Influence of operational and economic factors on the optimal design of an electric vehicle battery cooling system

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Abstract. Electric vehicles are a leading alternative to traditional vehicles. However, high expenditure on battery replacement due to rapid capacity loss limits their market penetration. Given that the high temperatures reached during operation greatly contribute to capacity loss, battery cooling systems are often necessary to extend battery life. In designing a cooling system, lifetime cost is a crucial consideration as both capital expenditure and battery replacement cost savings are associated with the system. To extend the prior initial study, this study investigates the influence of various factors on the economically optimal design. Similar to the initial study, the investigated case is that of a typical electric jeepney in Manila, Philippines. Existing models for the electrothermal and aging behavior of the battery, thermal behavior of the cooling system, and capital costs of the cooling system components are linked to form a system simulation. The simulation, implemented in Simulink is coupled with a genetic algorithm implementation in MATLAB to generate the optimal cooling system design. As with the initial study, air and phase change material are the cooling media considered. Given their significant expected influence on the optimal design, the following factors are investigated: drive cycle, ambient temperatures, and component capital costs. The results of this study agree with the preliminary study. The optimization results do not favor air cooling in any case investigated; none of the cases justify its high capital and operating costs. Phase change material (PCM) cooling is also unfavored in all cases, save for that using the US06 drive cycle, showing that only extreme temperature rise due to high current draw can justify investment in PCM cooling. Although previous studies have found that lowering battery temperature extends battery life, this study reveals that the capital and operating costs of battery cooling systems are still a hurdle to be overcome.

Keywords: Battery cooling system, Electric vehicle, Optimization, Genetic algorithm

1. Introduction
Given the increasingly alarming problem of climate change, alternatives to fossil fuel-burning machines, facilities, and activities are being sought. A popular alternative technology is the electric vehicle (EV), given its environmental, economic and technical advantages. EVs have been found to
outperform other alternative vehicle technologies in terms of overall costs, health and non-health benefits, and greenhouse gas reduction [1].

However, the market penetration of EVs is greatly hindered by the costs associated with short battery life, i.e. the rapid loss of battery capacity. Batteries generate heat during operation; hence their temperature rises [2], and these resulting high temperature have been found to be a leading factor in capacity loss [3].

To the problem of high battery temperatures and the consequent short battery life, a common and effective solution is a battery cooling system. There is a large and growing body of research on battery cooling systems, especially on the three most common cooling media – air, liquid, and phase change material (PCM) [4].

As short battery life results in greater electric vehicle ownership costs, an extended battery life results in a great reduction in this cost [5]. However, the battery cooling system often necessary to achieve this entails significant added cost – capital, and operating and maintenance, which are quite large for active systems, i.e. those with active components such as fans or pumps [6]. This aspect is largely unexplored in literature, which mainly focuses on improving the thermal performance of these cooling systems.

Taking an economic approach is crucial in designing a battery cooling system for net benefit, and hence was the focus and novelty of the preliminary study [7]. In this study, the optimal design of a cooling system for an electric jeepney in Manila, Philippines was determined. Selection was made between two cooling media – air and PCM, by optimizing a design utilizing each, and identifying the option with lower cost per kilowatt hour (kWh). The optimal design was determined for a routine use case, employing a drive cycle, and an extreme use case discharging the battery at 3C.

While the prior study was able to determine the optimal cooling system for a particular case, it is important to consider that different electric vehicles are subjected to different operating patterns and conditions. Also, given the insignificant benefit from the cooling system for the routine use case in the prior study due to the high associated costs of the cooling system [7], it is worth exploring whether more demanding operating patterns and conditions are enough to justify such an investment, and whether lower cooling system capital costs can increase the benefit.

The vast majority of research works in literature study the thermal performance of cooling systems, and design modifications for the improvement of this. Optimizing the cooling system design to achieve the lowest cost per kWh possible under different operating patterns and conditions, which is necessary given the system’s interacting economic impacts stated above, is the research gap this study addresses.

2. Simulation

![Figure 1. System Simulation and Optimization Overview](image)

At the core of the implementation of the design optimization is a system simulation that models the relevant behaviors of the battery – electrical, thermal, and aging, as well as that of the cooling system.
As seen in Figure 1, the summary of the system simulation and optimization, the overall model takes in two sets of input – vehicle parameters and ambient temperature.

While the approach, software, and settings of the simulation from the prior study is retained here, and its results are presented alongside the latest ones, as mentioned above, this study explores the influence of three operational and economic factors on the optimal design of the cooling system. The first is the drive cycle, which has been shown to significantly affect the cycle life [8], and battery temperature and cooling requirement [9]. While the original case runs on the relatively less demanding Phase 2 Diesel Jeepney Drive Cycle [10], the effect on the optimal solution of using the more aggressive US06 Drive Cycle [11] is explored here. For comparison, the jeepney drive cycle has a top speed of about 54 km/h, while the US06 cycle has a top speed of 129.2 km/h.

It has also been shown in [8] that the ambient temperature has a significant effect on battery cycle life; hence, this factor is also explored in this study. While the tropical ambient temperatures in Manila used in the preliminary study are high, reaching 33 °C [12], the ambient temperatures in Phoenix, Arizona, which were the highest in [8], are significantly higher. The lowest temperature on the sample day in Phoenix is nearly as high as the Manila maximum, while the highest temperature is 46.1 °C.

Lastly, as it was found in the previous study that the high capital costs of the cooling systems are a major culprit in their minimal economic benefit, the scenario wherein the cooling system components’ capital costs are reduced to 25% is explored. An extreme cost reduction is selected for this study; since the capital costs for both the air cooling system’s vapor compression system, and the octadecane PCM are extremely high, it is worth exploring what the effects of a “more reasonable” capital cost of the cooling system are.

3. Optimization Problem

The optimization problem is the same as that in the prior study, including the use of a genetic algorithm (GA) implemented using MATLAB [7]. The objective function minimizes the cost per kWh, which is obtained by dividing the sum of the present costs of the cooling system ($C_{\text{cool}}$), cost of the battery cells ($C_{\text{batt}}$), and operating cost or electricity cost ($C_{\text{op}}$), by the lifetime amount of energy allotted to traction ($kW_{\text{trac,life}}$)

$$\min C/kWh = \frac{C_{\text{cool}} + C_{\text{batt}} + C_{\text{op}}}{kW_{\text{trac,life}}} \quad (1)$$

As with the prior study, the optimization is performed for both an air cooled and a PCM cooled design, and the results are compared with each other and to a baseline uncooled case to determine the most economically beneficial option. For the air cooled system, the capital cost consists of those for the fans and the vapor compression system for cooling the air below ambient. For the PCM cooled system, it covers the cost of the octadecane PCM and aluminum foam. The electricity cost for both designs is the lifetime cost of charging the battery.

Meanwhile, the denominator includes only the energy allotted to traction to account for the effect of the parasitic energy consumption of the air cooled system. The higher this energy consumption is, the lower the fraction of the lifetime energy output of the battery is allotted to traction.

As with the prior study, the optimization variables of the air cooled system are: the inlet air velocity, cooling capacity of the vapor compression system, upper set point temperature, and lower set point temperature. The optimization variable of the PCM system is the thickness of material surrounding each cell. All optimization variables are constrained to reasonable bounds, considering the dimensions of the jeepney and the acceptable battery temperature range of 15 to 35 °C.

4. Results and Discussion

Tables 1 to 3 contain the objective function values of each investigated case, along with the components of each – the total net present cost and lifetime energy spent on traction. Table 1 contains those of the uncooled cases, Table 2 the air cooled cases, and Table 3 the PCM cooled cases. Each
table presents the three explored scenarios – US06 drive cycle, Phoenix, Arizona ambient temperatures, and lower cooling system capital costs side by side.

Table 1. Baseline Cases Objective Function Values

|                | Manila Jeep | US06 | Phoenix |
|----------------|-------------|------|---------|
| C/kWh ($/kWh) | 0.7050      | 1.1942 | 0.9647 |
| Total Net Present Cost ($) | 16,535 | 16,320 | 15,806 |
| Lifetime Energy Spent on Traction (kWh) | 23,454 | 13,666 | 16,384 |

It can easily be seen in Table 1 that there is a significant difference between the cost per kWh of each scenario, as well as the available energy for traction, signaling that driving pattern and ambient temperatures do have an effect on battery life. On the basis of cost per kWh, the more intense drive cycle is seen to have a greater impact on battery life, reflecting the preliminary study’s finding – the notable effect of the simulated extreme use case on the cost per kWh.

Table 2. Air Cooled Cases Objective Function Values

|                | Manila Jeep | US06 | Phoenix | Lower Cost |
|----------------|-------------|------|---------|------------|
| C/kWh ($/kWh) | 0.7016      | 1.1859 | 0.9599 | 0.7016     |
| Percent Improvement (%) | 0.48% | 0.70% | 0.50% | 0.48% |
| Total Net Present Cost ($) | 16,537 | 16,320 | 15,805 | 16,537 |
| Lifetime Energy Spent on Traction (kWh) | 23,570 | 13,762 | 16,465 | 23,570 |

Aside from the quantities stated above, Tables 2 and 3 also present the percent improvement of the objective function from the baseline cost per kWh. The lower cost scenarios are compared to the baseline case of the Jeepney drive cycle ran in Manila. It is clearly seen in Table 2 that no significant improvement from the baseline is achieved with air cooling in any scenario. This is true even for the lower cost scenario, whose objective function value is virtually equal to the original case. The results indicate that not even the increased need for cooling due to a more intense drive cycle or higher ambient temperatures can justify the high cost of air cooling. Furthermore, the results in Table 2 indicate that even a 75% reduction in component capital costs is not enough to drive down the cost per kWh.

Table 3. PCM Cooled Cases Objective Function Values

|                | Manila Jeep | US06 | Phoenix | Lower Cost |
|----------------|-------------|------|---------|------------|
| C/kWh ($/kWh) | 0.7248      | 0.8597 | 0.9672 | 0.7072     |
| Percent Improvement (%) | -2.81% | 28.01% | -0.26% | -0.31% |
| Total Net Present Cost ($) | 17,106 | 18,061 | 15,955 | 16,691 |
| Lifetime Energy Spent on Traction (kWh) | 23,601 | 21,008 | 16,496 | 23,602 |

Although the optimization results in Table 2 are not strongly in favor of air cooling, the results in Table 3 show that in most cases, the optimal PCM design yields a higher cost per kWh than their respective baselines, likely owing to the high cost of the material. The only exception is for the US06 cycle case, where significant reduction in cost can be achieved, in line with the results of the
preliminary study for 3C discharge. Similar to the results for air cooling, it can be seen that reducing capital costs by 75% does not yield a favorable result for the PCM system.

Table 4. Air Cooling Optimization Variable Values

|                      | Manila Jeepney | US06 | Phoenix | Lower Cost |
|----------------------|----------------|------|---------|------------|
| Inlet Air Velocity (m/s) | 0.10           | 0.12 | 0.12    | 0.10       |
| Vapor Compression System Cooling Capacity (W) | 0.00           | 0.00 | 0.00    | 0.00       |
| Upper Set Point (Switch ON) (°C) | 27             | 27   | 23      | 27         |
| Lower Set Point (Switch OFF) (°C) | 15             | 19   | 20      | 18         |

Table 5. PCM Cooling Optimization Variable Values

|                      | Manila Jeepney | US06 | Phoenix | Lower Cost |
|----------------------|----------------|------|---------|------------|
| PCM thickness around battery (mm) | 1.0            | 8.6  | 1.0     | 1.0        |

Tables 4 and 5 show the optimization variable values of the air and PCM systems for the different scenarios explored. Table 4 shows that none of the cases justify the addition of a vapor compression system for cooling the air, not even the 75% reduction in capital cost. It can also be seen that the virtually equal objective values of the original and lower cost air cooled scenarios, seen in Table 2 are due to the nearly identical objective variable values. Meanwhile, it can be seen that in spite of the higher cooling requirement for the US06 and Phoenix cases, the inlet air velocity is not significantly higher. This is likely due to the high operating cost of the fans, as with the preliminary study. Table 5 shows that only the high current draw of the US06 drive cycle justifies the addition of more PCM, similar to the preliminary results.

Figure 2. Battery and Ambient Temperatures for Uncooled Cases

Figure 2 shows the battery and ambient temperatures for the uncooled cases, mainly for comparison with the battery temperatures for the cooled cases, shown in Figures 3 and 4. Notable patterns are the
small departure of the battery temperatures from the ambient for the original and lower cost cases, both running the Jeepney drive cycle. It can also be seen that the US06 drive cycle greatly increases the battery temperature, similar to the 3C discharge in the preliminary study.

**Figure 3.** Battery and Ambient Temperatures for Air Cooled Cases

Figure 3 shows the battery and ambient temperatures for the air cooled cases. The most notable feature of Figure 3 is that it is nearly identical to Figure 2, lending an explanation for the insignificant improvement in cost per kWh seen in Table 2. The virtual similarity of the optimization results for the original and lower cost air cooling systems is also reflected in their temperature curves being virtually the same.

**Figure 4.** Battery and Ambient Temperatures for PCM Cooled Cases
Figure 4 shows the temperature curves for the PCM cooled cases. The two cases running the Jeepney drive cycle are similar to the uncooled and air cooled cases except for the melting range of octadecane, 28 to 30 °C. Meanwhile, for the US06 case, although the temperatures reached during discharge are still greater than the acceptable 35 °C limit, the temperature spikes are greatly decreased, explaining the significant improvement in cost per kWh.

5. Conclusion
This work extends the initial study that determined the most appropriate cooling system for an electric jeepney running in Manila, Philippines considering the economic benefit, i.e. basing the selection on the cost per kWh. The results of the initial study were used as points of comparison for the results of the present study, which investigated the influence of several factors on the optimal cooling system design. These factors, which were varied one at a time, were: drive cycle, ambient temperature, and cooling system capital cost. To investigate the influence of the drive cycle, the optimization results when the US06 drive cycle is used in place of the Jeepney drive cycle are compared to the results of the initial study. It is to be noted that the other factors, i.e. the Manila ambient temperatures, and cooling system capital costs, remain unchanged. To investigate the influence of the ambient temperatures, the optimization results when Phoenix ambient temperatures are used in place of Manila ambient temperatures are compared to that of the initial study. Again, the other factors, i.e. the Jeepney drive cycle, and cooling system capital costs, remain unchanged. Lastly, to investigate the effect of capital costs, 75% lower capital costs were used in place of the full capital costs, keeping the other two factors the same. It was found that the high operating cost of air cooling was not justified in any case, and that PCM cooling is only justified by the high heat generation during the US06 drive cycle. It is notable that not even the extreme reduction in capital costs can allow the allotment of greater cooling capability, likely due to the operating costs still hindering economic benefit for air cooling, and the capital costs still being too high for PCM. Furthermore, it can be concluded that the factor with the largest influence on cooling requirement and cooling system design is the current draw, i.e. the drive cycle. Similar to the results of the prior study, it can be seen that the favorable results for PCM are due to the significant reduction in peak temperatures it brings. Literature indicates that lowering battery temperature extends battery life, but the present study reveals that before electric vehicles and other battery operations can enjoy this benefit, the capital and operating costs of battery cooling systems need to be reduced.

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