pack. Housing materials are disassembled via conventional recycling techniques, and thus will be relatively simple to perform, and should give a high yield. Assuming 100% yield, we get a value of 17.5 USD from recycling the battery pack housing.

If we further tear down the cells, and extract the anode and cathode foils with a 95% yield, this may have a value of around 62 USD.

The most valuable materials are definitely the rarer components of the battery cells requiring much more elaborate recycling processes to extract. While laboratory level tests have shown yields in the 90% range, current industrial processes are closer to 50%, with some companies projecting to achieve 80% yields (Gulia 2019). Taking 80% as our assumed yield, recycling of the cells will yield a value of about 256.8 USD.

Thus, if we completely recycle the battery and pack, we expect to extract a total of about 336.3 USD worth of materials from the battery housing and cells.

The next question we must address is how much it costs to operate the plant. According to JMK Research and Analysis, Lithium-Ion battery recycling operations in India cost about 1.4 USD per kilo (Gulia 2019). For a 250kg pack this results in a cost of 350 USD. With a yield of 336.3 USD of recyclables materials we actually lose around 14 USD per battery pack. This supports the previously quoted assessments that, at least at present costs, Li-ion battery pack recycling is not profitable. This is likely to be affected by various market and technology trends including the increase in demand for crucial battery materials, and perhaps improved battery recycling technologies.

While complete battery pack recycling is not likely to be profitable in the short run, recycling of the housing and materials may be, as this is a relatively simple process. Additionally, the individual cells may still be used for battery pack remanufacturing, or in other applications.

5.2 EV BATTERY RECYCLING PROCESSES

Electric Battery recycling can be broken down into several distinct processes depending on the level of recycling to be performed. Removing a battery from an intact vehicle is a straightforward procedure with the only difficulty being the weight and non-standard mounting points of batteries. Vehicles which have been involved in crashes should be carefully inspected for battery damage before attempting removal. Once removed the batteries should be transported to the recycling facility, and carefully checked for damage. The packs label should be consulted and logged into a battery tracking system. The battery should be checked for state of charge and discharged if necessary. Any batteries or cells should be stored in well ventilated flame proof areas.

BATTERY PACK TEARDOWN

Initial teardown of the battery pack can then be performed. This is straight forward and consists of opening the battery pack housing, and removing the individual cells or modules. The rest of the packing material, consisting of the housing, electrical and mechanical connectors, wires and Battery Management System, may then be recycled via conventional processes.

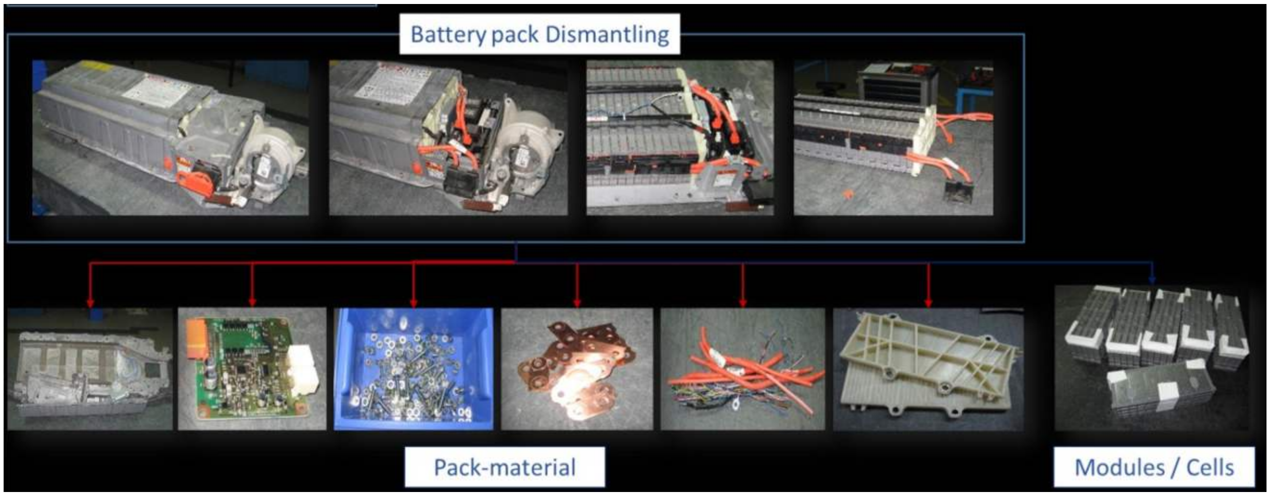

Figure 10 Battery Pack Dismantling at Umicore (Elwert 2016)

BATTERY CELL RECYCLING

Individual battery cells or modules can then be further broken down for additional recycling. This, however, can be problematic due to the wide range of materials and battery formats. Many of the electrolyte materials can react violently with oxygen, and create fire hazards. Additionally, as many of them contain fluorine any fire will emit highly toxic gasses. For a center focusing on recycling a wide range of incoming batteries (ie. from different manufacturers and years of production) the batteries are processed pyrometallurgically, that is they are basically melted down in a high-temperature furnace, or smelter, producing a mixed metal alloy, slag and flue gasses and dust. The gaseous and dust effluent must be carefully monitored and “scrubbed” or collected as they may contain harmful compounds of fluorine and other elements. The smelting process is carefully controlled so that Cobalt, Nickel and Copper are converted into alloy and Aluminum and Lithium are concentrated in the slag fraction.

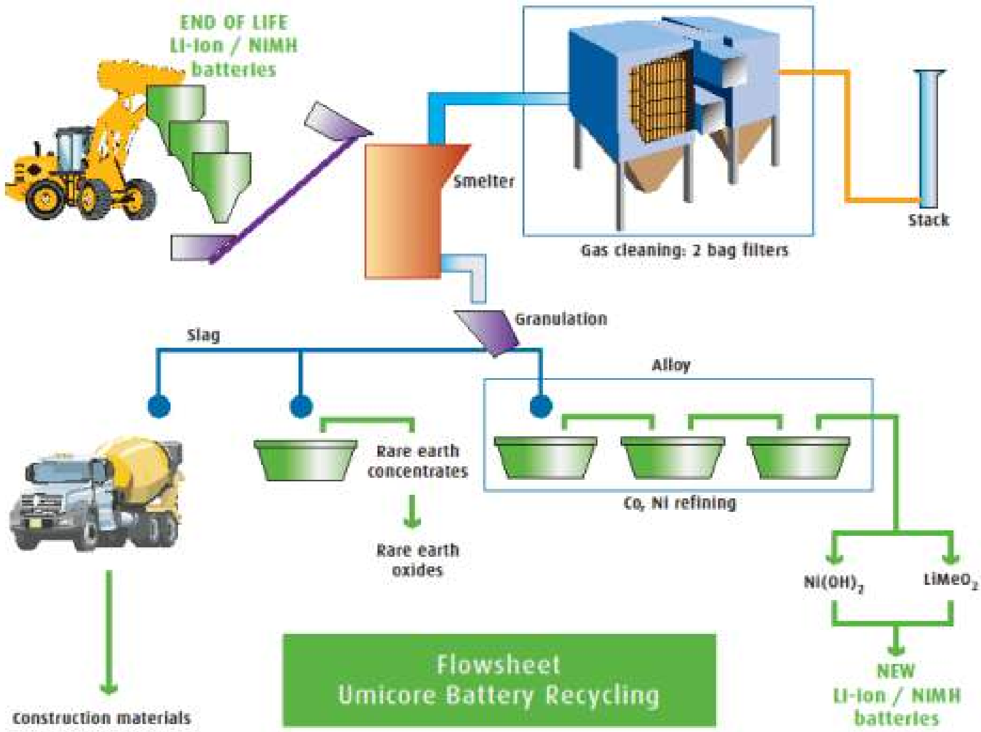

Figure 11 Simplified Umicore process

After the smelting process the alloy fraction must be ground up and hydrometallurgical treated. The granulated materials are dissolved into a solution where the various metals can be separated out into salable solutions for making new batteries.

The slag from the smelter is inert and can be used as construction material, or can be further processed to extract lithium, but the aluminum is generally unrecoverable.

ALTERNATIVE RECYCLING METHODS

In order to achieve higher reclamation rates and lower energy inputs, several other battery cell recycling processes are being considered. Generally, these include various degrees of shredding, thermal treatment, magnetic and gravimetric separation, condensation of volatile compounds, and additional hydro- or pyro-metallurgical processes. So far none of these appears to be universally applicable, and all of them require a high degree of effluent sequestration and filtering to avoid expelling harmful compounds.

RECYCLING SYSTEM COSTS

Recycling of the batteries requires high-temperature processing of the batteries, as well as subsequent grinding and hydro processing. Some of this has to take place under an oxygen-free atmosphere to avoid fire hazards. These facilities require high standards of environmental safeguarding as many of the potential effluents are hazardous, and tend to be fairly expensive to set up.

Complete Battery Recycling Plant and Operation Expences

These projections are for a complete metalugical recycling of the battery for 100,000 tons per year

Facilities Planning and Construction		
	Cost	Duration
Item	**USD**	**Months**
Plant Planning	40000	6
Siting and Land Acquizition	100000	3
Building and Permitting	2000000	12
Equipment	3799100	6
TOTAL	**5939100**	**27**

Recuring Expences			
Item	**Cost**	**Term**	**Cost Annual**
Power	100	Monthly	1200
Water	10	Monthly	120
Sewage	10	Monthly	120
Truck Fuel	800	Monthly	9600
Smelter Fuel	1500	Monthly	18000
Leachant Consumables	5000	Monthly	60000
Land Tax	100	Annual	100
Business Permit	100	Annual	100
Vehicle Maintenance	500	Annual	500
Vehicle Taxes	250	Annual	250
Facilities Maint/Upgrade	1000	Annual	1000
Insurance	1000	Annual	1000
Financial Auditing	1500	Annual	1500
Total (per year)			**93490**

SUMMARY OF PROJECTED EXPENCES		
One Time Setup Cost	**5939100**	**USD**
Building/Equiping Time	**27**	**Months**
Annual Overhead	**279490**	**USD**

Plant Staffing Costing			
Position	**Pax**	**Cost/pax**	**Cost/Mont**
Director	1	1500	1500
Ops Manager	1	1200	1200
Admin	3	700	2100
Logisstics	2	600	1200
Driver	4	400	1600
Engineers	2	1000	2000
Materials Handelers	4	500	2000
Shop Forman	2	450	900
Technitions	8	350	2800
Cleaning	1	200	200
Total (per month)			**15500**
Total (Per Year)			**186000**

Equipment			
	Units	Cost/unit	Cost
Drills	4	50	200
Saws	2	1000	2000
Handling Device	4	2500	10000
Shelves	50	250	12500
Vents/Filters	4	25000	100000
Truck	4	10000	40000
Schreder (N2 bath)	2	50000	100000
Computer	4	1000	4000
Camera/Scanner	2	200	400
Furnature	20	500	10000
Smelting Ovans	2	1500000	3000000
Ventilation Fans	4	20000	80000
Solvent tanks	2	50000	100000
Dryers	2	20000	40000
Seperators	2	150000	300000
Total			**3799100**

Figure 12 Costing breakdown of Complete EV Battery Recycling Plant Including Operational Expenses

Generally, it is considered economically unfeasible to build systems for volumes less than about 100,000 tons per year of batteries. A smelting plant capable of processing this volume might cost on the order of 60M USD according to Dr. Les McLean, a prominent metallurgist (McLean 2019). The highest projected battery pack volumes from Bhutan only yield about 100,000 tons of recyclable batteries per year after 2056. Thus, it is improbable that a complete battery recycling facility is likely to be economically viable before the 2050-2060 range. This view was confirmed in private correspondence with Richard Schutte, the Technical Director for Retriev Technologies who runs several battery recycling plants in North America.

A detailed plant cost breakdown is shown in Figure 12 indicating a build cost of 6M USD, 27 month build time, and annual operating expenses of 280,000 USD. This plant could process 100,000 tons of batteries per year. As per the previous analysis, complete battery recycling would yield 335$ per 250kg, or about 1.34 USD per kg, thus 100,000 tons of batteries would yield about 1.34 M USD per year on an operating budget of about 300,000 USD per year. Assuming that a profit of 1M USD could be realized per year, it would take six years to pay off the original plant cost. This means that even under the most optimistic projections the battery recycling plant would not be financially profitable until approximately 2062, admittedly too far in the future to be able to accurately forecast.

As an alternative to complete recycling of the battery packs and cell, a more viable option would instead be to just do the initial pack teardown and housing material recycling, while shipping off the individual battery cells or modules to a battery remanufacturer or recycling center. Given the economies of scale and logistical considerations it is likely that this would mean either shipping the cells to India or China. It is likely that individual cells recovered by this process could be sold for a modest price, especially if they were to be used to rebuild similar battery packs. This might become economically viable at much lower volumes, perhaps a few thousand tones of batteries per year, which could happen as early as 2033. Such a plant might require an area of around 10,000 square meters, and cost on the order of 500,000 USD to build.

Simple Battery Recycling Plant and Operation Expences

Simple battery case tear down, and wire recycling plant capable of ~10 units of 200kg batteries per day

Facilities Planning and Construction		
Item	**Cost USD**	**Duration Months**
Plant Planning	10000	3
Siting and Land Acquizition	100000	3
Building and Permitting	250000	12
Equipment	22100	3
TOTAL	**382100**	**21**

Recuring Expences			
Item	**Cost**	**Term**	**Cost Annual**
Power	100	Monthly	1200
Water	10	Monthly	120
Sewage	10	Monthly	120
Truck Fuel	100	Monthly	1200
Land Tax	100	Annual	100
Business Permit	100	Annual	100
Vehicle Maintenance	500	Annual	500
Vehicle Taxes	250	Annual	250
Facilities Maint/Upgrade	1000	Annual	1000
Insurance	1000	Annual	1000
Financial Auditing	1500	Annual	1500
Total (per year)			**7090**

SUMMARY OF PROJECTED EXPENCES		
One Time Setup Cost	**382100**	**USD**
Building/Equiping Time	**21**	**Months**
Annual Overhead	**93490**	**USD**

Plant Staffing Costing			
Position	**Pax**	**Cost/pax**	**Cost/Mont**
Director	1	1500	1500
Ops Manager	1	1200	1200
Admin	1	700	700
Logisstics	1	600	600
Driver	2	400	800
Shop Forman	1	450	450
Technitions	5	350	1750
Cleaning	1	200	200
Total (per month)			**7200**
Total (Per Year)			**86400**

Equipment			
	Units	Cost/unit	Cost
Drills	4	50	200
Saws	2	100	200
Handling Device	2	200	400
Shelves	10	50	500
Vents/Fans	4	100	400
Truck	1	10000	10000
Schreder	1	5000	5000
Computer	4	1000	4000
Camera/Scanner	2	200	400
Furnature	10	100	1000
Total			**22100**

Figure 13 Simple EV Battery Recycling Plant Including Operational Expenses

Based on a simple model this plant will achieve a much lower operating cost of around 94,000 USD per year. Our previous battery recyclables model predicted about 17 USD per 250kg battery, or about 70 USD per ton of batteries. For a system like this to be viable we would have to process 1340 tons of batteries per year. Assuming 200 operating days per year, that works out to about 6.7 tons of batteries per day, or perhaps 10 to 30 battery packs per day. Within a few years, if the plant can increase volumes with out significantly increasing the costs, it could start paying back the initial investment, and might become financially viable by around 2040.

5.3 RECOMMENDED EV BATTERY RECYCLING PROCESS

Given the distant time horizon for economical implementation of a recycling plant in Bhutan, a shorter-term solution is required. There are two main options for the dispensation of used electric vehicle battery packs: first is the re-use in other electrical storage products (either via direct utilization of batteries or sales of batteries to companies and individuals for their own use), and the second is shipment to external battery recyclers. In either case it is advisable to establish a national center for the safe collection and disposition of batteries. This could be expanded to include other rechargeable batteries such as lithium batteries from computers, handphones and other electronic equipment.

Currently lithium batteries from waste computers, handphones and other devices are handled by Thromdes for the private sector, and the Department of National Properties (DNP) for government generated waste (Dorji 2016). Given the large size and weight and potential danger of EV Batteries it is proposed to create a separate entity to deal directly with EV batteries, a so-called National EV Battery Recycling Center (NBRC).

The first step in establishing a National EV Battery Recycling Center would be to develop a list of EV Battery removal workshops. Generally, this will consist of existing automobile dealerships and other EV specific workshops. It will be important to make sure that these shops all work in accordance with the relevant handling regulations. Ideally these shops would provide batteries for pickup by a collection vehicle for transportation to the national collection center. Batteries would then be checked, discharged, and dispose of according to the needs and capabilities of the second life products, consumers and recyclers. Disposal can be handled via current scrap dealer contacts, by establishing links to specific EV Battery recyclers or by selling the batteries, modules or cells directly.

ELECTRIC VEHICLE BATTERY RECYCLERS

China by far recycles the most EV batteries, and thus is likely the first choice for bulk EV battery recycling. The following is a list of the larger EV battery recycling houses in china. Full contact details appear in Appendix 2.

- GEM Co. Ltd.
- Hunan Brunp Recycling Technology Co. Ltd.
- Quzhou Huayou Cobalt New Material Co. Ltd
- Ganzhou Highpower Technology Co. Ltd
- Guangdong Guanghua Sci-Tech Co. Ltd

As these companies routinely recycle EV batteries from the China market as well as various foreign countries, they will be quite capable of accepting spent EV batteries from Bhutan.

ELECTRIC VEHICLE BATTERY REUSE (2nd LIFE PRODUCTS)

Batteries from electric vehicles which are no longer capable of acceptable range in an EV may still have significant electrical storage capability. For example, when a battery pack degrades to 80% of its initial capacity it is still capable of storing and releasing 80% of the original capacity. While the degradation in range may make it unacceptable for use in a vehicle, it can still perform efficiently in a wide range of other electrical storage applications. For large energy applications (10’s of kWh) the battery packs may be used intact without any further teardown. For applications requiring smaller amounts of energy, torch lights for example, the packs may be broken down into individual modules or cells depending on the pack design. In some designs the EV Battery packs are made up of standard sized cells, for example the common 18650 (Figure 14) or 21700 cylindrical cells, in which case the individual cells can be separated out for direct use in existing product designs.

Figure 14 18650 Cylindrical Lithium Battery Cel (left) and AA Battery (right) for comparison

Below is a short list of potential 2nd life products using “spent” EV Batteries and packs. They have been separated into different energy storage classes based on loose products demands, with further explanations below.

VERY HIGH ENERGY (100-1000 kWh)
Grid scale storage

HIGH ENERGY STORAGE (100 kWh)
EV Charging Station “buffer”

MODERATE ENERGY STORAGE (10’s KWh)
Less demanding four-wheeled EVs
Two-wheeled EVs
Small business UPS
Roadside Street Lights

LOWER ENERGY STORAGE (<100 Wh)
Individual appliances
Single point UPS

Power providers might want to invest in large scale grid energy storage systems made up of hundreds or thousands of old EV battery packs storing energy during periods of low demand (typically at night) and releasing it back onto the grid during peak demand periods, improving overall grid efficiency, and reducing or eliminating blackouts (Breslin 2013).

Fast charge EV charging stations require large currents, some of which could come from a local battery pack, reducing the current draw from the grid, thus allowing a less expensive overall installation.

As EV battery packs typically hold 10s of kWh of energy, they are well suited for large uninterruptable power supplies (UPS). Most small UPS systems rely on small ~100 Wh batteries which can only run a few small appliances (eg. a laptop or a few lights) for 30 minutes or so. Household systems are usually rated at 1-2kWh and can run many of the appliances in a house for a few hours. Systems on the order of 10kWh could run a small house for around a day. With the 24-50kWh available in EV battery packs even modest sized businesses could operate for a day or so on a single charge. In many countries, especially India and the Philippians, 2-5kW gensets are common items in many retail outlets for use during the frequent blackouts experienced in these countries (Satake 2015). A several kilowatt hour UPS based on an old EV battery would be an especially elegant use of the battery pack as it could automatically engage, and continuously recharge from the line when the power was on, eliminating the blackout and need for a genset altogether.

Even when EV batteries are no longer useful in the original road-going vehicle, they may still have enough capacity for other vehicles, for example they can be used in “short range” EVs such as urban delivery vehicles, as well as on smaller vehicles such as light duty 2-, 3- and 4-wheeled vehicles which typically have battery packs of less than 10kWh capacity.

As a mountainous country Bhutan has hundreds of kilometers of roads with many dangerous twists and turns. Lighting these in the evening and early morning could reduce accidents, however providing grid power to every curve would be quite expensive. Instead, a single pole, light, solar panel and battery storage system could perform the same task, with a lower overall cost. This is an excellent use for discarded EV batteries which could directly serve a need within Bhutan, Figure 15.

Figure 15 Solar powered street light with battery storage in box (Flood 2018)

Finally, at the individual cell level there are hundreds of products which could use end of life EV battery cells. This includes things such as torch lights, radios, emergency lighting and many other applications.

Perhaps the easiest way of dealing with EOL batteries is to sell them outright to external parties for use in 2nd life products. There is a market for whole EV Battery packs, as well as individual modules and cells. A recent (24-01-2020) survey of Ebay indicated that EOL 24kWh Nissan Leaf battery packs are being offered for 3,500 to 4,500 USD, while the individual modules (there are 48 modules in the 24kWh pack) were being offered at 100 USD. If packs are dismantled to the module or individual cell level, the battery pack material can be recycled via conventional processes and the modules or cells then sold.

DEVELOPMENTAL REQUIREMENTS

Establishing a National EV Battery Recycling Center (NBRC) will require coordination with many different organizations, and eventually building some infrastructure. While ownership of the related assets is at the digression of the government (ie. outsourcing, vs. doing via an existing or new governmental body) we are proposing the following actions as though operated directly by the government.

1. Establish List of EV Workshops
2. Train up the workshops and NBRC staff on EV Battery Handling
3. Put together a national data base for battery tracking
4. Establish connections with existing scrap dealers and EV Battery Recyclers
5. Negotiate contracts for EV Battery sales/scraping
6. Identify potential 2nd Life Product development Partners
7. Work with 2nd Life Partners on product development (provide samples, etc.)

Putting together a National EV Battery Recycling Center will require some administrational overhead, perhaps a staff of one or two people part time initially, and eventually expanding to a few full time staff as battery volumes increase (around 2030). The first task of this center would be to determine what workshops will be the designated sources of old EV batteries. These workshops, as well as the staff associated with the NBRC should all be trained up in the safe handling and transportation of batteries. Once batteries become available they should be tracked, requiring a "national battery tracking database". The NBRC staff will similarly have to establish connections with existing and new scrap dealers, including specifically the potential EV Battery recyclers listed earlier. Negotiating the best deal on bulk purchases of spent EV batteries will be one of the important tasks of the NBRC staff. This work could potentially start in the next few years as batteries from EV Taxis will become available starting in about 2021-2025 time frame.

In parallel to work with scrappers, the NBRC staff should work together with local industries, and perhaps academia, to help them develop second life products using the battery packs, modules or individual cells. This will consist of providing samples and realistic price and volume projections so that the product developers will be able to generate saleable products for the mass market. If 2nd life product volumes become sufficiently high, the staff can decide to do the battery pack tear down within the NBRC, or via an external body, such as at one of the 2nd life product companies. Obviously any of the recyclable materials from the battery pack will be recycled upon battery pack tear down, offsetting most or all of the cost of pack teardown. While volumes of batteries may not be available for a number of years, product development may also take years, so establishing these industrial contacts early, and even getting some samples to the various developers should be done as soon as batteries become available, ie. some time in the next few years.

While initially support of the NBRC will require some government funds, it is expected that eventually, when battery volumes become sufficient, the center will become a minor revenue generator via the sales of the scrap batteries.

In order to ease the development of the National EV Battery Recycling Center it is recommended that the relevant government personnel, as well as industry (EV workshops and 2nd life developers) and various associated academia people receive technical training related to Electric Vehicle technologies, EV Battery handling and safety, data modeling and projections, economics, and electrical engineering. These are explained in greater detail below in section 9.0 of this report.

STAGED APPROACH TO BATTERY RECYCLING

As shown earlier in section 4.1 Bhutan will not expect to have more than a few end of life EV batteries for the next ten years. After this time there may be some hundreds of units becoming available annually, and by the 2040's this could grow to become thousands of units. It is therefore recommendable to take a "staged" approach to EOL EV Battery disposal. In the near term (2020-2030) a National Battery Recycling Center would largely be responsible for gathering the appropriate EV statistics (eg. how many units there are on the road, what is the state of health of their batteries, when they will likely become available), and identifying both the sources (EV workshops) of batteries, and destinations (samples to research institutes and "2nd life" companies) for the few batteries becoming available. In the 2030-2040 range, as the volume of EOL batteries is expected to rise, the NBRC could then shift to primary battery pack teardown and recycling of battery pack material, while selling modules and cells to 2nd life manufacturers or designated external battery recyclers. Finally in the 2040-2050 range the NBRC could look again into the economics of complete battery recycling, given updated volumes, prices and technologies.

6.0 ELECTRIC VEHICLE BATTERY HANDLING

Batteries, like any other energy storage system, can be dangerous if improperly handled. This is especially true of Electric Vehicle batteries which have been involved in accidents. Damaged EV batteries have been known to cause fires some times several days after the initial accident. Additionally an Electric Vehicle recycling plant in Trail, British Colombia, Canada caught fire and exploded on 7 November 2009 (TMTV 2009).

Figure 16 Fire at EV Battery Recycling Plant in Trail, BC, Canada

In view of the potentially explosive nature of EV Batteries, their safe handling and storage require adherence to special handling and storage guidelines. Fortunately, several sources on the handling, storage and transportation of EV batteries exist (UW 2018, USN 2010, Long 2013).

The basics of safe Electric Vehicle Battery handling consist of the following:

- First, damaged batteries should only be handled by personnel specifically trained in the handling of suspect EV batteries.
- Batteries should be discharged before transporting.
- Battery discharge should be performed in accordance with the battery specific chemistry.
- Electrical Power Connection Terminals should be secured, and insulated to prevent accidental contact with battery voltages.
- Batteries should be transported, as much as possible, on trolleys to prevent accidental dropping.
- If batteries appear to be leaking, they should be placed in a leak-proof bag and tray.
- In case of contact with battery electrolyte, the personal should immediately wash their hands.
- EV Batteries should never be transported in passenger cabins of vehicles.
- EV Batteries should not be stored in habited areas.
- EV Storage areas should be clearly marked by an identifying sign.
- EV Battery storage areas should have appropriate fire fighting equipment on hand.
- Type “D” fire extinguishers should be available to fight Lithium fuelled fires.
- EV Batteries should be stored in ventilated, flame proof metal containers away from flammable

materials.
- Keep the batteries as cool as possible.

For a battery storage facility it will be important to house individual batteries in well ventilated areas, with fire proofing to prevent a battery fire from spreading to adjacent battery packs.

DAMAGED BATTERY HANDLING

Electric Vehicles are very safe, and generally considered safer than conventional petrol vehicles, however one of the biggest risks with Electric Vehicle Batteries is that of damaged batteries. When a battery is damaged its internal safety mechanisms may be compromised, and rupturing of the cells can expose the contents to atmospheric oxygen which can potentially result in fire or an explosion. In some cases, the batteries from crashed EVs have burned or exploded hours or days after the crash and initial fire was extinguished (Chen 2018). Therefore, it is important to have appropriate procedures for dealing with damaged EV batteries.

Figure 17 An Electric Vehicle gutted by fire (Chen 2018)

Although Lithium batteries are a relatively new innovation, there are already procedures for handling crashed EVs and damaged Lithium batteries. A good example is a report on best practices for handling crashed EV batteries by the National Fire Protection Association of the US (Long 2013). A brief summary of the main points is presented below. Much of this is common fire fighting practice, however we are highlighting aspects that pertain specifically to the EV Battery.

In general, the normal firefighting procedures apply, including the use of water, standard Personal Protection Equipment (PPE) and, in the case of fumes or fire, the use of Self Contained Breathing Apparatus (SCBA) to prevent the inhalation of toxic fumes.

Generally for firefighters the use of water does not pose an electrical shock danger, however EV fires may require much larger volumes of water than conventional vehicle fires. Because high voltage batteries are in protective cases, it is very difficult to get any extinguishing agent directly onto the burning cells. The application of large volumes of water may cool the high voltage battery sufficiently to prevent the propagation of fire to adjacent cells. Large amounts of water should be used to extinguish and cool damaged EV’s and batteries. Using only small amounts could result in the release of toxic gasses.

Care should always be taken to avoid contact with conductive components of the electrical system, and specifically never attempt to open the motor or battery compartment unless prepared to appropriately deal with the high voltages contained therein.

1) Identify if the vehicle is an Electric Vehicle, or conventional

2) Immobilize the vehicle: The vehicle must be prevented from accidently moving

3) Disable the vehicle: The vehicle should be shut OFF, and if possible the 12V ground line should be severed to prevent re-energization of the vehicle. This may include the actuating of a manual high voltage disconnect. It is recommended that anyone attempting this should use high voltage safety gloves.

If the vehicle is plugged into a charger, it should be unplugged, and/or the power to the charger should be disabled. If it can not be disabled or unplugged, then the vehicle/fire should be treated as an energized electrical fire, with all due precautions.

4) Extrication: Remove any occupants of the vehicle, being careful to avoid contact with any high-voltage components.

5) Fire Extinguishing: Battery components may be difficult to directly access with water. Although the motor compartment may be opened for better access, never attempt to breach or cut into it blindly as this may expose the firefighter to electrical power shock hazards.

6) Overhaul operations
Once any fire has been extinguished the vehicle should be monitored, as EV fires may re-ignite even after hours or days. If possible, the battery should be discharged in accordance with the manufacturers recommended guidelines by qualified personnel before transportation of the damaged vehicle.

EV Batteries can reignite hours or days after a crash or fire has been extinguished, especially if the battery is not fully discharged. Thus, it is recommended to insure the battery is discharged in an appropriate manner, and all non-discharged damaged EVs and batteries should be stored and monitored for at least two weeks in a well ventilated, flame proof setting.

Damaged vehicles or batteries should be kept at least 15 meters away from other vehicles, buildings or flammable objects. Damaged Batteries and EV’s should not be stored in fully enclosed spaces as explosive gasses could accumulate. Also, the windows of damaged EV’s should be fully opened to allow ventilation of explosive gasses.

7.0 GOVERNMENT POLICY BEST PRACTICES

Governmental policy relating to Electrical Vehicles generally focuses on four separate areas, namely:

1) Vehicle

Range
Energy Consumption and Efficiency
EV Information Display (eg. Battery State of Charge, Expected Range, etc.)
Vehicle Labeling
End Of Life Vehicle Recycling and re-use

2) Battery

Battery Performance
Battery Durability (Life Cycles)
Battery Recycling
Battery re-use (post Mobility EOL)

3) Infrastructure

On-Board Charging System
Off-Board Charging Standard
Wireless Charging
Use of Vehicle as Electric power Supply

4) Market Deployment

Regulatory Incentives
Financial Incentives
Consumer Awareness
Government Purchasing Policies

An excellent summary of best practices in legislation is provided (UN 2014). When considering government policy development, it is important to honestly asses the motivation for formulating the policies. Each and every policy requires substantial investment of resources beyond the basic policy development. There must be provisions for enforcement, including measurement of conformity, as well as schedules of repercussions in the event of non-conformity. Given the relatively small market of Bhutan it is unlikely that we will be able to develop a comprehensive national automotive test center capable of confirming extensive technical specifications.

Figure 18 The Automotive Research Test Center of Taiwan

The Automotive Research Test Center in Taiwan is a full service conformity vehicle testing center. It is located on 119 hectares of land, and cost hundreds of millions of USD to develop.

VEHICLE RECYCLING

Relatively few countries have enacted regulations relating to EOL vehicle recycling. Europe, Japan, South Korea and China have regulations in place relating to End Of Life recycling of conventional vehicles. These same regulations are applied to Electric Vehicles as well.

VEHICLE LABELING

Many countries have mandated labels for vehicles offered for sale. Generally, EV Labels may include the following items:

- Emissions (CO_2 equivalent emissions per kilometer)
- Usage Energy Consumption Cost (over a set number of years or the life time of the vehicle)
- Energy Efficiency Rating
- Battery Capacity
- Expected Range
- Battery Charge/Discharge Cycles

BATTERY PERFORMANCE

Battery Performance regulations generally include procedures for measuring the batteries power consumption, storage and output capacity.

BATTERY DURABILITY

The most extensive and widely used regulation is the UN R100 for cars and UN R136 for light duty EVs (UN 2010). These regulations generally define the procedures for assessing battery lifecycle for a given vehicle. Additionally, other battery specific tests may be included such as shock/vibration, puncture resistance, water Ingress Protection (IP), thermal cycling and etc.

Malaysia notably has a minimum specification of 300 charge/discharge cycles for light duty Electric Vehicles, and will test to confirm manufacturers stated claims of ultimate battery life in terms of either number of cycles or kilometers.

It is very likely that ASEAN will develop Electric Vehicle standards including, among other things, procedures for measuring the battery life (in cycles and kilometers) and also have a minimum useful battery life.

BATTERY RE-USE AND RECYCLING

Many countries have generic regulations relating to automotive battery recycling for conventional vehicles, including targets of recycling rates. For example Canada has general recycling and disposal laws applied to vehicles. Europe has various regulations relating to automotive recycling, including regulations relating to the maximum quantities of hazardous materials in batteries, recycling and disposal procedures (Directive 2006/66/EC), but these are not specific to Electric Vehicles.

In 2018 China introduced legislation to streamline and increase the recycling of EOL EV Batteries, including the implementation of individual battery tracking numbers (similar to Vehicle Identification Numbers). Additionally China is pushing vehicle and battery manufacturers to use more standardization in battery manufacturing to facilitate battery extraction and recycling. Finally they have designated several companies as “white listed” EV Battery recyclers.

More recently Europe has just enacted additional legislation including recycling provisions for lithium EV batteries. In an assessment of EV Battery recycling they acknowledged that EV Battery recycling may not currently be economically viable, however this is expected to change as commodity prices and EOL EV Battery volumes increase. They believe that recycling targets are one of the keys to increasing battery recycling volumes as it insures a supply of batteries for recyclers (EC 2019).

8.0 RECOMMENDATIONS FOR GOVERNMENTAL REGULATIONS

With any new technology there are new opportunities, but also new risks. The objective of the governmental regulation is to encourage the appropriate exploitation of the technologies' advantages while eliminating or mitigating the risks. While our main intention here is to ensure the safe handling and disposal of Electric Vehicles batteries, there are also peripheral risks which bear mentioning.

RISKS

The main risk and focus of this study are the safety of EV Batteries and what to do with their waste. There are environmental concerns associated with some battery technologies, however the Lithium batteries are mostly benign. Damaged batteries pose an especially high danger of fire, explosion and leakage, thus requiring special precautions. Finally one often overlooked risk is that of disproportionate popularity of Electric Vehicles themselves. While this question is somewhat peripheral to the main focus of this study, it is apparent from the vehicle projection data (the automotive fleet in Bhutan is expected to double in less than 10 years), and existing traffic situation (daily traffic jams in the major cities) that Bhutan is not prepared for a large increase in the total road vehicle fleet, electric or otherwise.

FACTOR	RISK	MITIGATION
EV Battery Handling	Possibility of electrical shock, fire and explosion if mishandled	Handling as per section 6 Various policies as presented below
EV Battery Materials	Environmental Contamination	Proper recycling and disposal as detailed in section 5.3
Damaged EV Batteries	High possibility of fire, outgassing of toxic fumes	Fire fighting and handling as per "Damaged Battery Handling" in section 6
Road Vehicle Overpopulation	With increasing prosperity and availability of EVs the number of EVs will greatly outstrip the existing road infrastructure	The government should look ahead to the inevitable problems associated with an increase in vehicle population, and plan accordingly.

Figure 19 Potential Risk Matrix associated with Electric Vehicles and Batteries

The major risk unaddressed by this study is simply the growth in the automotive fleet. While from the point of view of energy imports it makes sense for Bhutan to encourage the adoption of electric vehicles, this should be done as part of an integrated approach to transportation planning. The government has many options for controlling vehicle types and populations adopted by consumers. These include things such as importation taxes, licensing fees, fuel pricing, quotas or limits, and even implementing a "Certificate of Entitlement" for the purchase of a vehicle, as done in Singapore. While the details of this is beyond the scope of this study, it is strongly recommended that the government of Bhutan take a holistic approach to transportation development including public transportation, road planning, and private vehicle control to avoid disrupting and detrimental impact on the Bhutan society caused by an uncontrolled increase in road vehicles.

Based on the present study we are recommending the following government regulation for adoption in Bhutan:

1) VEHICLE LABELING: All Electric Vehicles imported to Bhutan must be clearly labeled as Electric Vehicles

2) Manufacturers should supply instructions (on a per model basis) for battery removal, discharging and

any special precautions associated with battery handling

3) BATTERY LABELING: Batteries in the EV's should be clearly labeled as to battery type (chemistry), and voltage and capacity

4) Any vehicle types failing to comply with the above regulations can be prohibited from further importation and sales in the country.

5) Any vehicle types deemed to be unsafe based on actual road usage can be prohibited from further importation and sales in the country.

6) BATTERY RECYCLING: As batteries may be valuable and/or hazardous they should only be disposed of via government approved battery recyclers. Spent batteries from Electric Vehicles cannot simply be disposed of as normal waste.

7) Police and Fire Response personnel should become trained in the proper handling of Electric Vehicle accidents, including the handling of damaged EV batteries.

8.1 VEHICLE LABELING

The most important aspect of vehicle labeling is so that in the case of an emergency, flood, fire or accident, everyone, including medical, fire, police and others can clearly identify the vehicle as an electric vehicle, and take the appropriate precautions.

Secondarily new vehicles may be labeled for things such as vehicle range and expected battery life, energy efficiency, annual cost, equivalent emissions, battery capacity, and etc. The drive cycle and test procedure used to obtain the information for the label may also be included. This can be used to encourage consumers to consider the long-term cost of owning a vehicle, thereby enhancing the prospects of EVs as compared to conventional vehicles which have a lower up front cost, but higher long term cost.

8.2 BATTERY LABELING

The battery should be clearly labeled with the battery nominal voltage and capacity (Watt hours, or Amp Hours), and battery type including chemistry. This is important for safety and handling, as well as recycling purposes. The following information should be clearly labeled on the battery packs:

- Battery Electrode Polarity
- Battery and Pack Manufacturer
- Date of Manufacture
- Operating Voltage (Volts)
- Maximum Current draw (Amps)
- Capacity (Ah, or kWh)
- Battery Cell Chemistry

- Any special handling information or precautions

8.3 RECYCLING

Batteries should be extracted from the vehicle by a qualified service center, and handled in accordance with the battery handling guidelines. Used EV Batteries should be sent to an approved recycling center. At the recycling center batteries will be separated into four separate categories:

1) For disposal
2) For shipment to outside recycler
3) For recycling
4) For re-use

Recycling can take one of several forms:

1) Basic Recycling of battery Case, Terminal wires
   Reuse of individual cells in other applications
   Disposal of individual cells
   Recycling of individual cells
   Shipment of individual cells to a third party for further processing
2) Complete metallurgical recycling of all important metals
3) Complete hydro-metallurgical recycling of all important metals

8.4 RECOMMENDED BATTERY RECYCLING PROCEDURE

NOTE: All handling of the EV Battery should be done with High Voltage Personal Protection Equipment (HVPPE) in place, such as electrically insulating gloves.

1) Inspect the battery for physical damage
2) Record the batteries identification information (Vehicle type, registration number, Battery Manufacturer, type, voltage and capacity)
3) Measure the battery voltage and State Of Charge (SOC)
4) If battery is above 10% charge, it is discharged to no more than 10% SOC
5) Battery Case is opened
6) Internal components are dismantled, separating individual cells from the casing and internal electrical conductors
7) Recyclable materials (especially aluminum, copper, other metals and plastics) are then sent for recycling at an appropriate plant
8) Individual cells can now be recycled or scrapped (if deemed unusable), or tested for capacity (if potentially usable). If the capacity is sufficient, then the batteries may be sold for re-use.

The recycling center should have the following facilities in place:
1) Heavy load lifting capabilities (battery packs may weight up to several hundred kilos)
2) Fire prevention equipment
3) Flame-proof individual battery storage system (to prevent fire from one battery spreading to another)
4) Adequate ventilation for removal of dust, and fumes in the event of a fire or cell outgassing
5) Battery voltage and current measurement tools
6) Battery Discharge tool
7) High Voltage compatible hand tools and Personal Protection Equipment

8.5 OTHER VEHICLE AND BATTERY STANDARDS

Other aspects occasionally regulated, but not initially recommended for Bhutan include:

Vehicle Range Specification

- Defining drive cycle, temperatures, conditions of various peripherals (eg. heaters, lights)
- Minimum achievable range

Battery Capacity and Performance

- Methods and conditions for testing and measuring battery power delivery capability, energy storage capacity, battery charge, etc.

Battery Life Cycle Specification

- Methods and conditions for determining average life cycle count
- Minimum Life Cycle

Battery Robustness

- Shock and vibration resistance
- Temperature range
- Pressure Range

Energy Efficiency Measurement

Vehicle Recycling

Charging Systems

- Connector types and voltages
- Wireless Charging Systems

Note: This last category is being performed separately from this study.

9.0 TRAINING RECOMMENDATIONS

Electric vehicles are an exciting new technology, but with them come new challenges. One of the challenges Bhutan will face is the need for greater technical knowhow in the EV technologies. This will be required in the various government organizations as well as industry and academia partners within Bhutan dealing with traffic, vehicles and of course EV battery recycling. Some of the training programs listed below are intended for administrators, and only require a very basic technical depth, where as other programs are more technically oriented and are intended for the personnel involved in the National EV Battery Recycling Center, and various second life battery utilization companies. While some of these are "general" courses offered by numerous institutions (eg. Vehicle Dynamics), many of these are highly specialized courses, only available from a few institutions such as Focus Applied Technologies (Focus 2020).

1) Electric Vehicle Battery Handling and Safety
This short course covers the dangers of EV Batteries, as well as how to avoid accidents. Battery handling, discharge and transportation procedures are described in depth.

2) Electric Vehicle Basics: Technology Overview, Power, Range, Voltage, Current and Battery Capacity
This is a "high level" technical overview of Electric Vehicles intended for administrators and project managers. The basic technologies are briefly described, and fundamental calculations are developed showing the typical power consumption and range versus battery capacity for an automotive EV.

3) Electric Vehicle Technologies: Motors, Controllers, Batteries, BMS and Vehicles
In this course the technologies of EVs are described in great detail, with special attention on the motor, controller battery and Battery Management System. Vehicle speed, torque and power requirements are analyzed and compared to the motor's speed and torque as well as the voltage and current. This allows direct calculation of the vehicles range at any given operating condition.

4) Vehicle Standards and Testing and the Vehicle Type Approval Process
This course provides an overview of how national vehicle standards are developed, how compliance testing is performed, and how a typical national level Vehicle Type Approval process works.

5) Data taking, screening and analysis, and System Modeling
This course gives a fundamental look at modeling systems (such as population growth, vehicle volumes, etc.) as effected by various parameters. With known data and known or assumed growth rates, future numbers can be predicted. Additionally related data taking is covered, along with data screening (how to evaluate whether or not the data is reliable) and analysis. Examples from transportation systems are featured throughout, with real-world data from Bhutan and publically available sources.

6) Vehicle Dynamics
This course provides an in-depth analysis of vehicle power requirements based on a number of factors including the weight, rolling resistance, size, aerodynamics, speed, acceleration, hill climb angle and relative wind. Results can be further analyzed to give electric vehicle power requirements, and even range estimates for a given battery capacity. Similar analysis can be performed for combustion engine vehicles yielding vehicle mileage (km/liter) and trip costs.

7) On-Road Vehicle Data Logging for EVs
This course covers actual on-road vehicle measurements specific to Electric Vehicle including the instantaneous battery voltage and current, electrical power, mechanical power, speed and torque, overall system efficiency, battery capacity and range. Additional measurements can be taken during charging to

give the charging efficiency and actual vehicle trip cost.

10.0 CONTACT

For further information on this or related matters, please contact us directly:

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Website:	WWW.FocusAppliedTechnologies.com

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APPENDIX 1: TRANSCRIPTS OF PRIVATE CONVERSATIONS

Hello!

I'm working a project for the Bhutan government looking into the feasibility of putting together an EV battery recycling plant in Bhutan. Obviously it is a very small country, and the volumes don't look (to me at least) like they can justify operating a plant of their own. They are, however, one of the "darlings" of international granting, so they believe they can get funds to build a plant... I just don't see it being economically viable. I'll be recommending perhaps simply recycling the case and conductors, but I think the smelting of the individual cells is going to be uneconomical.

I wanted to interview someone from Retriev who has an informed opinion on the cost of putting together a plant (I'm looking at volumes of 100,000 tons about 35 years out) and the economics. I kind of suspect that even in Li-ion battery recycling is economically viable, they'd be better off shipping 'em out to India (just next door).

Please put me in contact with who ever there might be able to help.

Thanks!

-Horizon
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Dear Dr Gitano,

Thank-you for your email. As a private company we do not reveal economic information. I can tell you however that your assessment of the situation is correct. A disassembly facility for battery packs would be the best approach to start, and then shipping the cells to a larger centre. If volumes reach a 100,000 tonnes per year then it is likely more justifiable - but it is hard to plan for 35 years out.

I can also tell you that we currently charge for battery packs, as the contained metal content is not sufficient to cover recycling costs. However, in other parts of the world people do purchase end-of-life cells or take them for free.

Regardless of volumes/costs - there will still be a need to manage vehicle battery packs in Bhutan. It is more a matter of are people willing to pay for it.

If you have any further questions, please do not hesitate to contact me.

Regards,
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APPENDIX 2: LIST OF EV BATTERY RECYCLERS AND COMPONENTS

GEM – China

Website: http://en.gem.com.cn/index.php/feijiudianchiheniefeiliao/
Address： 20F Block A, Marina Bay Ctr., South of Xinghua Rd.Bao'an Center Area Shenzhen, China
ZipCode： 518101
Tel： 86-755-33386666
Fax： 86-755-33895777、33662928（18F）

Hunan Brunp Recycling Technology Co., Ltd.

Address: No.018 Jinzhou Road, Jinzhou New District, Changsha City, Hunan Province

Quzhou Huayou Cobalt New Material Co. Ltd

Website: http://en.huayou.com
Address： No.18, Wuzhen East Road, Tongxiang Economic Development Zone, Zhejiang Province
Metal trade office: electrolytic cobalt, electro-deposit copper
Tel： 0086-573-88589989
Email： fmq@huayou.com

Ganzhou Highpower Technology Co., Ltd

Website: https://www.highpowertech.com/products-recycling
Address: Building 1, 68 Xinxia Road, Pinghu Town, Longgang District, Shenzhen, Guangdong, China
ZipCode： 518111
Tel: (86) 755-8968 6533, (86) 755-8968 6916
Email: Marketing@highpowertech.com

Guangdong Guanghua Sci-Tech Co. Ltd

Website: http://www.ghtech.com/Eapplication/recovery_100000000297454.html
Address： NO.295, Daxue Road, Shantou, China
Tel: (86）0754-88213888
Fax: (86）0754-88221999
Email： export@ghtech.com

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