Case Study on PV Integrated Grid Independent Electric Bus

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Abstract

In this paper, it has been theoretically and conceptually examined the technical, design, and economic viability of using Photovoltaic (PV) technology in combination with battery operated Electric vehicle (EV) in Public Bus sector in India, where solar energy is readily available. The study is further analyzed to propose the utilization and economics of "PV integrated EV" technology along with solar and battery integrated solution. The available battery chemistries are studied, and the best suited solution based on parameters such as cost, weight NMC battery is chosen. Finally, the number of solar panel and battery requirement is calculated based on the power consumption of the vehicle and concluded.

Keywords: Electric vehicle, battery, solar energy, energy efficiency, system integration, power density, PV arrays.

1 Introduction

Global warming has captured the attention of many nations that are concerned about the gradual increase in the temperature of the earth due to the greenhouse effect, which makes the gases (primarily carbon dioxide) trap the

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solar radiation close to the earth's surface. The burning of fossil fuels has shown the major contributor to the greenhouse effect and hence the global warming [1, 2].

One effective way to reduce the global warming is to reduce the use of fossil fuels in automotive vehicles. Accordingly, the design, development, and utilization of Battery Electric Vehicles (BEVs) have been increasing rapidly. BEVs operates by the chemical energy stored in the rechargeable battery packs, which power the electric motors and controllers for propulsion of the vehicle. BEVs are available in wide range of applications such as bicycles, motorcycles, forklifts, cars, trucks, and buses. The well-known BEV products in the current market include the Model S from Tesla Cars Inc., with a driving range of 458 km/charge, Chevy Bolt from General Motors with a drive range of 380 km/charge and Leaf from Nissan Cars with a drive range of 240 km/charge [3].

There are few variants in BEVs that are not entirely dependent on pure battery power. For example, Plug-in Electric Vehicles (PEVs) utilize BEV technology but also have an internal combustion engine which powers the vehicle and such vehicles are also known as Plug-in hybrid vehicles [4]. BEVs do not emit CO2, but the electricity needed for their charging stations comes primarily from coal-fired power plants, India's primary energy source. To make the EVs more sustainable, renewable energy in the form of Solar PV panels are used in the charging of the EVs as explained in [5]. This PV interconnection with the grid helps in reducing the dependency of charging the EV from grid. Powering the EV with main energy source as Solar PV panels has also been tried in the light vehicle segment [6]. In this paper this idea is extended to an Electric Bus.

Solar Electric Bus: A solar electric bus is commonly charged/powered by solar energy which is used for powering electric equipment on the bus & propulsion of the vehicle. Most of the existing hybrid vehicles which run on batteries supplementary recharged from common resource, usually power grid, along with harnessing the solar energy from PV panels [7]. A launch of standalone solar operated bus service often goes hand in hand with investments for large-scale installations of stationary solar panels with photovoltaic cells.

2 Case Presentation: India

The 150,000 diesel buses are accounted for the primary mass transit in Indian cities which are responsible for contributing to urban smog and carbon

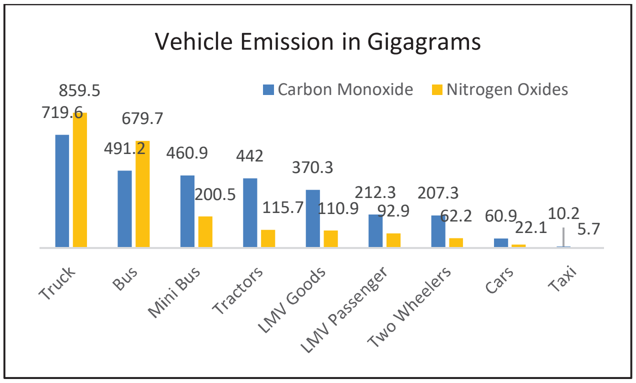


Figure 1 Vehicle emission: carbon monoxide and nitrogen oxide.

emissions that are warming the planet. When a bus powered by diesel is substituted with an electric vehicle approximately 25 tonnes of carbon dioxide emission can be avoided. With this data, if the 150,000 diesel buses are substituted by EV buses, we can stop the emission of 3.7 million tons of CO2 into the atmosphere. Transportation sector is responsible for the emission of one tenth of greenhouse gas emission in India [8]. In India, because of this emission, 670,000 people have lost their lives due to the air pollution [9]. India is a fast-developing country and is also a major contributor of the emission. India accounts for one third of the rise in emission among the global countries in 2014 [10]. The total emissions of nitrogen oxides, carbon monoxides and CO2 for pan India are represented in Fig. 1 and 2 respectively. From the data, amongst the commercial vehicles, Buses contribute significantly in the emission of green-house gases.

The case study involved the test run of China manufactured electric bus for a duration of three months in the city of Bangalore in India. Although both the buses developed the revenue almost equally, there was difference in the profits earned. The EV bus developed 82% higher profit [8]. This high profit margin is accounted by the lesser maintenance and variable costs of the Electric bus and higher energy efficiency. The Table 1 shows the calculation of Return of Investment (ROI) for the Electric Bus. The downside of EV is the higher capital cost of the vehicle. With the manufacturing of the vehicle in India, this cost can be reduced further. But because of the higher profit earned per day, the ROI of EV bus is much lesser than its diesel counterpart.

The non-existence of exhaust gases, noiseless operation and very less energy consumption by the motor under idle conditions at the traffic signals

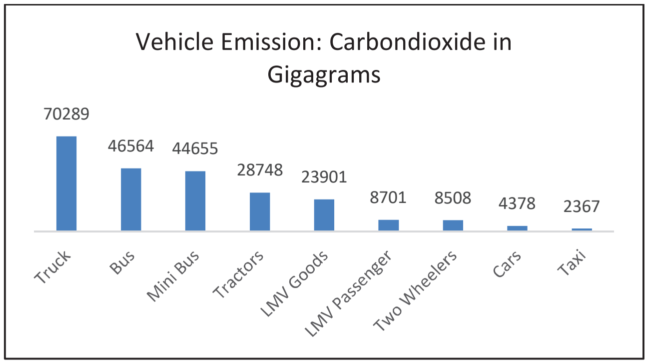


Figure 2 Vehicle emission: carbon dioxide.

Table 1 Estimation of ROI for EV and diesel bus

Parameter	Electric Bus	Diesel Bus
Average revenue per day	182$	143$
Average travel cost per day	32$	74.5$
Average profits earned per	150$	68.5$
Annual profits earned	58360$	31962$
Price of the bus	461538$	130769$
Return on Investment (ROI)	7.9 years	4.09 years

and at the bus stops make these EV buses one of the best suited technology for the cities in India. In this paper we are trying to propose the integration of solar PV panels with Electric bus and try to make it a sustainable vehicle.

3 Solar Hotspots Available in India

The regions which have remarkable solar power abundance available for the commercial utilization of energy are solar hotspots. Locating these solar hotspots in the geographical region of a country assist in accomplishing ever rising power demand in effective, decentralized and sustainable methods. The insolation data of the Indian territory obtained from satellites with high resolution is as shown in Figure 3 [11]. The Table 2 shows the monthly insolation and the average temperature.

The analysis involving technical and economic aspects of the solar power which enables maximum power generation by exploiting minimum land area, demonstrate the ability of enormous power generation and also potential

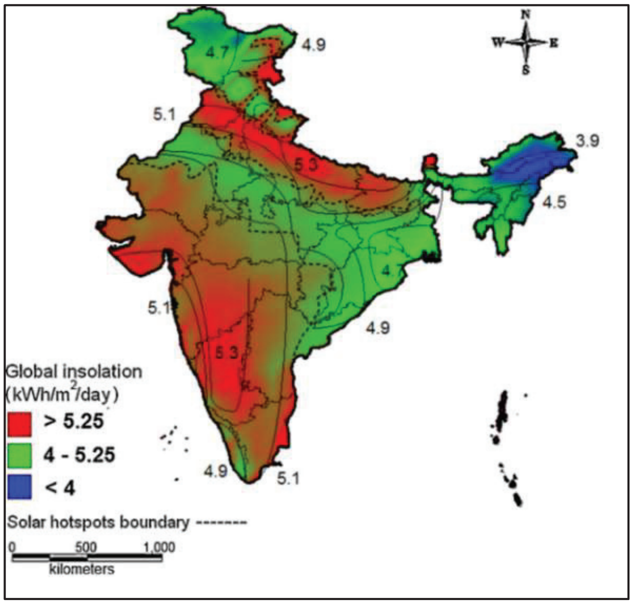


Figure 3 Annual average Global insolation map of India showing the isohels and solar hotspots.

Table 2 Solar energy radiation on monthly details

Month	KWh/m^2/day	Temperature Degrees Celsius
January	5.06	23.5
February	5.82	26.1
March	6.36	29.6
April	6.51	30.1
May	6.28	31.7
June	4.84	28.6
July	4.26	27.1
August	4.18	26.8
September	4.52	26.8
October	4.79	25.8
November	4.85	24.5
December	4.74	23.2
Year Average	**5.2**	**27.0**

reduction in emission of greenhouse gases. From the data we obtain that 58% of geographical regions in India have the potential of having average solar insolation value greater than 5 kWh/m^2/day.

4 Further Development

The proposed concept of bus design with solar array panels is represented in Fig. 4 mentioning the dimension of the vehicle. The same is validated to travel a total distance of 90 km before reaching the charging station at an average speed of 60 km/hr. The battery type is selected and battery capacity, solar array area is calculated for concept design which is proposed to meet the requirements.

4.1 Solar Electric Bus Specifications

The technical parameters of the proposed EV bus are shown in table 3 below. It mentions the details regarding the power required, surface considered for the vehicle movement and the inclination angle of the road etc.

The figure of a typical solar PV panel is shown in Figure 5. The electrical data of the panel and the dimension, weight of the panel is mentioned in Table 4 having power input with insolation of 5.5 kWh/m^2/day.

4.2 Area of Solar Panels

With the analysis and calculations, the available area on the roof top is shown in Table 5 with the final arrangement of mounting the solar panels on the roof top is represented in Figure 6. The proposed method involves two roof top conditions of the solar panels. When the vehicle is under movement, the first

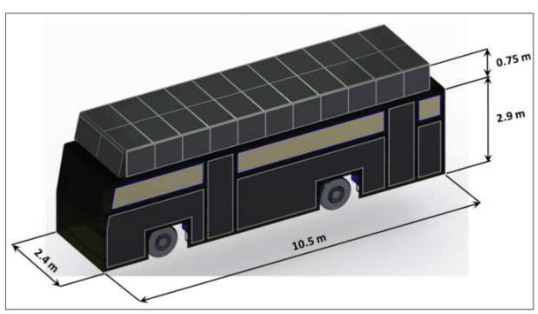


Figure 4 Concept Solar Bus with overall dimensions.

Table 3 Solar Electric Bus Specifications

Description	Parameters	Value
Nominal EV Bus Power	kW	40
Vehicle Starting Power	kW	154
Maximum Peak Power	kW	172
Maximum speed	km/hr	60
Maximum distance range	km	90
Acceleration time	sec	15
Co-efficient of Rolling Resistance	Concrete	0.015
Gradient	Degrees	5
Maximum Wheel Speed	RPM	412
Gross vehicle weight	kg	10200
Occupancy	numbers	24 (max 30)

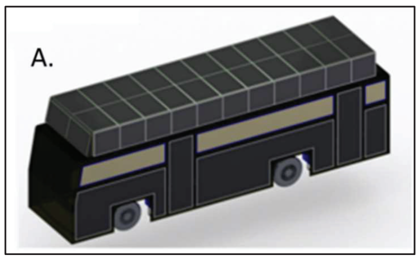
Figure 5 Typical solar panel.

Table 4 Solar PV Panel data

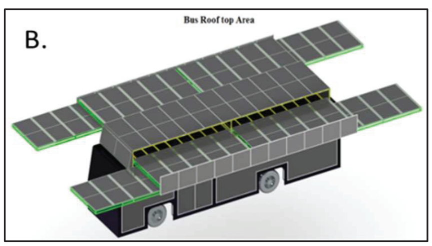
Description	Value
Peak Power Pmax Wp	322.5 W
Maximum Voltage Vmpp	37.7 V
Maximum Current Impp	8.55 A
Open Circuit Voltage Voc	46.1 V
Short Circuit Current Isc	9.08 A
Module Efficiency η	0.1662
Voltage at Pmax	34.6 V
Current at Pmax (A)	6.84 A
Length $\times$ Width $\times$ Height	1956 $\times$ 992 $\times$ 40 mm
Weight	27 kg

Table 5 Electric Bus Solar rooftop area

Electric Bus Solar rooftop area available for Energy absorption			
Sl. No.	Roof Top Condition	Actual Area in Sq. m	Available Area for Solar Charging Sq. m
1	Panels wide open during parking	125	112
2	Panels closed during running	60	54



A. Area of Solar panel closed under vehicle running condition 60 Sq.m



B. Area of Solar panel open under vehicle parking condition = 125 Sq.m

Figure 6 Roof top solar PV panel arrangement concept.

set of solar panels which are always open and exposed to the sky and can harness the solar energy as shown in Figure 6A. The second set of panels are of retracting type. These panels, under normal conditions will be closed and are completely spread out only when the vehicle is under parking condition as shown in Figure 6B. To achieve best extraction of power from the PV panels during the unbalanced irradiance within a day, the Maximum Power Point Tracking (MPPT) algorithm must be implemented along with PID controller as mentioned in [12–14]. The mounting of the Solar PV panels on the roof top can be followed as explained in [15], to obtain better cooling of solar panels and weight balance of the vehicle.

Table 6 Roof top solar power generation split-up

Solar Power Generation in kW (7 hours charging)		
Parameters	During Parking	During Running
Panel Area	112	54
Hours of charge	5.5	1.5
$kWh/m^2/day$	5.5	5.25
W/m^2	786	750
$\eta = 16.67\%$	131	125
Power Generated in Kw	80.696	10.125
Total Power Generated	90.8 kW	

Table 7 Battery and Solar panel parameters

Design parameters	
Energy lost in system factor	1.2
Panel generation factor for India	5.5
Battery loss	0.85
Depth of Discharge	0.6
Peak power Pmax in Wp	320

The Table 6 represents the calculations of the power generated per day from the roof top solar panels. For the design, it has to be considered that 112 Sq.m panel area is available for charging at parking with a consideration of 5.5 $kWh/m^2/day$ and the power generated amounting to 80.7 kW at efficiency close to 17%. Similarly, during the vehicle under movement the charging panel area exposed is 54 Sq.m with same watt hours charging per day that is generates an output power of 10.13 kW. Totally, the power generated due to the solar array placement with the proposed roof top arrangement is 91 kW for a duration assumed as seven hours charging during the sunlight.

4.2.1 Solar panel calculation

The number of solar panels required are calculated by considering the energy required to power the Solar bus. With the calculation of Energy required, the loss factors are considered using the Table 7. With this extra margin, the number of solar panels required are calculated as shown in Equations (1)–(4)

$$\begin{aligned}\text{Power consumption} &= \text{Power required} * \text{Travel time} \\ &= 40000\mathrm{W/h} * 1.5\ \mathrm{h} = 60000\ \mathrm{Wh}\end{aligned} \tag{1}$$

$$\begin{aligned}\text{PV panels energy generation} &= \text{Power consumption} * \text{Energy loss factor}\\ &\quad * \text{Battery loss} * \text{Travel time}\\ &= 60000 * 1.2 * 0.85 * (90/60) = 91.8\ \text{kWh}\end{aligned} \tag{2}$$

$$\begin{aligned}\text{Peak power } W_p &= \text{PV panel energy generaton}\\ &\quad * \text{panel generation factor}\\ &= 91800/5.5 = 16691 W_p\end{aligned} \tag{3}$$

$$\begin{aligned}\text{No. of PV panels} &= \text{Total } W_p/\text{Solar panel } W_p\\ &= 16691/320 = 52\end{aligned} \tag{4}$$

4.2.2 Validation of bus rooftop area

$$\begin{aligned}\text{Area of each solar panel} &= \text{Length} * \text{Width}\\ &= 1.956\ \mathrm{m} * 0.992\ \mathrm{m} = 1.94\ \mathrm{Sq.m}\end{aligned} \tag{5}$$

$$\begin{aligned}\text{Total Solar Array Area} &= \text{No. of modules} * \text{Area of each module}\\ &= 52 * 1.94 = 100.9\ \mathrm{Sq.m}\end{aligned} \tag{6}$$

Total available Bus rooftop area 112 Sq.m. Hence 57 panels are installed to obtain 90.8 kWh.

Considering the design parameters and energy lost in system factor, a total power of 91.8 kWh is required. With the available roof area of 112 Sq.m a total power of 90.8 KW power is generated as shown previously in Table 6.

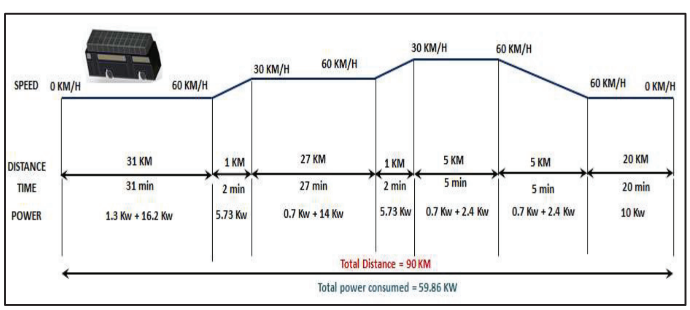


Figure 7 Power requirement calculation for the route considered.

4.3 Solar Electric Bus Route Analysis

The bus is validated to travel a total distance of 90 Km before the charging station is reached with an average speed of 60 Km/hr. The route is analyzed to measure the total power required to travel a distance of 90 Km. The total time taken for the travel is 93 minutes considering two gradients each of 5 degrees with a length of 1 Km each. With the split-up of power consumption as shown in Figure 7, the total power required for the travel is 60 kW for 93 minutes.

The average power requirement for 1 km travel is calculated and it can be denoted by $P_{avg/Km}$ as shown

$$\begin{aligned} P_{avg/km} &= \text{Total power consumed}/\text{Distance travelled} \\ &= 60000/90 = 666.67\ \mathrm{W/km} \end{aligned} \tag{7}$$

Post calculation, it must be noted that 667W/km is the requirement based upon the route selected for Solar Bus.

4.4 Battery Technology

Taking consideration of the mechanical structure of the EV bus, certain restrictions are put on the type of battery. The constraints regarding the battery dimension and weight for the EV bus are the maximum allowed volume for the battery is 1.89 m^3 and the maximum allowed weight is 3060 kg. With these constraints to be satisfied, the various available battery technologies are evaluated and the best suitable option is chosen.

Of the various batteries available, the best suited batteries for electric vehicle in general are Nickel Cadmium battery (NiCd), lead acid battery, Nickel Metal hydride battery (NiMH), and Lithium ion and Lithium polymer batteries. The Lithium family batteries considered are Lithium Iron Phosphate (LFP), Lithium Nickel Manganese Cobalt Oxide (NMC), Lithium Cobalt Oxide (LCO) and Lithium Manganese Oxide (LMO).

The Table 8 provides the comparison of the factors considered for selecting the battery [16, 17]. The key factors to be considered while selecting a battery are the Energy density or Specific Energy, Cycle life of the battery and the thermal runaway temperature (for Lithium batteries). Based on the cycle life of the batteries, the Lithium batteries have higher cycle life and LFP and NMC are the best available chemistry. Of these two, each have an advantage and drawback. The LFP battery have higher temperature for thermal runaway, which leads to destruction of battery due to rise in the temperature of the

Table 8 Different battery chemistry comparison

Battery Type	Cell Voltage V	Specific Energy in Wh/kg	Cycle Life at 100% DoD	Thermal Runaway in Degree Celsius
NiCd	1.2	40–60	500	–
NiMH	1.2	60–120	300–800	–
Lead Acid	2.1	30–40	50–100	–
LFP	2.4	90–120	2000–3000	240
NMC	3.7	150–220	1000–2000	230
LCO	3.8	150–200	500–1000	190
LMO	3.7	100–150	300–700	240

Table 9 Adjustment factors related to battery

Symbol	Parameter	Value
TC	Temperature Compensation	1.08
DA	Days of Autonomy	1
DM	Design Margin	1.1
DOD	Depth of Discharge	0.6
Wh	Total watt hour per day	60,000W
n	Battery efficiency	0.85

battery uncontrollably. On the other hand, NMC batteries have higher specific energy which means lesser battery weight for same amount of energy.

There is a move towards NMC-blended Li-ion as the system can be built economically and it achieves a good performance. The active materials used in the NMC battery can be blended to be useful in wide range of Electric vehicles. The capacity fade of NMC battery system is less compared to other battery systems [18, 19]. The NMC family is growing in its diversity and is one of the preferred batteries for EVs [20]. Under the condition of overcharge, the irreversible damage done to the battery can be avoided in NMC chemistry [21].

4.5 Battery Capacity Calculation

The battery capacity is calculated based on the energy required to perform one sided travel of the Solar bus. Along with this, parameters like efficiency of the battery, the Depth of Discharge of the battery, the temperature compensation and the design margin are taken into consideration. With this, the capacity of the battery in Ah is calculated and then the energy required is calculated in kWh. The Table 10 lists the adjustment parameters considered in calculation of the battery capacity.

$$\begin{aligned}\text{Battery Capacity} &= (Wh * DA * DM * TC)/n * DoD * Vlg \\ &= (60000 * 1 * 1.1 * 1.08)/(0.85 * 0.6 * 58.4) = 2393\ \text{Ah}\end{aligned} \tag{8}$$

$$\begin{aligned}\text{Energy Required} &= \text{Battery Capacity} * \text{Voltage} \\ &= 2393 * 58.4/1000 = 140\ \text{kWh}\end{aligned} \tag{9}$$

4.6 Number of Battery Calculation

Based on the energy requirement of Solar bus, the number of batteries are calculated.

$$\begin{aligned}W_p \text{ per battery} &= \text{Nominal Vlg} * \text{Nominal Capacity} \\ &= 58.4 * 120 = 7.008\ \text{kWh}\end{aligned} \tag{10}$$

$$\begin{aligned}\text{Batteries required} &= \text{Total Bat Capacity/Wh per Bat} \\ &= 140\ \text{kWh}\ 140\ \text{kWh}/7.008\ \text{kWh} = 20\end{aligned} \tag{11}$$

$$\begin{aligned}\text{Total Battery weight} &= \text{Per Bat weight/No of Bat} \\ &= 60\ \text{kg} * 20\ \text{nos.} = 1200\ \text{kg}\end{aligned} \tag{12}$$

4.7 Batteries Required

For the proposed EV requirements, based on all the validations and analysis NMC battery is considered. The battery packs are arranged on either side of the vehicle. On each side there are 20 batteries with a battery capacity of 140 kWh and a total of 40 batteries are placed with a battery capacity of 280 kWh as represented in Figure 8. The set of batteries on one side are used for energizing the motor for propulsion and auxiliary systems of the vehicle while the set of batteries on other side are used for charging when the bus is in motion or parking. With this, the total weight of the batteries will be 2400 kg which is within the design constraint of 3060 kg.

The battery capacity is designed in such a way that initially batteries placed on one side of the vehicle are fully charged for powering the solar

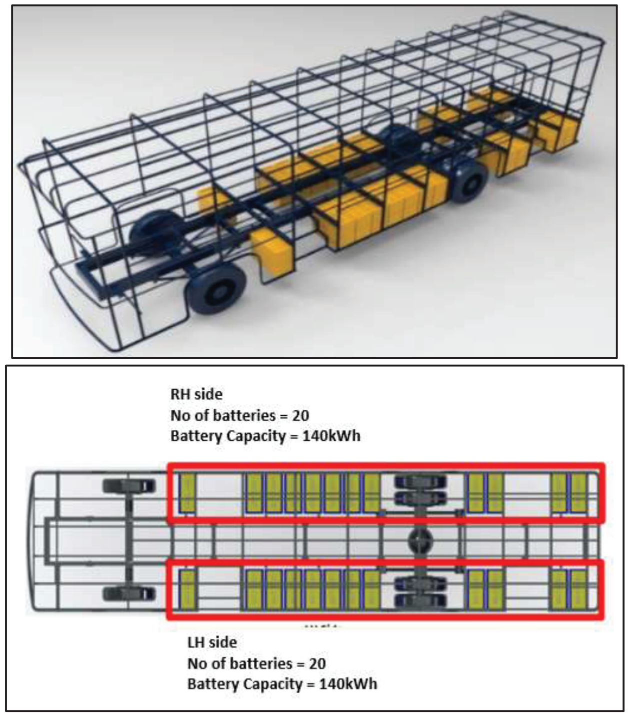


Figure 8 (a) Battery arrangements in Concept bus model (b) Top view.

bus to cover a total distance of 90 km. At the same time the set of batteries on the other side will get charged throughout the day.

5 Discussion

By analyzing the parameters like Battery Specific energy density, Total battery weight, Battery life, Battery volume required for EV, NMC battery technology is most favorable. The cost comparison of various battery technology is shown in table 10. Based on the comparison, NMC battery is the economic and cost-effective battery type for usage in BEV.

The cost per kWh of the NMC batteries has been reducing over the years of time. The possibilities of further reduction is more over the years to come. As per the analysis done in [22], the cost of NMC based Lithium batteries are expected to cost less than 100 USD/kWh with next 5–10 years (2025–2030). If the first life cycle of the NMC battery are well tracked with data

Table 10 Battery cost comparison

Battery Type	Cost/Wh in USD	Power Required kWh	Total Battery Cost in kUSD
NiCd	1.5	140*2	420
NiMH	1	140*2	280
Lead Acid	0.17	140*2	47.6
Li-ion	0.47	140*2	131.6
Nano Lithium titanate	0.48	140*2	134.4
NMC	0.43	140*2	120.4
LFeMgP	0.47	140*2	131.6

collection from Battery management system (BMS), the possibility of reusing the batteries as second life batteries are more as explained in [23].

6 Conclusion

An overview is analyzed, and results are demonstrated on how a successful integration of Solar PV panels with the public sector electric bus can be achieved. In the proposed model, the energy required by the Electric bus is 60 kWh and the energy generated through the solar panels is 90.8kWh per day. The battery chosen is NMC which has higher specific energy and thus results in lesser weight. And based on the requirement, the number of batteries used are 40 numbers each of 7.008 kWh. These are split into two strings which help in achieving complete independence from the grid for charging the Electric Bus. One set will power the vehicle while the other set off batteries get charged through the solar panels. The cost analysis of the type of battery is performed and the NMC battery proves to be a suitable option.

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Biographies

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Anand Raghavendra Rao has received his PhD in Electrical Engineering, post graduated in Electronics and graduated in Electrical and Electronics. Started career in 1992 and is currently with research and development at Otis elevator company, experience includes acting as a technical analyst on new products and research on the latest technology in the industry. He is in the approval board for design review committee, has been certified in various programs for energy auditing, new era of elevators with latest technology of PM Machine technology with regenerative inverters. He has 28+ years of diversified experience in vertical transportation with research interest on PM motors, drives, energy auditing, energy management and system integration. His specialized areas include new product development, systems technical analysis and process standardization.

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