Solar Electric Bus: Benefits and Costs

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Abstract— This paper explores the air pollution caused in the city of Ahmedabad due to the transport sector. A scenario of replacement of three diesel buses with electric buses for a route of 250 km is considered. It is envisaged to construct a grid connected solar rooftop plant that will charge the battery operated electric bus at night from the grid and return the energy during daytime to the grid while the bus is in operation. The major capital costs required for the development of the infrastructure for charging and procurement of buses and batteries are identified and compared with the fossil fuel (diesel) savings over a period of 25 years. The air pollution mitigated over this period is also calculated. A summary of benefits and costs of such an initiative is made.

Key words: Sustainable, Electric, Solar, Transport, Bus, Renewables, Benefits, Cost

I. INTRODUCTION

According to the Central Electrical Authority (2014), Ministry of Power, GoI, India's grid is highly carbon intensive with 950 gCO_2/KW h compared to other countries in the world. While it is difficult to reduce the electricity consumption in today's era, the generation of electricity through renewables needs to be explored in various avenues including bus transport. This calls for adoption of strategies and practices that can reduce the carbon emissions and the use of electric buses utilizing solar batteries for locomotion is envisaged as an attractive concept towards achieving sustainability goals. Benefits in form of reduction in air pollution, climate change mitigation and energy security can be achieved through adoption of Electric buses. Challenges remain in the form of capital intensive infrastructure and funding issues made more difficult by lack of indigenous manufacture of charging stations, high storage batteries and electric automobiles in India.

II. AIR POLLUTION & TRANSPORT SECTOR IN AHMEDABAD

A. Air Pollutants [1,2]

According to the Central Pollution Control Board, the five main pollutants responsible for the majority of the health impacts in Indian cities are particulates (PM), sulfur dioxide (SO_2), nitrogen oxides (NOx), carbon monoxide (CO), and ozone (O_3). Ambient standards and emissions standards exist for all of these pollutants. There also exist regulatory standards for the volatile organic compounds (VOCs). Primary pollutants that are emitted at the source are PM, SO_2, CO, NOx and VOCs, whereas ozone which is formed as product of chemical reaction of pollutants is a secondary pollutant.

B. Transport as a Dominant Contributor of Air Pollution in Ahmedabad [1,2]

The transport sector is the dominant source of air pollution in most of the cities in India. A study on urban air pollution analysis in six major cities of India including Ahmedabad has been carried out by Guttikunda and Jawahar (2011). The study reveals several interesting facts about the association of transport sector with the air pollution in the city. According to the study, the transport sector in Ahmedabad is responsible for 16 % of PM_{10} emissions, 27 % of $PM_{2.5}$ emissions and 35% of CO_2 emissions. Among the size fractions, $PM_{2.5}$ is considered more harmful than PM_{10} and with $PM_{2.5}$ as the controlling pollutant, the direct vehicle exhaust is the largest contributor. The study which was carried out for a domain size of 44 km x 44 km reveals a total annual PM_{10} Emission of 35,100 tons/year for the case of Ahmedabad. The study document further states that vehicle exhaust contributes to about 10-20 % annual average PM_{10} concentrations. About 18% of estimated passenger kilometers travelled in Ahmedabad are through buses. Therefore, while the bus is definitely a greener mode of transport as compared to the private vehicles, the emissions from CNG and Diesel buses have their own share in contribution to air pollution.

III. CONCEPTUALIZATION OF SOLAR ELECTRIC BUS

A. Concept and Assumptions

The scenario proposes two modifications to existing scenario of diesel bus transit for reduction in carbon emissions and other pollutants:

- Replacement of the diesel bus with an electric battery operated bus
- Generation of electricity for bus using grid connected solar rooftop instead of thermal power plant

The average solar irradiation in the state of Gujarat is 1266.52 W/sqm which is supportive in making feasible such an initiative. The data collection is done based on documents by CPCB, MNRE and report on urban air pollution analysis in six major cities of India prepared by Guttikunda and Jawahar. The rates for buses, batteries and charging station are based on international quotes based on market study in absence of availability of sufficient local data in the context.

Key assumptions made in the study are:

- No. of diesel buses replaced with electric buses: 3
- Range of each bus: 250 kms

- Cost of each bus: 2 crore INR
- Cost of batteries: 60 lakh INR
- Cost of charger: 1 lakh INR
- Service life of bus: 15 years
- Service life of rooftop: 25 years
- Service life of batteries: 5 years
- Service life of charger: 15 years
- Cost of diesel: INR 50/Liter with increase of 6% every year
- Mileage of diesel bus replaced: 2.1 km/liter
- Charging time: 4-5 hrs
- Further, it is assumed that the buses will be charged at night taking power from the grid and operational during daytime during which the solar rooftop power will be returned to the grid.

B. Area Consumption of Solar Rooftop and Bus Parking

Assuming that 1 kWp generates 5 kWh of electricity per day (considering 5.5 sunshine hours), a 324 kWh battery- bus requires about 65 kWp of grid connected solar rooftop generation. This requires a net area of about 650 sq. m. of solar rooftop per bus. This area could be made viable by superstructure built on ground with bus parking and charging provisions below it. This possibility will incur additional cost of superstructure construction and land acquisition for the construction. However it will serve the purpose of bus parking as well. Alternatively, available rooftop area on a commercial or institutional building could be explored for rooftop installation, which will save the construction cost; however the bus parking and charging space near to the building needs to be made available.

C. Cost Consumption of Solar Rooftop [3,6]

The solar rooftop plant costs about 156 lacs INR without subsidy. The ministry on new and renewable energy has implemented a "grid connected rooftop and small solar power plant programme" since June 2014 wherein solar rooftop plants with 1 kWp to 500 kWp capacities can be set up and can avail a central financial assistance of 15 % of the benchmark cost of the power plant. This particular subsidy does not apply for commercial and industrial establishments in the private sector. With the support of this subsidy, the cost of the plant can be brought down to 132.6 lacs INR.

D. Cost of Bus, Battery & Charging Infrastructure

A major investment is anticipated for electric bus procurement, high storage batteries and charging stations. The cost of one electric bus will vary from dealer to dealer but can be fairly estimated at 250 lakhs INR. The service life of such a bus can be estimated to be 15 years, thus the buses need to be procured twice in the period of 25 years for which costs are being projected. It requires high storage batteries costing 60 lakhs each time that have a service life of 5 years. The bus comes equipped with the battery, thus meaning that such batteries have to be procured three times during the service period of rooftop. A typical public charging station is estimated at 1 lakh INR for one station which can be common for both buses being charged one after the other. A summary of major costs and benefits incurred at the end of 25 years is presented later.

E. Vehicle Emissions Reduction [4]

The vehicular emissions factors in gm/km are based on the CPCB/MoeF study and are illustrated in Table 1. This amounts to 41.2 lakh kg of CO_2 mitigated for the service life of the roof top. A summary of vehicle emissions mitigated are given in Table 1.

Vehicular emission factors in gm/km for Diesel buses from CPCB/MoEF study					
	CO	HC	NO_X	CO_2	PM
Vehicular emission factor (gm/km)	3.92	0.16	6.53	602.01	0.3
Vehicular emissions mitigated for 3- 250 km diesel bus trips					
Vehicular emissions mitigated for 3- 250 km trips (gms)	2940	120	4,898	4,51,508	225
Vehicular emissions mitigated for 1 year (Kg)					
Vehicular emissions mitigated for 1 year (Kg)	1073	43.8	1787	164800	82.13
Vehicular emissions mitigated for service life of 25 years (Kg)					
Vehicular emissions mitigated for service life of 25 years (Kg)	26,828	1,095	44,690	41,20,000	2053.3

Table 1: Summary of vehicle emissions mitigated

F. Major Financial Costs and Benefits

Assuming a mileage of 2.1 kmpl, each bus saves about 119 litres of diesel consumption and consequently a saving of about 17,580 INR in 3-250 km trips which amounts to 65.15 lakhs INR annually considering the current rate of diesel in Ahmedabad as INR 50 per liter or 2801.6 lakhs INR for the service life of the rooftop assuming a 6 % hike in diesel prices per year.

A summary of major costs incurred in developing a solar electric bus mobility using grid connected solar rooftop installation is presented in Table 2. Major monetary benefits in form of diesel savings and major monetary costs in form of procurement of electric buses, batteries, chargers and installation of rooftop are considered.

Year	Diesel cost/liter	Annual diesel saving	Cum. Diesel saving	Cost of rooftop	Ebus cost	Battery bank cost	Charger cost	Benefit	Cost	B/c
1	50.00	6515250	6515250	13,260,000	60000000		100000	6,515,250	73,360,000	0.088812
2	52.50	6841013	13356263					13,356,263	73,360,000	0.182065
3	55.13	7183063	20539326					20,539,326	73,360,000	0.27998
4	57.88	7542216	28081542					28,081,542	73,360,000	0.382791
5	60.78	7919327	36000869					36,000,869	73,360,000	0.490742
6	63.81	8315293	44316162			18000000		44,316,162	91,360,000	0.485072
7	67.00	8731058	53047221					53,047,221	91,360,000	0.580639
8	70.36	9167611	62214832					62,214,832	91,360,000	0.680985
9	73.87	9625992	71840823					71,840,823	91,360,000	0.786349
10	77.57	10107291	81948114					81,948,114	91,360,000	0.89698
11	81.44	10612656	92560770			18000000		92,560,770	109,360,000	0.846386
12	85.52	11143289	103704059					103,704,059	109,360,000	0.948281
13	89.79	11700453	115404511					115,404,511	109,360,000	1.055272
14	94.28	12285476	127689987					127,689,987	109,360,000	1.167611
15	99.00	12899749	140589736					140,589,736	109,360,000	1.285568
16	103.95	13544737	154134473		60000000		100000	154,134,473	169,460,000	0.909563
17	109.14	14221974	168356447					168,356,447	169,460,000	0.993488
18	114.60	14933072	183289519					183,289,519	169,460,000	1.081609
19	120.33	15679726	198969245					198,969,245	169,460,000	1.174137
20	126.35	16463712	215432957					215,432,957	169,460,000	1.271291
21	132.66	17286898	232719855			18000000		232,719,855	187,460,000	1.241437
22	139.30	18151243	250871098					250,871,098	187,460,000	1.338265
23	146.26	19058805	269929903					269,929,903	187,460,000	1.439933
24	153.58	20011745	289941648					289,941,648	187,460,000	1.546685
25	161.25	21012332	310953981					310,953,981	187,460,000	1.658775
26	169.32	22062949	333016930	13,260,000	60000000		100000	333,016,930	260,820,000	1.276807
27	177.78	23166096	356183026					356,183,026	260,820,000	1.365628
28	186.67	24324401	380507427					380,507,427	260,820,000	1.458889
29	196.01	25540621	406048049					406,048,049	260,820,000	1.556813
30	205.81	26817652	432865701					432,865,701	260,820,000	1.659634
31	216.10	28158535	461024236			18000000		461,024,236	278,820,000	1.653483
32	226.90	29566462	490590698					490,590,698	278,820,000	1.759525

33	238.25	31044785	521635483					521,635,483	278,820,000	1.870868
34	250.16	32597024	554232507					554,232,507	278,820,000	1.987779
35	262.67	34226875	588459382					588,459,382	278,820,000	2.110535
36	275.80	35938219	624397602			18000000		624,397,602	296,820,000	2.103624
37	289.59	37735130	662132732					662,132,732	296,820,000	2.230755
38	304.07	39621887	701754618					701,754,618	296,820,000	2.364243
39	319.27	41602981	743357599					743,357,599	296,820,000	2.504405
40	335.24	43683130	787040729					787,040,729	296,820,000	2.651576
41	352.00	45867286	832908016		60000000		100000	832,908,016	356,920,000	2.333599
42	369.60	48160651	881068666					881,068,666	356,920,000	2.468533
43	388.08	50568683	931637350					931,637,350	356,920,000	2.610213
44	407.48	53097117	984734467					984,734,467	356,920,000	2.758978
45	427.86	55751973	1040486441					1,040,486,441	356,920,000	2.915181
46	449.25	58539572	1099026013			18000000		1,099,026,013	374,920,000	2.931361
47	471.71	61466551	1160492563					1,160,492,563	374,920,000	3.095307
48	495.30	64539878	1225032441					1,225,032,441	374,920,000	3.26745
49	520.06	67766872	1292799313					1,292,799,313	374,920,000	3.4482
50	546.07	71155216	1363954529					1,363,954,529	374,920,000	3.637988

Table 2: Summary of major costs and benefits

The costs of solar rooftop have been calculated by the financial calculator provided by MNRE website. The costs of electric buses, high storage batteries and charging station have been taken from international market. It is observed that over a 25 year period, the cost of infrastructure is as high as 1874 lakh INR thus indicating it to be a capital intensive project. But the savings in terms of diesel cost assumed far outweighs the cost incurred over a 50 year life span. It can be observed that after the 13th year, the cumulative benefit to cumulative cost ratio assumes a figure of mostly one and above. Till then, for about a period of 13 years the infrastructure cost has to be wholly or partly supported by subsidy, advertisement revenue and ridership fares. In order to bring out evenness in the costs incurred, bear the risks of new technology as well as ease the process of land acquisition, a public private partnership model of BOT may be adopted.

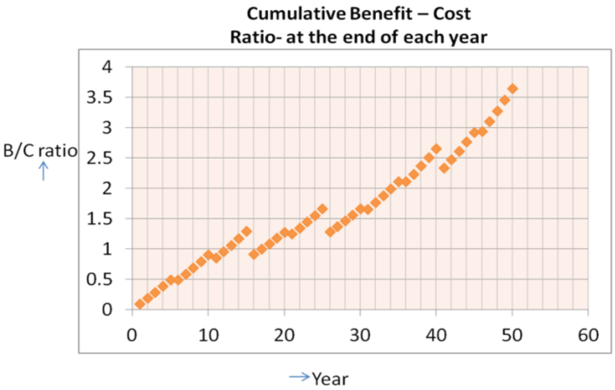

Fig. 1: Cumulative benefit to cumulative cost ratio at end of each year

IV. CASE STUDY: SAMPLE CALCULATIONS FOR ROUTE NO 11 BRTS, AHMEDABAD

Fig. 2: Route No. 11- map

Total fleet	230 buses
AC	184
NON AC	46
Total travel	53570 km/day
Route 11	12 buses
Travel	212 km/day
Parking	Ranip depot

Particular	Timings	Frequency
Peak hours	08:00 -10:30 17:00 - 21:00	10 min
Non Peak hours	06:00 - 07:00 21:00 - 23:00	15 min
Rest	07:00 - 08:00 10:30 - 17:00	12 min

Fig. 3: Calculations

A. Infrastructure Details

It is a circular route (i.e: RTO – Shivranjani – L.d college – Kalupur – Vadaj – RTO). There are total 37 no of stations on this particular route. The idea of setting up the parking infrastructure as the solar charging station depends upon the rooftop area available at the bus depots or the workshops. The BRTS buses are currently parked at the below mentioned depots & their approximate rooftop area is as below.

Parking cum Potential location for Solar system:

- Ranip Depot = 2700 Sq.mt
- Chandkheda Depot = 2500 Sq.mt
- Chandra nagar BRTS Depot = 2500 Sq.mt
- Subhash bridge bus terminal = 4000 Sq.mt (*Under Construction)
- Total = 11,700 Sq.mt rooftop area is available.

B. Energy Demand: Supply calculations

The solar rooftop system design calculations are done & the energy demand for converting all the 12 buses of this route into electric buses is estimated. Similarly based on the rooftop area available the maximum potential energy that can be supplied is also calculated. The calculations are done cconsidering 4 – 5 Kwh of energy generation per day (5.5 sunny hours)

Energy Demand	
For 1 bus :	
Total length	250 km
Energy consumption	1.3 Kwh/km
Total demand	325 Kwh
Solar panels	72 to 82 Kw
Area required	10 Sq.mt/Kw
Total area	720 Sq.mt to 820 Sq.mt
For 3 buses :	
Energy demand	975 Kwh
Area Required	2160 to 2460 Sq.mt

Energy supply	
Area Available	2700 Sq.mt
Solar panels	270 Kw
Energy supply	1215 Kwh
Total Km replaced by E-Bus potentially	848

Fig. 4: Energy Demand

C. Energy Management

The energy management in such a climate dependent model needs to be efficient. In order to make climate independent "Net metering model" has to be used. As the daily sunny hours in the monsoon season will be less , the energy generation would also be less. During this period, the energy has to be imported by the grid, hence the net energy required for the E-buses will be fulfilled year long, & it is called Net-metering. The entire model becomes an on-grid project. The solar charging station would be connected to the grid & will export excess energy generation when maximum sun hours are available. On the other hand the charging station will import the energy from the grid in the monsoon. A policy framework has to be prepared between the government & energy supplying authority(i.e. Torrent power in case of ahmedabad).

V. CASE STUDY: CONCLUSION & FURTHER STUDY

Conclusions drawn from the study are:

- Albeit the fact that the deployment of solar based bus mobility is a capital intensive project, the long term benefits achieved from the project offset the costs both in terms of emissions reduced and fossil fuel value saved.
- A payback period of 15 years would be a fair guess if all cost components were included and this may not be considered high keeping in mind the operational benefits achieved post the payback period.
- Over a period of 50 years, the project may be considered environmentally and financially sustainable.

The study may be deepened further by:

- An exhaustive market study of these items and made sensitive towards the case of the city considered.
- Inclusion of other miscellaneous cost components such as O&M, tracking stations, inverters, ducting etc. and other benefit components such as ridership revenue and advertisement revenue; could constitute a detailed financial analysis.
- Indigenous manufacture of components is sure to bring financially positive results towards the initiative, calling for aggressive R&D in this sector.
- Other financial models such as NPV and use of CDM may be examined.

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