# Energy Autonomous Solar/battery Auto Rickshaw

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## Abstract
*Auto rickshaws are small, three-wheeled vehicles which are used extensively in many Asian countries for transport of people and goods. The vehicles are small and narrow allowing for easy maneuverability in congested Asian metropolises. In India, auto rickshaws are commonly used as taxis, as they are very inexpensive to operate. Despite the apparent advantages in the vehicle design, auto rickshaws present a huge pollution problem in major Indian cities. This is due to the use of an inefficient engine, typically a 2 or 4 stroke, with almost no pollution control. This paper presents a transportation system based on auto rickshaws that operate in an environmentally friendly way. Existing vehicles are to be replaced by an all-electric counterpart redesigned in a manner which improves the efficiency of the vehicle. In addition, a recharging infrastructure is proposed which will allow for the batteries to be charged using mostly renewable energy sources such as solar power. Thus far, we have looked at the existing vehicle and the environment in which it operates, made a model of the vehicle in ADVISOR software, produced a prototype electric vehicle, and investigated recharging infrastructure requirements and designs. In particular, our proposed recharging infrastructure consists of a central recharging station which supplies distribution points with charged batteries. Since we aim to incorporate renewable energies in the infrastructure, we used HOMER software to design a feasible infrastructure system.*

## Keywords
*battery electric vehicle, auto rickshaw, recharging infrastructure, energy storage, renewable energy*

## 1. INTRODUCTION
India is home to over 2.5 million auto rickshaws. In recent years, rickshaw companies have come out with alternative models such as Compressed Natural Gas (CNG) and Liquefied Petroleum Gas (LPG) rickshaws to mitigate the pollution problem caused by traditional petrol models [Rajkumar, 1999]. Two main disadvantages exist with incorporating those technologies on the rickshaws: (1) oil is still added to the chamber in the two-stroke configurations, which adds to the pollution, and (2) LPG and CNG are nonrenewable energy sources. The best way to redesign the rickshaw is to make the main power source renewable. One way to do this is to use an energy system that can take advantage of several sources of renewable energy – namely, electricity.

Rickshaws are an ideal candidate for electrification due to the low speeds of the vehicle and a relatively small distance covered in a day. Therefore, we have set out to make auto rickshaws the example of environmental consciousness in India by replacing the existing hydrocarbon-powered vehicles with electric vehicles and recharge the batteries using mostly renewable energy sources.

We began the project by doing research to determine the rickshaw's role in the culture and economy of India, and the political and cultural atmosphere with regard to issues concerning renewable and sustainable technology. The student team made an in-depth market study in the form of over 700 surveys conducted in two different cities of India, the results of which steered further economic and design research. In addition, GPS data was recorded from a number of rickshaws in major Indian cities. With this information collected, we worked to develop a driving cycle of the auto rickshaw in a typical large Indian city – in this case, Delhi. The driving cycle provided performance demand characteristics, which helped us to develop a model of the actual vehicle in ADVISOR software, and to determine the necessary vehicle parts chosen for the prototype vehicle.

We then converted the stock rickshaw to an all-electric vehicle, fitting the vehicle with a data acquisition unit to gather the relevant data. The vehicle model was then altered accordingly so that the simulated values match the actual performance data. The end result is agreement between the simulated and actual results. Once the model validity was confirmed, the relationship between battery technology used and the resulting motor efficiency was studied in order to analyze the effect on vehicle range.

In addition to the work done on developing the vehicle, the recharge infrastructure was considered in great detail. With the help of HOMER software, we developed a range of designs for a large solar and wind powered battery recharge station, with the option of an assisting LPG generator located in the vicinity of Mumbai, India. The method of transporting the batteries to and from the customer was also investigated. We chose to transport the batteries to and from the customer via all-electric converted trucks to further minimize the pollution. A small truck, TATA ACE, was identified as the vehicle of choice for the transport. The effect on the system efficiency of transporting the batteries was also considered in the design of the mother recharging station. The result is a comprehensive vehicle and infrastructure system design, with much future work entailed.

## 2. DRIVING PATTERN RESEARCH

In the first stage of research, team members investigated the political, economic and technological scene in India today with respect to this vehicle. Surveys helped to identify operator (driver) and passenger demographics, routines and interest in environmentally-friendly transport. This research also isolated what is needed to make the electric rickshaw a success (infrastructure recommendations, technical improvements, political/government support, etc) [Mulhall et al., 2007]. From the surveys, a greater understanding of the economics of the auto-rickshaw operator and the typical usage pattern helped establish the design criteria [Lukic et al., 2007]. In addition to survey data, GPS data was collected to build a driving cycle for the rickshaw. In light of the amount of data collected, we developed two standard driving cycles to replicate the entirety of the driving conditions during daytime and evening hours. The procedure used to arrive at these driving cycles is described in detail in [Lukic at al., 2007]. The driving cycles are shown in Figure 1 and Figure 2.

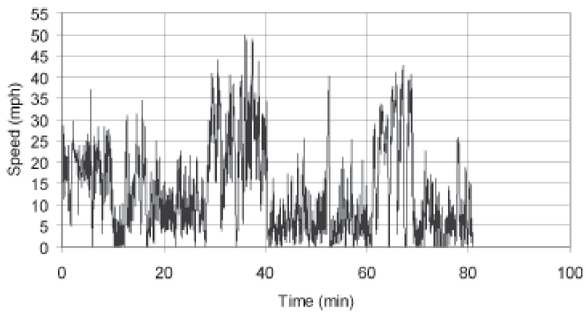


**Fig. 2** Standard evening driving cycle

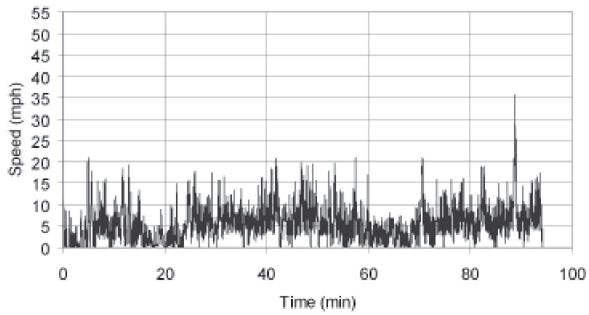


**Fig. 1** Standard daytime driving cycle

## 3. VEHICLE ANALYSIS AND ELECTRIC VEHICLE DEVELOPMENT

The electric vehicle prototype considered here reuses the chassis of the existing rickshaw – in particular the very popular Bajaj vehicle (Figure 3). The vehicle parameters are given in Table 1.

**Fig. 3** Bajaj Auto Rickshaw

**Table 1** Vehicle parameters

| | |
|---|---|
| Outline (LxWxH) | 2.67x1.24x1.69 m |
| Clearance | 0.2 m |
| Frontal Area | 2.09 m2 |
| Coeff. of drag | 0.5 |
| Center of veh. mass | 0.4 m |
| Wheel Base | 1.07 m |
| Kerb weight | 290 kg |
| Engine | 35 kg |
| Transmission | 15 kg |
| Battery | 10 kg |
| Tank | 10 kg |

The existing engine, transmission and differential were removed and replaced by two brushed permanent magnet electric motors. The two motors were installed in parallel to power the rear wheels independently as seen in Figure 4. Four twelve-volt Nautilus Gold deep cycle marine batteries were connected in series providing a total of 48 Volt output to the motors. These batteries were chosen as an inexpensive option which would be

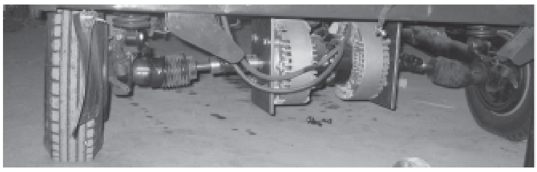

**Fig. 4** Two Etek motors mounted on the autorickshaw

readily available in India.

Two motors were used because such a setup eliminates the losses in the differential. In addition, the setup allows for the testing of the electronic differential concept [Gair et al., 2004; Perez-Pinal et al., 2007]. The introduction of the electronic differential, where the current is split unevenly between the motors when the vehicle is taking a turn, will make the vehicle more stable when turning, as well as improve the efficiency. At this stage, the motors were given the same current command. In the future, the advantages of implementing the electronic differential will be evaluated.

The all-electric vehicle was constructed and tested. The test results in conjunction with the known vehicle parameters were used to adjust the model in ADVISOR software, which was then used to evaluate the benefit of implementing certain improvements to the vehicle. Such a study was performed to investigate the effect of passenger load, driving pattern and battery chemistry on the range of the vehicle. More information about the modeled batteries is used later in the paper. The results are presented in Figure 5. Note that the solid horizontal lines represent the average of light and heavy traffic, while the vertical lines represent the actual heavy and light traffic range.

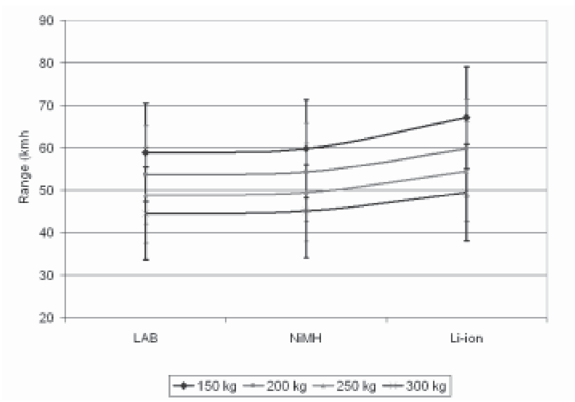


**Fig. 5** Summary of the effect of passenger weight on the range with error bars accounting for the variation in range depending on the driving style (daytime or evening)

## 4. RECHARGING INFRASTRUCTURE REQUIREMENTS

We established several goals for the design of the recharge infrastructure. Firstly, we set goals of the operation: the battery swap process should appear as quick as petrol refueling in the eyes of the rickshaw driver, and should be as efficient and effective as possible. Secondly, the economic goal in designing this system is to maximize the amount of energy to be produced by renewable energy sources, while simultaneously minimizing the time to recover the invested money. Thus we decided to go with a centralized recharging station. The fact that the batteries are charged at a central location allows for easy maintenance by trained staff, thus ensuring longevity of the packs. In addition, the placement of renewable sources at a centralized location ensures these resources will be operated in an efficient manner. Thirdly, we wanted to eliminate the additional stress on the grid; as the electric power grid in India is either weak or non-existent in rural areas, the additional stress for transportation energy is unjustified.

Several options were considered for transferring batteries from the drop-off location to the central station: (1) use of the existing electrical grid (2) construction of a separate electrical distribution grid (3) transport of batteries by trucks. We decided to avoid using the existing electricity grid for various reasons: we aim to (1) insure that the energy used to charge the batteries is clean, (2) add no extra burden on an already weak grid, and (3) add possibilities for remote locations which have no access to the grid. On the other hand, the construction of a separate grid is prohibitively expensive.

Research and investigation into the current petrol (gas), Compressed Natural Gas (CNG) and Liquefied Petroleum Gas (LPG) stations revealed models of the possibilities for the supporting infrastructure for EV auto rickshaws, as well as incorporating solar technology in current and future stations. Based on this research the refueling system is envisioned to operate as shown in Figure 6. Once the batteries are charged, they are transported on trucks to "daughter" stations. These daughters are existing gas stations where the batteries can be stored until the rickshaw driver comes for a replacement. Finally, the charged battery pack is installed into the rick-

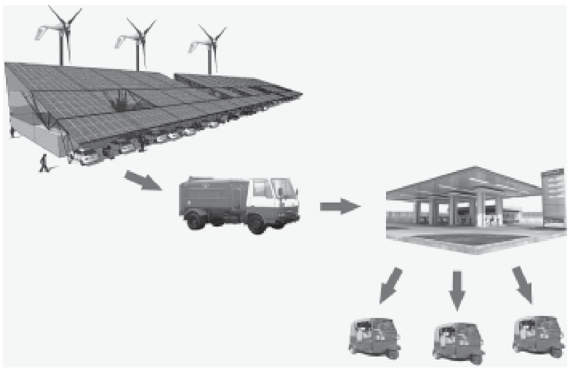

**Fig. 6** Recharging infrastructure layout

shaw, while the discharged pack is taken back to the mother recharging station. We used HOMER software to find the most cost effective way of supplying energy to the batteries. In addition, once the layout of the station is known, we calculated the average amount of power produced by renewable energy sources.

For a complete efficiency analysis of the infrastructure design, we deemed it necessary to investigate the trucks used for battery transport. To do this, we determined that the use of all-electric converted trucks is ideal, specifically the TATA ACE trucks shown in Figure 8. Due to the short distances considered, the all-electric option is viable and desirable. In addition, the large number of batteries in use by the trucks can be used for load leveling at the recharging station.

The battery delivery system and the location of the mother and daughter stations are laid out as shown in Figure 7. The issue here is to design a method to service all of the daughter stations. It was shown that regardless of the branch taken by the truck, the truck does not cover more than 10 km going one way. Therefore, the size of the truck battery pack can be sized accordingly. In addition, the cost of transporting the batteries on a per mile basis can be calculated.

We chose the Tata ACE truck shown in Figure 8 because of its small size and maneuverability. Table 5 shows the specifications of the vehicle. This allows economical trips to one of the daughter stations each time. The truck battery pack needs to be kept small to minimize the "dead weight" that the vehicle is carrying. Based on the layout of the recharging infrastructure, it is apparent that the vehicle only needs to cover a distance of less than 20 km between stops at the mother recharging stations. This results in a goal to size the batteries so that the vehicles can achieve a reasonable range while minimizing the battery pack size. Therefore, the pack size was chosen to be large enough so that the vehicle can cover at least 20 km with a full payload, regardless of the driving conditions (heavy or light traffic). Note that the vehicles will be simulated over the driving cycles developed for the rickshaw. Ideally, GPS information would be collected from trucks used for LPG delivery. However, at this stage the rickshaw driving cycle approximation is an acceptable one.

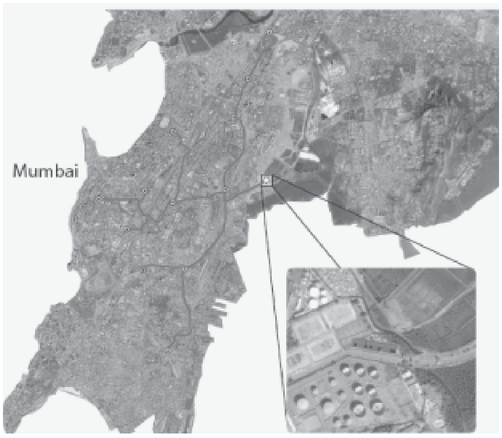


**Fig. 7** Proposed locations of mother and daughter stations in Mumbai, India

**Table 2** Conventional TATA truck specifications

| Parameter | Value |
|---|---|
| Overall Length | 3800 mm |
| Width | 1500 mm |
| Wheel base | 2100 mm |
| Overall height | 1820 mm |
| Track Front | 1300 mm |
| Track Rear | 1320 mm |
| Min Turning Circle Diameter | 8600 mm |
| Max. GVW | 1550 kg |
| Kerb weight | 805 kg |


**Fig. 8** TATA ACE truck

**Table 3** Electric truck specifications

| Parameter | Value |
|---|---|
| Battery Type | Lead Acid |
| Pack Capacity | 120 Ah |
| Pack Voltage | 100 V |
| Motor Type | Brushed DC |
| Motor Peak Power | 50kW |
| Kerb weight (w/o pack) | 570 kg |
| Pack Weight | 320 kg |
| Gross weight with 5 pack load | 1700 kg |

## 5. RECHARGING STATION LOAD ESTIMATION

To be able to estimate the operation and optimize the size of the recharging station, the daily energy demand from the station needs to be computed. In this section we try to estimate this load based on some assumptions of how the rickshaws will be operated and how the batteries will be transported.

One parameter which will have a major influence on the energy demand is the battery technology. Based on extensive research, three batteries representative of the three prevalent battery chemistries are considered. Their parameters are shown in Table 4. According to ADVISOR simulations, a battery pack twice the size of that of the rickshaw is sufficient to cover the target distance. This means that a battery pack that has an energy capacity of 12kWh is sufficient for one trip, and the weight of this pack is used as the minimal "dead weight on the truck". The results are summarized in Table 5. Note that the figure for the energy required for each transport is arrived at with the following assumptions:

- Truck travels an average distance of 8km to the daughter station (16km per trip)
- The truck can be loaded up to 1130kg (maximum truck payload)
- Truck is considered to travel 50% of the time in low and 50% of time in high traffic conditions

Note that the average energy required for each transport is most likely overestimated, since the vehicle will mostly be driven in light traffic conditions where less energy is used per mile. At this stage, each mother station will be designed to service a 10 mile radius with 600 vehicles. Based on these the size of the electrical load on the mother station can be approximated. To calculate the load on the power plant certain assumptions about the power plant were made based on the above discussion:

- Average weight load on the vehicle is 200kg
- The vehicle covers an average daily distance of 100km

**Table 4** Battery pack specification

| Battery Characteristic | Lead-Acid 40kg, 1500Wh, 11L | Ni-MH 11.6kg, 750Wh, 5L | Lithium-ion 1.5kg, 225Wh, 0.6L |
|---|---|---|---|
| Battery Cell Type | Conventional Plates-Based | Prismatic HEV20 | Cylindrical |
| Module Type | 12V120Ah | 12HEV60Ah | 3.6V60Ah |
| Number of Modules | 4 | 8 | 28 |
| Nominal Capacity | 120Ah | 120Ah | 120Ah |
| Nominal Pack Voltage | 48V | 48V | 48V |
| Total Energy | 5.72 kWh | 6 kWh | 6.2 kWh |
| Specific Energy | 35 Wh/kg | 65 Wh/kg | 150 Wh/kg |
| Energy Density | 135 Wh/L | 150 Wh/L | 380 Wh/L |
| Pack Weight | 160 Kg | 93 kg | 42 kg |
| Pack Volume | 44L | 40L | 19L |
| Cost per kW | $ 200 | $ 700 | $ 1000 |

**Table 5** Energy expended for battery transportation

| | LAB | NiMH | Li-ion |
|---|---|---|---|
| Max payload on truck (kg) | 1130 | 1130 | 1130 |
| Actual payload on truck when fully loaded (kg) | 1120 | 1116 | 1092 |
| No of packs on truck when fully loaded (kg) | 5 | 10 | 24 |
| Truck maximum Range high traffic (km) | 20.5 | 21.2 | 21.5 |
| Truck maximum Range low traffic (km) | 36.9 | 37.4 | 37.7 |
| Average Range (km) | 28.7 | 29.3 | 29.6 |
| Average mother-daughter distance (km) | 8 | 8 | 8 |
| Energy stored in the pack (kW) | 11.4 | 12 | 12.4 |
| Energy per battery transportation (W) | 1672.47 | 819.113 | 337.838 |

**Table 6** Total daily energy expenditure by the all-electric rickshaw

| | LAB | NiMH | Li-ion |
|---|---|---|---|
| Unit energy expenditure (Wh/km) | 111.9 | 110.7 | 100.2 |
| Daily distance covered (km/day) | 100 | 100 | 100 |
| Daily energy expenditure (Wh) | 11,194 | 11,070 | 10,025 |
| No. of Daily Transports (based on 100km/day) | 1.86 | 1.84 | 1.67 |
| Transport Energy Expenditure (Wh) | 1672 | 819 | 337 |
| Daily Transport energy (based on 6kWh pack) | 3110 | 1507 | 563 |
| Total Daily Energy Expenditure per rickshaw (Wh) | 14,304 | 12577 | 10588 |
| No. of Rickshaws | 600 | 600 | 600 |
| Total Load per day | 8,582,400 | 7,546,200 | 6,352,800 |
| No. of packs in use | 1,440 | 1,265 | 1,060 |
| "Transmission" efficiency | 78.3% | 88% | 94.6% |

- The driving is done half in heavy and half in light driving conditions (average range).

Based on these assumptions, the total daily energy expenditure per rickshaw can be calculated for each of the battery technologies.

The load on the recharging station should be distributed in such a way to match the output of the solar array. At the same time, the amount of energy put into the batteries needs to balance the energy used by the rickshaws and the battery transportation buses within 24 hours. On average, the amount of power produced by the mother station will match the energy used by the auto rickshaws plus the energy needed for transport.

## 6. MOTHER STATION OPTIMIZATION

As described above, the mother station will have to produce enough energy to power 600 rickshaws as well as to provide the additional energy lost in transportation. Based on the calculations above, we have arrived at the total daily energy requirements for the recharging station as a function of the battery technology used.

As was noted earlier, it was decided that the mother station will not be connected to the grid. Therefore the energy sources have to be sized in such a manner as to ensure that the station will always have enough energy to supply the daily requirements. The mother station topology chosen for investigation is shown in Figure 9. The system was modeled in HOMER software. The software was used to optimize the size of each of the components.

It was decided that the use of both wind and solar energy would be beneficial since the availability of power form these two sources is somewhat complementary. In addition, there is a need for a power source when the availability of the renewables is not sufficient. It was decided to utilize a propane powered generator. Note that other more environmentally friendly options are also possible, such as fuel cells. In this case, a regenerative (reversible) fuel cell will allow the reduction of the size of the battery bank.

### *6.1 Component models*

The wind turbine data was obtained from a 7.5 kW Bergey Windpower turbine assuming turbine height of 25m. The curve is shown in Figure 10. The solar panels are modeled using an efficiency value shown in Figure

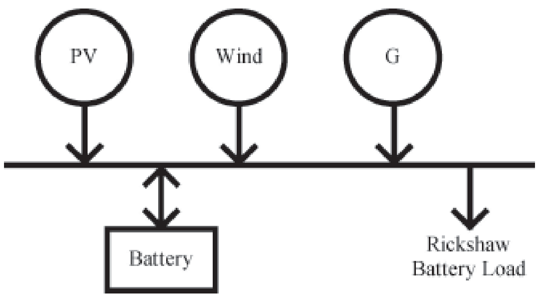


**Fig. 9** Mother recharging station architecture

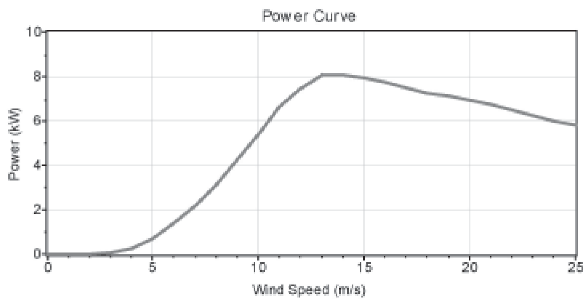


**Fig. 10** 7.5 kW bergey windpower turbine characteristics

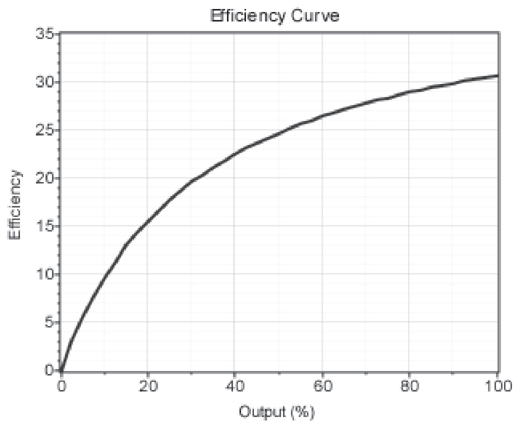


**Fig. 11** Solar panel characteristic

11. The efficiency is derived using two simple assumptions:

- A two-axis tracking system is employed ensuring that radiation is perpendicular to the solar panels
- Factors such as soiling of the panels, wiring losses, shading, aging, and temperature-related effects are all lumped into a single derating factor.

### *6.2 Environmental conditions*

To be able to predict the power production of the PV's and the wind turbines, the environmental conditions at the recharging station need to be determined. The average values on a monthly basis for global horizontal radiation and the wind speed at 10m above ground are shown in Figure 12 and Figure 13 respectively. Solar irradiation is straightforward to measure, and is consistent over larger areas. The values used in this study are derived from the information available in HOMER, given the longitude and latitude of Mumbai. Wind speed is much harder to predict, as it is dependent on the precise location, and obstacles present around the chosen location. Therefore the average monthly wind speeds are derived from HOMER. The daily variations are then estimated using data available and the wind speed at 25m can be extrapolated using procedures presented. [Sorensen, 1998].

### *6.3 Charging station component size optimization*

To optimize the size of the recharging station components, the following procedure is used:

(1) Determine the ratio of wind to solar capacity which minimizes the month-to-month renewable energy availability. This number will be computed based on historical resource availability data

(2) Set load profile to match the profile of renewable energy availability and still meat the daily energy demand

(3) Set the size of renewable resources to meet the load during the month when renewable resources are at

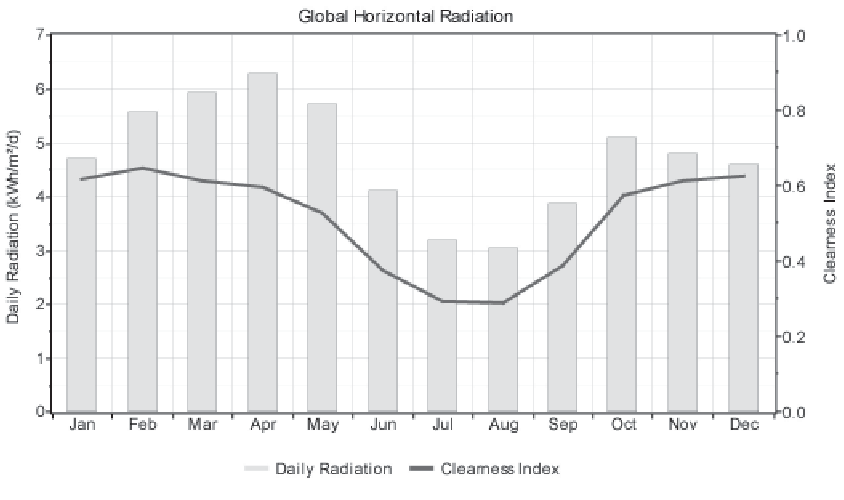


**Fig. 12** Average solar irradiation

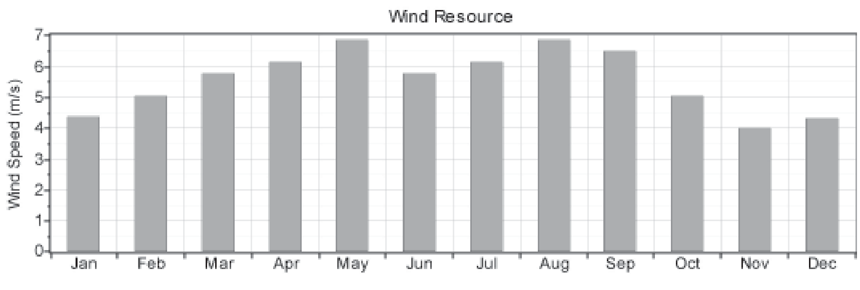


**Fig. 13** Average wind speed

their peak

(4) Vary the size of the renewable resources so as to minimize the excess electricity produced.

#### *6.3.1 Determining the ratio of wind to solar capacity*

The first task was to determine the relative size of the PV array to the size of the wind turbine. It was decided that the relative size of these two components should be chosen such that their total power output varies as little as possible. It was found that $\frac{P_{PV}}{P_W} = \frac{100}{73}$ gives the least variation on a monthly basis, as shown in Figure 14. Note that the fraction is based on minimizing the variability on a month-to-month basis. There are daily peaks of power produced by renewable resources which would much exceed the daily average. As the load is somewhat flexible in terms of instantaneous power supplied, the load profile can follow the power supplied by the renewable resources. Therefore, the batteries will act as a dynamic load which follows the power supply.

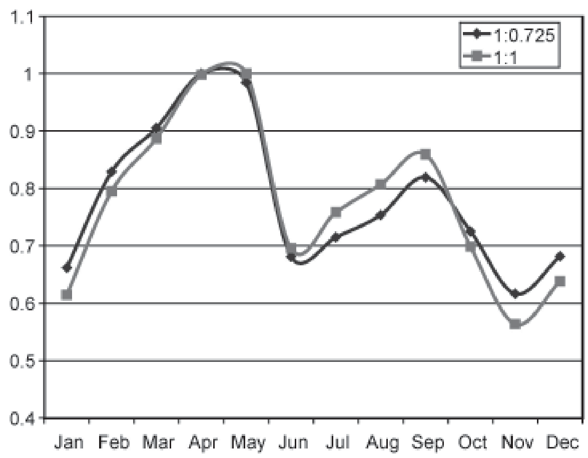


**Fig. 14** Minimizing renewable energy fluctuation by optimizing the wind to PV peak power capacity ratio

#### *6.3.2 Determining the load profile*

In light of the fact that the load can be made to follow the availability of the renewables, and that the availability of renewable resources can be predicted fairly well for a 24-hour period, we can optimize the operation of the off-grid mother recharging station. The goal is to set the operation of the generator at a fixed value that will ensure that the batteries are fully charged by the end of the 24 hour period. The generator power can then be set using equation (1).

$$\overline{P_{GEN}} = \frac{\int_{24hrs} P_{RENEWABLE} - P_{LOAD}}{T_{RECHARGE}}$$

Results of such a control strategy are presented in Figure 15 for April 1-3 given $T_{RECAHRGE}$=24hrs. From equation (1) it is apparent that if the renewable production exceeds the amount of energy the load can absorb within a day, some of the produced energy will go to waste.

#### *6.3.3 Sizing the off-grid recharging station*

The next step was to determine the actual size of the PV and the wind turbine to maximize the renewable fraction while minimizing excess electricity production due to overcapacity. One method would be to size the renewable resources so that they meet all of the demand during the months of April and May. This would be the maximum size of the renewable resources, as larger renewable resources would produce substantial losses in the months of April and May. At the same time, care should be taken to ensure that just enough power is delivered to the batteries on a per day basis. Therefore,

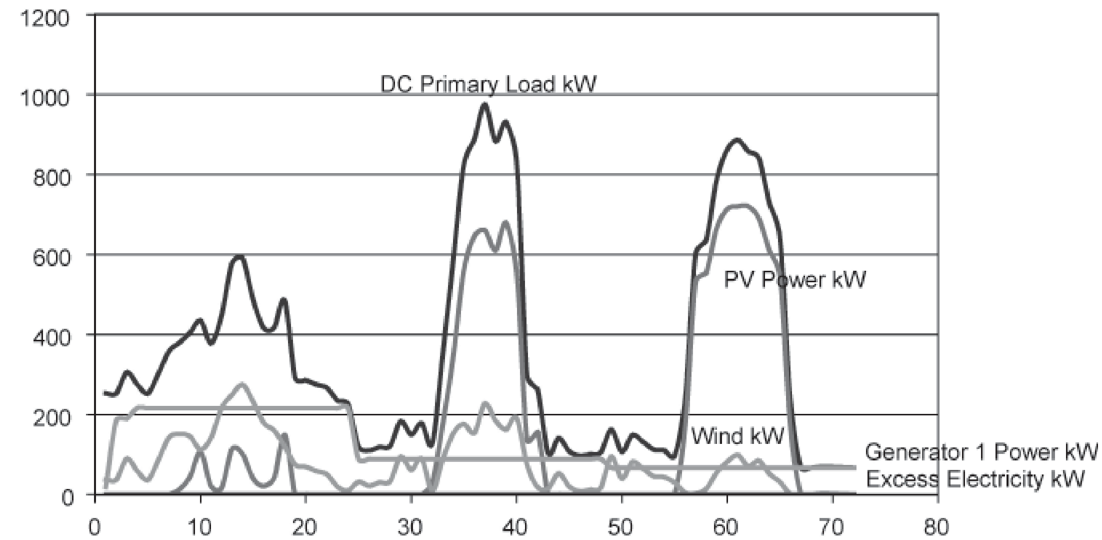


**Fig. 15** System operation for April 1-3

**Table 7** Case study for sizing the mother station

| | Size (kW) | | | Output (MWh/yr) | | | Excess | | |
|---|---|---|---|---|---|---|---|---|---|
| | PV | Wind | Gen | PV | Wind | Gen | % | MWh | % Renewable |
| Case 1 | 600 | 438 | 350 | 1288 | 1128 | 896 | 4.82 | 159 | 73.0 |
| Case 2 | 540 | 394 | 350 | 1159 | 1031 | 1053 | 2.74 | 89 | 67.5 |
| Case 3 | 480 | 358 | 350 | 1030 | 914 | 1246 | 1.11 | 35 | 61.0 |

the generator must be sized to provide sufficient power during November when least renewable power is available. Based on these constraints, three cases are considered in Table 7.

In addition, the size of the additional energy storage is studied. The goal of including the UPS is to minimize the renewable energy that will not be absorbed by the load. From Figure 16 it is apparent that increasing the size of the UPS will not reduce the excess energy produced. The reason is that most of the excess energy production occurs on consecutive days. This means that the load shifting capability of the energy storage system is used only once.

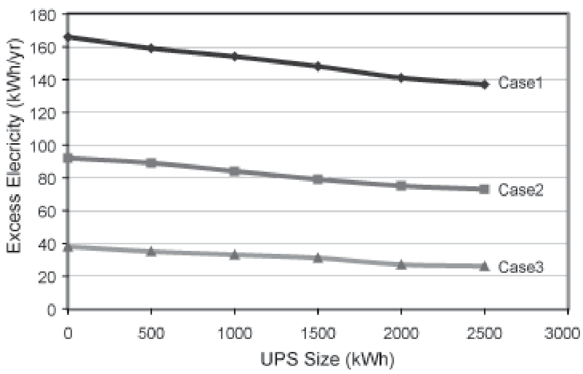


**Fig. 16** Effect of the size of the additional energy storage on the excess electricity produced

## 7. CONCLUSION

In this paper, we have investigated the use of all-electric auto rickshaws for transportation in Asia. The all-electric vehicle was designed and tested, and a model of the vehicle was developed for use in system level simulations. In addition, we presented the operation of the entire transportation infrastructure including an off-grid recharging "mother" station. It was shown that the mother station with 480kW PV, 358kW wind turbine, and 350kW propane generator can power 600 auto rickshaws while producing 61% of its energy using renewable resources. In the future, a grid connected mother station will be investigated.

## Acknowledgement

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