Electric motorcycle charging station powered by solar energy

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Abstract. This research proposes a design and verification of an off-grid photovoltaic system (PVS) for electric motorcycle charging station to be located in King’s Mongkut’s University of Technology Thonburi, Bangkok, Thailand. The system is designed to work independently (off-grid) and it must be able to fully charge the batteries of a typical passenger electric motorcycle every evening. A 1,000W Toyotron electric motorcycle is chosen for this study. It carries five units of 12.8V 20Ah batteries in series; hence its maximum energy requirement per day is 1,200Wh. An assessment of solar irradiation data and the Generation Factor in Bangkok, Thailand suggests that the charging system consists of one 500W PV panel, an MPPT charge controller, 48V 150Ah battery, a 1,000W DC to AC inverter and other safety devices such as fuses and breakers. An experiment is conducted to verify the viability of the off-grid PVS charging station by collecting the total daily energy generation data in the raining season and winter. The data suggests that the designed off-grid solar power charging station for electric motorcycle is able to supply sufficient energy for daily charging requirements.

1. Introduction
Motorcycles are by far the most popular vehicles in Thailand. There are over 20 million motorcycle registrations in Thailand in 2016, which are approximately 4 times of 4-wheel vehicles [1] and the number of motorcycles in Thailand has grown steadily every year as shown in figure 1. The huge number of vehicles in Thailand caused an increase in carbon dioxide (CO₂) emission and resulting in global warming. The CO₂ emission data from transportation in 2016 collected by Thailand greenhouse gas management organization (TGO) stands at 71.866 million tons- CO₂ as shown in figure 2 [2].

Renewable energy is a way to reduce CO₂ emission, because it is generated from clean resources. Current renewable energy technologies provide a variety of options such as solar, wind, geothermal heat, biomass, biofuels and hydroelectricity. Global trends in renewable energy investment [3] have also seen a steady increase since 2004 in both developed and developing countries as shown in figure 3.
Figure 1. Number of vehicle registered in Thailand 2012-2016.

Figure 2. CO₂ emission from energy consumption by sector in 2016

The global trends in new investment in renewable energy [3] show that Thailand is in the pole position in Non-Organization for Economic Co-operation and Development (non-OECD) in the Asia-Oceania countries with the renewable energy investment totaling USD 1.4 billion as shown in figure 4.

Figure 3. Global new investment in renewable energy developed and developing countries, 2004-2016.

Figure 4. Renewable energy investment in non-OECD Asia (excluding China and India) in 2016 and growth in comparison to 2015.

Given the large number of motorcycles in Thailand its likely a continuation to remain high due to the compactness, low cost and convenience using for both in the cities and rural areas, there is an opportunity to create an impact in reducing the carbon footprint related to their use by promoting the use of electric motorcycles. Moreover, the carbon dioxide emission reduction could achieve during the charging process by utilizing renewable energy.

This research focuses on the design of a photovoltaic system (PVS) to charge an electric motorcycle on a daily basis without using electricity from the grid (off grid system). Solar energy is selected to power the charging station because of the falling costs of PV panels, inverter and installation to below half of the average costs in 2009 as shown in figure 5 [4]. The proposed solution explored in this work is similar to the successful work in [5] which designs a rooftop grid-connected PVS charging station for electric vehicle with 10kW PV panels in the Netherlands. This work shows that a 10kW PVS is able to reduce grid energy exchange by 25%.
2. Methodology

This research attempts an off-grid PVS design for an electric motorcycle charging station, which must be able to fully charge the batteries of an electric motorcycle on a daily basis. The designed PVS contains 4 main devices: PV panels, charge controller, storage battery and inverter [6, 7] as shown in figure 6.

2.1. Total demand energy requirement

This section describes the methodology to determine the energy requirement by an electric motorcycle in this study. The electric motorcycle model is Toyotron TX-1 as shown in figure 7 and its specifications as shown on table 1.
### Table 1. Toyotron TX-1 specifications.

| Item          | Specification                                      |
|---------------|----------------------------------------------------|
| Motor         | Integrated rear hub 2,000 Watt high torque         |
| Battery       | 60 Volt (12V x 5)                                  |
| Wheels        | 12 inches Alloy                                    |
| Climbing      | 20-25 degrees                                      |
| Speed         | 50-60 km/h                                         |
| Range         | 1 person: 50-80 km                                 |
|               | 2 person: 40-60 km                                 |
| Brakes        | 180 mm. disk and drum rear                         |
| Dimensions WxLxH (mm.) | 460 x 1,920 x 1,150                              |
| Road clearance| 150-190 mm.                                        |
| Weight        | 95 kg                                              |

The Toyotron TX-1 electric motorcycle contains 5 LiFeMnPO$_4$ Prismatic 12.8V 20Ah batteries in series to make a 60V 20Ah battery. The battery specifications are shown on table 2.

### Table 2. Battery specifications.

| Item          | Specification                                      |
|---------------|----------------------------------------------------|
| Voltage       | 12.8V (working) /15.2V (peak) /10V (cut-off)       |
| Capacity      | 20 Ah                                              |
| Cycle life    | > 1000 cycles (80% of initial capacity at 0.2C rate, IEC Standard) |
| Energy density| 85.33 Wh/kg                                        |
| Charging rate | 1C rate (20A) recommended/ 3C rate (60A) Maximum   |
| Max discharge rate | Constant discharge current 40A (2C rate) Impulse discharge current (<10 sec) 200A (10C rate) |
| Dimensions WxLxH (mm.) | 78.5 x 180 x 168                               |
| Weight        | 3 kg.                                              |

The total energy requirement is equal to maximum energy storage of battery of electric motorcycle. Ohm’s law (1) states that

\[
V \times A = W
\]

where \( V \) is voltage, \( A \) is current and \( W \) is power in Watts. The maximum energy storage of the Toyotron electric motorcycle battery is 1,200 Wh. However, there is loss of energy in the PVS from the devices, hence a need to allow for extra energy production. A safety factor of 1.3 (assume 30% greater than
requirement because losses in system) is selected in the design [8]. Therefore, the maximum possible total energy requirement is 1,560 Wh/day.

In actual use, the electric motorcycle is rarely utilized until its battery is completely drained. Daily usage of electric motorcycle using data [9] shows a data of energy consumption in each day for 20 days by volunteers using the electric motorcycle in their regular routine, i.e. traveling between home and work. The average daily energy consumption is 842.25 Wh. The data is shown on table 3.

| Day | Energy (Wh) | Day | Energy (Wh) |
|-----|-------------|-----|-------------|
| 1   | 687         | 11  | 1,013       |
| 2   | 859         | 12  | 771         |
| 3   | 488         | 13  | 1,153       |
| 4   | 1,000       | 14  | 778         |
| 5   | 1,000       | 15  | 879         |
| 6   | 644         | 16  | 849         |
| 7   | 780         | 17  | 848         |
| 8   | 767         | 18  | 967         |
| 9   | 878         | 19  | 984         |
| 10  | 876         | 20  | 624         |

Table 3. Daily energy consumption of an electric motorcycle in real life usage over 20 days

2.2. PV sizing
This section provides a PV panel selection methodology. Different sizes of PV panels will produce different amount of power. The total peak Watt (Wp) produced depends on the size of the PV panel and climate of each location. The important factor for calculating the appropriate PV panel size is the peak sun hour. Peak sun hour (PSH) is an average daily solar insolation. It is the maximum value for a certain number of hours at 1 kW/m$^2$ of solar irradiation (peak solar radiation). In Thailand, average monthly PSH is approximately 4-6 hours per day, but in July, 2015 has the lowest average PSH of 3.5 hours per day [6]. The peak Watt of the PV panel can be calculated by equation (2)

$$Wp = \frac{\text{Load(Wh/day)}}{\text{PSH}(h/day)} \quad \text{(2)}$$

In this case, the Load is the maximum possible total energy requirement of 1,560 Wh/day and the worst case of PSH is 3.5 h/day. The Wp of PV is 445.714≈500 W, therefore the selected size of PV panel for this study is 500 Wp. This research has received an industrial support from Stars Microelectronics (Thailand) Public Company Limited who has provided TenKSOLAR Apex 500W PV module for use in this research. The PV panel specifications are given in table 4.
### Table 4. TenKSOLAR Apex 500W PV module specifications

| Item                              | Specification          |
|-----------------------------------|------------------------|
| Peak power ($P_{max}$)            | 500 W                  |
| Module size                       | 2,018 x 1,298 mm.      |
| Cell type                         | Mono-Crystalline (PERC)|
| Power tolerance                   | ±3%                    |
| Module efficiency                 | 19.1%                  |
| Max current output ($I_{MP}$)     | 9.1 A                  |
| Operating DC voltage ($V_{MP}$)   | 35-59 V                |
| Operating temperature range       | -40 to 85 °C           |
| Module NOCT                       | 46 °C                  |
| Temperature coefficient ($P_{MP}$)| -0.42% / °C            |

2.3. **Storage Battery sizing**

This section describes the method to determine the suitable size of storage battery. The suitable battery type for use in the PVS is a deep cycle battery. Deep cycle battery is designed for being discharged to low energy and be rapidly recharged more cycles than standard lead acid batteries. The storage battery should be large enough to store sufficient energy to operate over 3 days, even at night and on cloudy days. Battery sizing can be calculated by equation (3)

$$\text{Battery capacity (Ah)} = \frac{\text{Total appliances use}}{\text{battery efficiency} \times \text{DOD} \times \text{system voltage}} \times \text{Days of autonomy} \quad (3)$$

where total appliances use in this case is the requirement from Toyotrton electric motorcycle battery of 1,200 Wh/day. The battery efficiency is approximately 0.80-0.95. The depth of discharge (DOD) is used to describe how deeply the battery is discharged. Fully charged battery is 0% of DOD and fully discharged battery is 100% of DOD. DOD is a factor to be considered for sizing the battery because the DOD can affect to battery life span.

In this case, a conservative DOD value of 50% is chosen. There are three possible values of system voltage: 12V, 24V and 48V depending on peak power voltage of PV. The 48V system is chosen because it must be compatible with the PV panel operating DC voltage, which in this case is between 35-59V. Days of autonomy represent the number of days where no additional energy is supplied from the PV panel (completely no sun). In this case, the system is designed to have 3 days of autonomy. Therefore, the suitable battery size from is 48V 187.5Ah or 48V 200Ah.

2.4 **Charge controller sizing**

This section describes the methodology to determine the appropriate charge controller size selection. The charge controller is typically rated against current and voltage capacities. The solar charge controller must match the voltage of PV panel and the storage batteries. The size of charge controller can calculate by equation (4).
\[ I_{\text{charge controller}} = \frac{W_p}{V_{\text{system}}} \]  

where \( W_p \) of the PV panel is 500W and \( V_{\text{system}} \) is 48V. Therefore, the charge controller size is 10.42A or 11A. The design should include a 30% safety margin, hence, the charge controller size should be greater than 14.3A.

2.5. Inverter sizing
This section describes the inverter sizing selection. The inverter is a device to convert DC power input to AC power output. The inverter must have the same nominal voltage as the battery it is connected to. For off-grid systems, the inverter must be large enough to handle the maximum amount of power usage when all appliances are in use at the same time. The inverter size should be 25-30% higher than the total combined power of all appliances for safety. The size of the inverter can calculate by equation (5).

\[ W_{\text{inverter}} = \text{Total watt of all appliances use} \times \text{additional safety} \]  

where the total combined power of appliances is from the Toyotron electric motorcycle charging adapter. The adapter requires 220V AC 3.5A and an additional safety factor of 1.3 (30%). The suitable inverter size is 1,000W.

2.6. Collecting data
Solar irradiation data with 14 degree tilt angle from horizontal and facing South as the latitude of Bangkok, Thailand is 13.73617 North [6] is used in this study. The solar irradiation data is collected with the use of Kipp&Zonen CM11 pyranometer whose specifications are shown in table 5. The records show solar irradiation in 30 second time steps and average data to solar irradiation per day. Equation (6) shows the energy production from PV enough for energy demand can use solar irradiation data and calculate by equation (6)

\[ E = SI \times A \times \eta_{\text{pv}} \times \eta_{\text{system}} \]  

where \( E \) denotes the energy produced from PV, \( SI \) is solar irradiation, \( A \) is PV panel area (m\(^2\)), \( \eta_{\text{pv}} \) is PV efficiency and \( \eta_{\text{system}} \) is system efficiency.

Collecting daily 14 degree tilt to horizontal solar irradiation data by Kipp&Zonen CM11 pyranometer from 1 July 2016 to 31 December 2016. The solar irradiation data in figure 8 shows a variation over the 6 months because of the seasonal changes between the raining season and winter in Thailand.
Figure 8. Solar irradiation per day from 1 July to 31 December 2016.

Table 5. Kipp&Zonen CM11 specifications

| Item                               | Specification                                |
|------------------------------------|----------------------------------------------|
| Spectral range                     | 310-2,800 nm (50% points)                    |
|                                    | 340-2,200 nm (95% points)                    |
| Sensitivity                         | Between 4 and 6 µV/Wm²                       |
| Impedance                           | 700-1,500 Ohm                                |
| Response time                       | < 15 s (95% response)                        |
|                                    | < 24 s (99% response)                        |
| Non-linearity                       | < 0.6% (< 1,000 W/m²)                        |
| Temperature dependence of sensitivity | < 1% (-10 °C to 40 °C)                      |
| Directional error                   | < 10 W/m² (beam 1,000 W/m²)                  |
| Tilt error                          | < 0.25% (beam 1,000 W/m²)                    |
| Operating temperature               | -40 °C to 80 °C                              |
| Zero- offset due to FIR (Ventilated with CV 2) | < 7 W/m² at 200 W/m² net thermal radiation |
| Zero-offset due to temp. changes    | < 2 W/m² at 5 K/h temp. change               |
| Viewing angle                       | 2π sr                                        |
3. Results and discussions
From collected daily solar irradiation data can be calculated to find produced energy of PVS by equation (6), where $SI$ is solar irradiation, $A$ is $2.619364$ m$^2$ (from PV specifications), $\eta_{PV}$ is $19.1\%$ (from PV specifications) and $\eta_{system}$ is $70\%$ (30% loss from assumption). The results of produced energy calculation as shown in figure 9.

![Figure 9. Comparison between energy from PVS, maximum demand (1.2 kWh) and average energy in daily use (0.84225 kWh).](image)

Figure 9 shows that over 90% of the records, the calculated daily energy produced by the PVS has exceeded the maximum demand. The maximum record daily energy production is $2.57$ kWh on 6 September, while the minimum energy production is $0.44$ kWh, which is observed on 16 December. The average value of daily energy production in this period is $1.79$ kWh. There are only 18 days from 184 collecting data days where the produced energy is lower than the maximum demand.

Considering days of insufficient energy production (lower than $1.2$ kWh), the maximum number of days with insufficient energy that has been observed is 3 days in a row between 6-8 December. This is the only instance. When considering the average energy in daily use, there are only 3 separate days where insufficient energy is observed.

Considering accumulative energy of storage battery, this research design for 3 days of autonomy. The possible maximum storage energy of 48V 200Ah battery is $9.6$ kWh. The battery is charged in daytime and discharged for supply to electric motorcycle in nighttime. The accumulative energy of storage battery was shown in figure 10.

![Figure 10. Accumulative energy of storage battery over 184 days.](image)

From figure 10, the system starts with a fully charged storage battery of $9.6$ kWh on the first day and is discharged to electric motorcycle of $1.2$ kWh every night. The system is charged again in daytime from the PVS. The lowest accumulative energy of the battery of $7.34$ kWh is observed on day 169 (16 December) which is $23.54\%$ of DOD when compare with $50\%$ DOD designing.

With this system, the energy can supply $1.2$ kWh to an electric motorcycle without charging storage battery for 3 days at $50\%$ of DOD and can supply storage battery for 6 days at $100\%$ of DOD (including
battery loss from battery sizing calculation). However, higher percent of DOD can decrease battery life span.

4. Conclusion
The proposed design of the off-grid PVS provides a sustainable energy storage for charging an electric motorcycle from solar energy. The most challenging seasons for PVS to provide sufficient energy are the raining season and winter. Even during these seasons, the system is still able to produce more energy than the electric motorcycle requirements over 90% of the days. The system has shown that it is capable of holding sufficient energy for 3 days of autonomy with the maximum demand of daily use. However, this research still assumes 30% for total loss of PVS which not accurate for real application. There are many cause of loss in system such as loss from PV, loss from cable, loss from charge controller, loss from batteries and loss from inverter which depends on specification, type or market brand. Some system in real application has other device such as meter, diode, breaker or other safety device to cause more loss.

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