DENSO International America Final Project Report

Stand Alone Battery Thermal Management System

U.S. Department of Energy

National Energy Technology Laboratory

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Disclaimer

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Executive Summary

The objective of this project is research, development and demonstration of innovative thermal management concepts that reduce the cell or battery weight, complexity (component count) and/or cost by at least 20%. The project addresses two issues that are common problems with current state of the art lithium ion battery packs used in vehicles; low power at cold temperatures and reduced battery life when exposed to high temperatures. Typically, battery packs are “oversized” to satisfy the two issues mentioned above.

The first phase of the project was spent making a battery pack simulation model using AMEsim software. The battery pack used as a benchmark was from the Fiat 500EV. FCA and NREL provided vehicle data and cell data that allowed an accurate model to be created that matched the electrical and thermal characteristics of the actual battery pack. The second phase involved using the battery model from the first phase and evaluate different thermal management concepts. In the end, a gas injection heat pump system was chosen as the dedicated thermal system to both heat and cool the battery pack. Based on the simulation model. The heat pump system could use 50% less energy to heat the battery pack in -20°C ambient conditions, and by keeping the battery cooler at hot climates, the battery pack size could be reduced by 5% and still meet the warranty requirements. During the final phase, the actual battery pack and heat pump system were installed in a test bench at DENSO to validate the simulation results. Also during this phase, the system was moved to NREL where testing was also done to validate the results.

In conclusion, the heat pump system can improve “fuel economy” (for electric vehicle) by 12% average in cold climates. Also, the battery pack size, or capacity, could be reduced 5%, or if pack size is kept constant, the pack life could be increased by two years. Finally, the total battery pack and thermal system cost could be reduced 5% only if the system is integrated with the vehicle cabin air conditioning system. The reason why we were not able to achieve the 20% reduction target is because of the natural decay of the battery cell due to the number of cycles. Perhaps newer battery chemistries that are not so sensitive to cycling would have more potential for reducing the battery size due to thermal issues.

Introduction

In August 2011, DENSO International America was awarded a project (DE-EE0005410) to investigate the potential to reduced vehicle battery pack size by 20% using and advanced, dedicated thermal management system. The award was the result of DENSO application to Funding Opportunity DE-FOA-0000239 which was issued in December, 2010. The project contact was three years, and was granted a one year no cost extension to finish the final bench testing of the project. As a result, total project time was four years, October 2011 → September 2015. The project was broken into three phases, each phase was planned to be one year in length.

Organizations and Roles

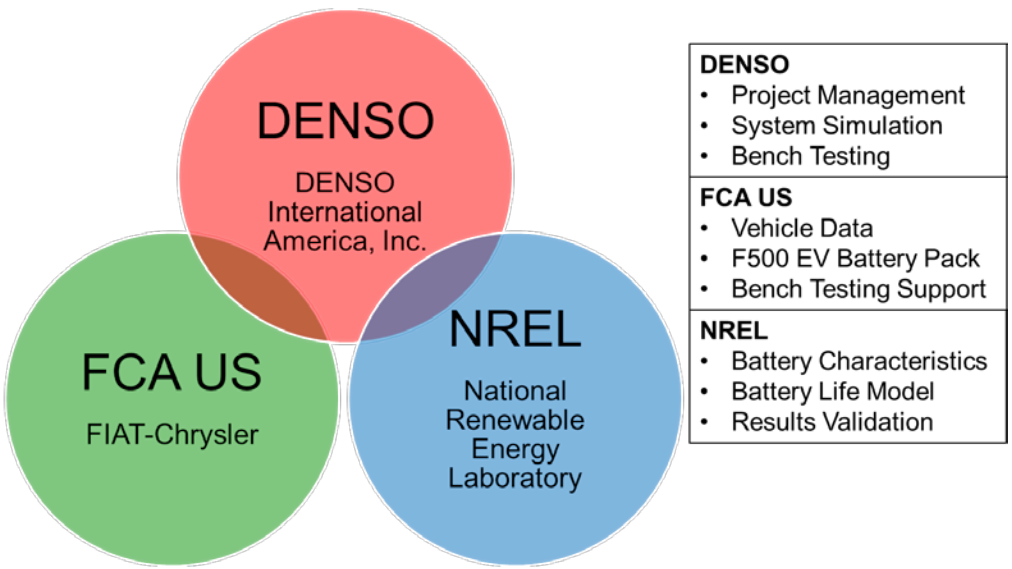


Figure 1: Organizations and Roles

As shown in Figure 1, there were three main organizations that were part of this project. DENSO International America was the lead organization which performed the project management, battery and thermal system simulation, and also actual bench testing.

Fiat-Chrysler supplied vehicle data to allow DENSO to complete the simulations using actual drive cycles and to verify the results from the battery pack simulation matched the results from actual vehicle testing. FCA also supplied the battery pack, and provided vital support when testing the battery pack on the test bench.

National Renewable Energy Laboratory supported the battery simulation with battery cell characteristics, battery life model and by performing bench testing of the actual components to validate the results achieved at DENSO.

Methodology

As mentioned previously, the project was broken into three main phases. Figure 2 shows these phases along with the work that was performed in each phase. Phase I was spent creating the battery pack simulation model in AMEsim software. This required the input from NREL and FCA. Phase II involved using the battery simulation model created in Phase I to evaluate the effect of various thermal systems and thermal technologies. After determining the best solution from Phase II, prototype parts were created in Phase III and tested both at DENSO test bench and NREL test bench.

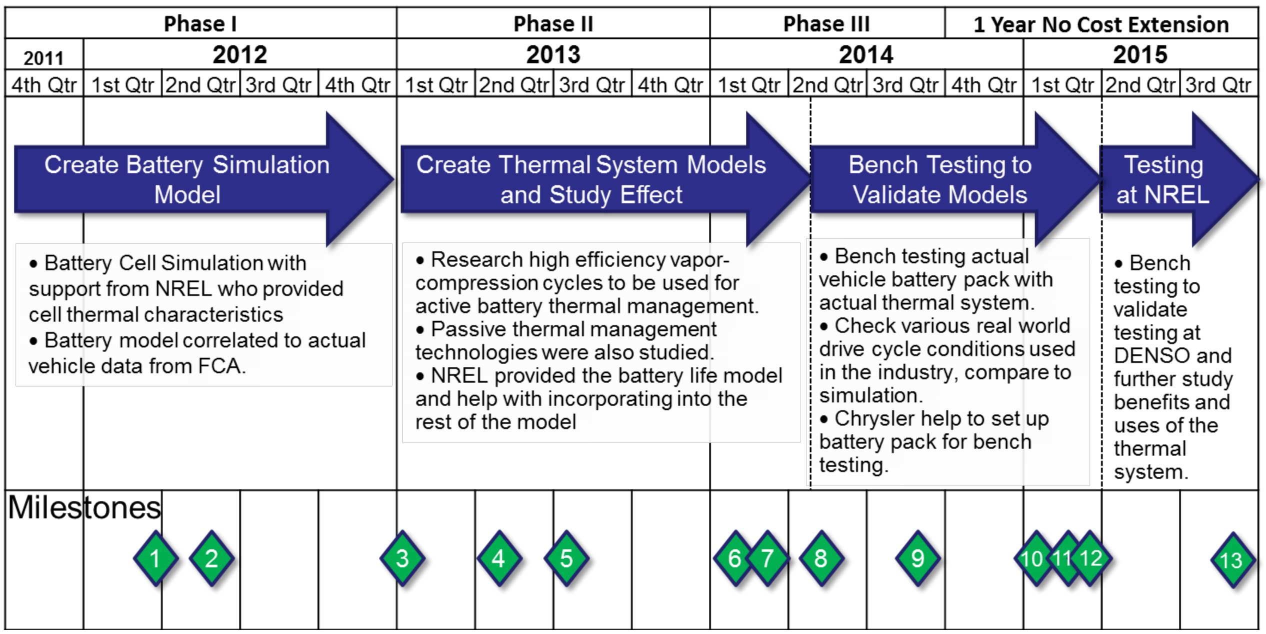


Figure 2: Methodology and Overall Schedule

Milestones

Figure 3 shows detail of each milestone that was established at the start of the project. Details of each of the milestones can be found later in the text.

		Date		Status
Phase I	1	4/30/2012	Milestone 1: Testing Conditions for Simulation and Bench for Entire Project	Complete
	2	5/16/2012	Milestone 2: Thermal Characteristics of Battery Cells / Modules	Complete
	3	1/15/2013	Milestone 3, Budget Period 1 Judgment: Simulation Complete: Does it Match Vehicle Test Data? (Yes/No)	Complete
Phase II	4	4/11/2013	Milestone 4: Heat Pump System Simulation Results	Complete
	5	7/10/2013	Milestone 5: Cascade Compressor Heat Pump Simulation Results	Complete
	6	02/10/2014	Milestone 6: PCM Simulation Results	Complete
	7	03/12/2014	Milestone 7: Vapor Compression Cycle with PTC Heater Simulation Results	Complete
	8	5/1/2014	Milestone 8, Budget Period 2 Judgment: System Design Complete: Can the Project Objective be Achieved? (Yes/No)	Complete
Phase III	9	09/30/2014	Milestone 9: Prototype Parts Completed	Complete
	10	02/27/2015	Milestone 10: Cooling System Testing Complete	Complete
	11	3/06/2015	Milestone 11: Heating System Testing Complete	Complete
	12	3/20/2015	MILESTONE 12: Initial Bench Testing Complete: Are Project Objectives Achieved? (Yes/No)	Complete
	13	9/2015	MILESTONE 13: Budget Period 3 Judgment: Final Bench Testing Complete: Are Project Objectives Achieved? (Yes/No)	Complete

Figure 3: Project Milestones

Phase 1: Creating Battery Pack Simulation Model

At the very beginning of this phase, the type of simulation model had to be specified. There are two types, or methods, of simulating the characteristics of a battery cell. First is a physics based model using first principles. This type of model can be computational intensive, but accurate and can extrapolate. It provides insights into mechanisms of behavior and requires detailed information on the battery cell dimensions, properties, chemistry and other detailed attributes. The physics based model is typically used for battery cell development and shape optimization. (Kim, G.H., 2008) The second type of battery model is called equivalent circuit model which is based on empirical data. Equivalent circuit model is easy to compute, and provides good accuracy if interpolating. It can be done in various software types like Matlab and does not require detailed knowledge of the internal batter cell design. This type of model is commonly used when modeling the battery as part of a larger system. Because this project is focused on the battery pack, detailed information on the battery cell is limited and simulation time is important, the equivalent circuit type model was chosen. Further research found that there are two types of equivalent circuits, AC Impedance and DC Resistance-Capacitor (RC) circuits. AC Impedance circuit is based on the frequency domain response of the battery cell, it requires offline specific testing to characterize the cell and is not intuitive or easily adoptable. (Chen, 2006) The DC Resistance-Capacitor (RC) circuit simulates the battery as a system of resistors and capacitors. It is easy to fit the model to existing data, not requiring special tests, and important for this project is temperature and C-rate effects can be incorporated. This is the most commonly used method for battery models. As a result of this research, the RC Equivlant circuit type model was used for this project.

RC circuits consist of a voltage source, series resistor and one or more RC pairs in parallel. The RC pairs account for the time delayed response of the battery voltage to changes in load. (Chen, 2006) Also, more RC pairs simulate various time constants of the battery chemistry. The best match for electric vehicles is three RC pairs, one each for the seconds, minutes and hours time constants. (R. Kroeze, 2008) Another circuit can be added for tracking state of charge (R. Kroeze, 2008), self-discharge and capacity fade ; all of which are important when considering battery life.

Originally, the plan was to create the battery simulation model in MATLAB / Simulink and have this be a sub-model for the main AMEsim software. However, it was decided to use the new battery simulation tool which was easy to modify and sues the RC type model. This enabled the battery model and all the thermal components to be modeled in the same software which enabled faster simulation time and less errors. The AMEsim software suite includes 40 libraries including 4500 multi-domain models related to Hydraulics, Thermal, Control, Mechanical, Engine, Energy, and Electromechanical. It is a "do everything" software suite that worked great for this project as we used models from many of the various domains. Figure 4 shows an image of the basic RC circuit.

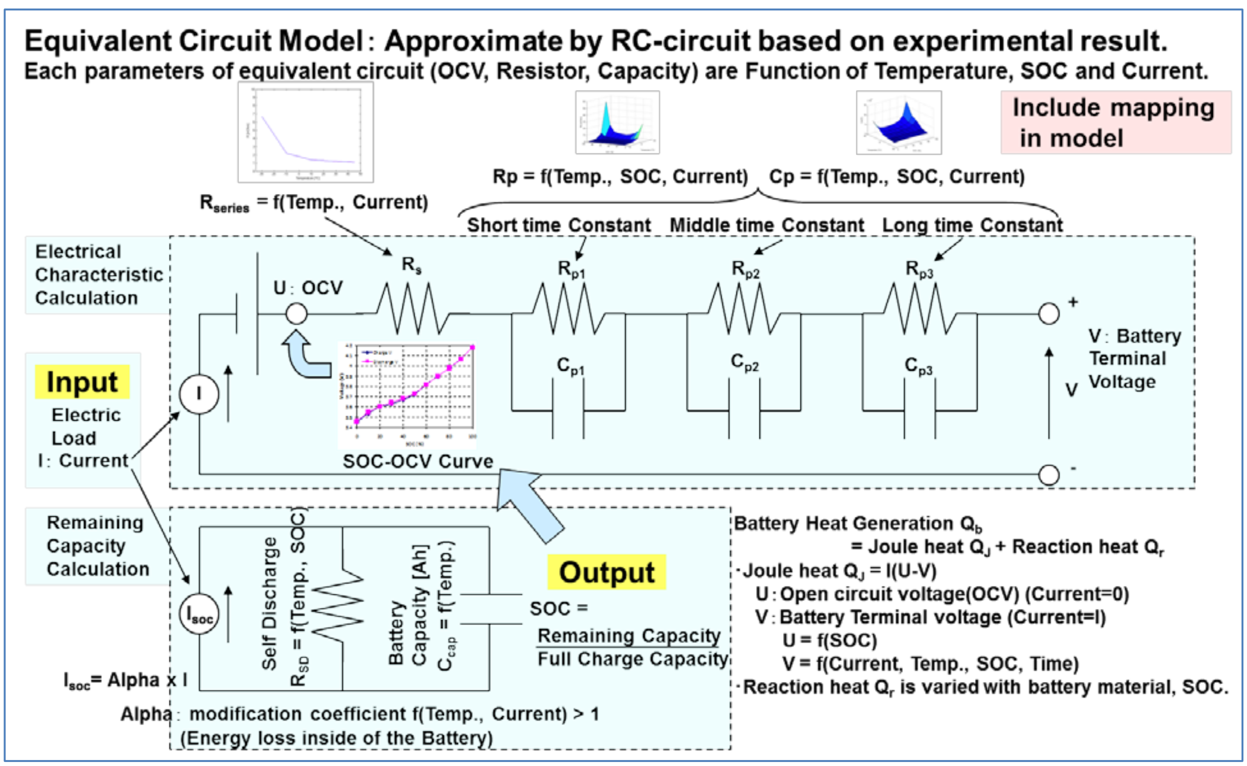


Figure 4: Resistance-Capacitance Circuit method used for battery simulation

After deciding and creating the basic battery cell model, it was required to think about what outside variables can affect the battery and battery life. These basically include charge / discharge rate, number of cycles, and temperature. Figure 5 is an image of how all those parameters are related to each other. Notice in the middle of Figure 5 is the battery life model from NREL.

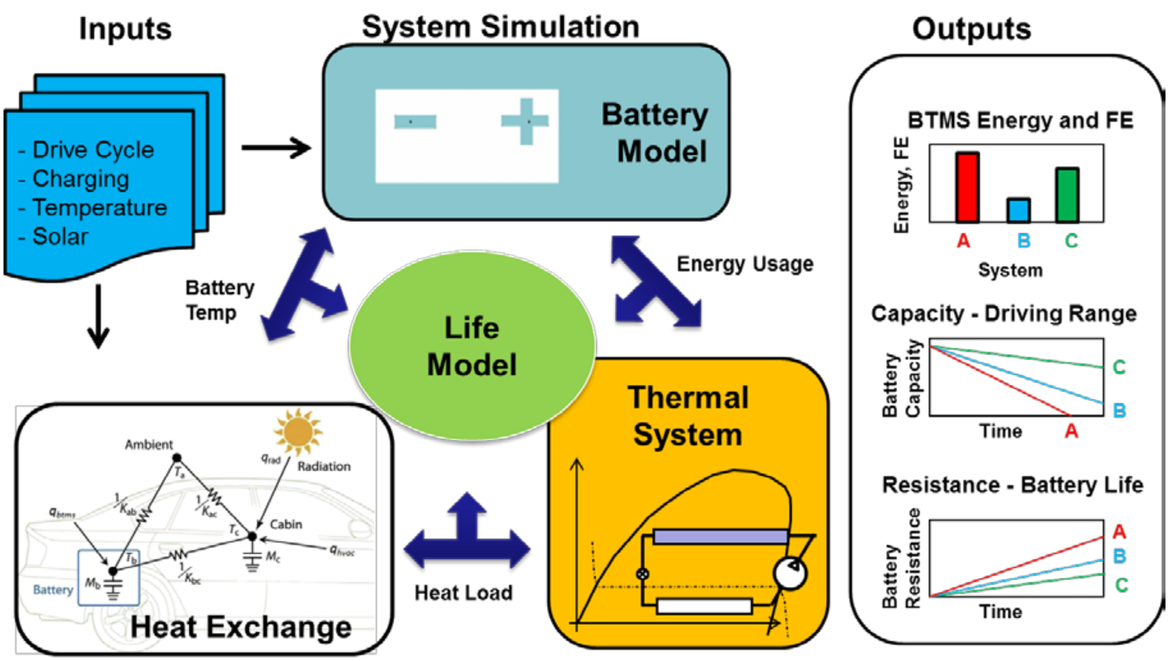


Figure 5: Battery Model Inputs and Outputs

After the battery model was created, the simulated battery and voltage during a drive cycle was compared to actual vehicles results provided by FCA. The results are shown in Figure 6, which shows the simulated voltage and current draw are a very close match to the actual data measured in the vehicle.

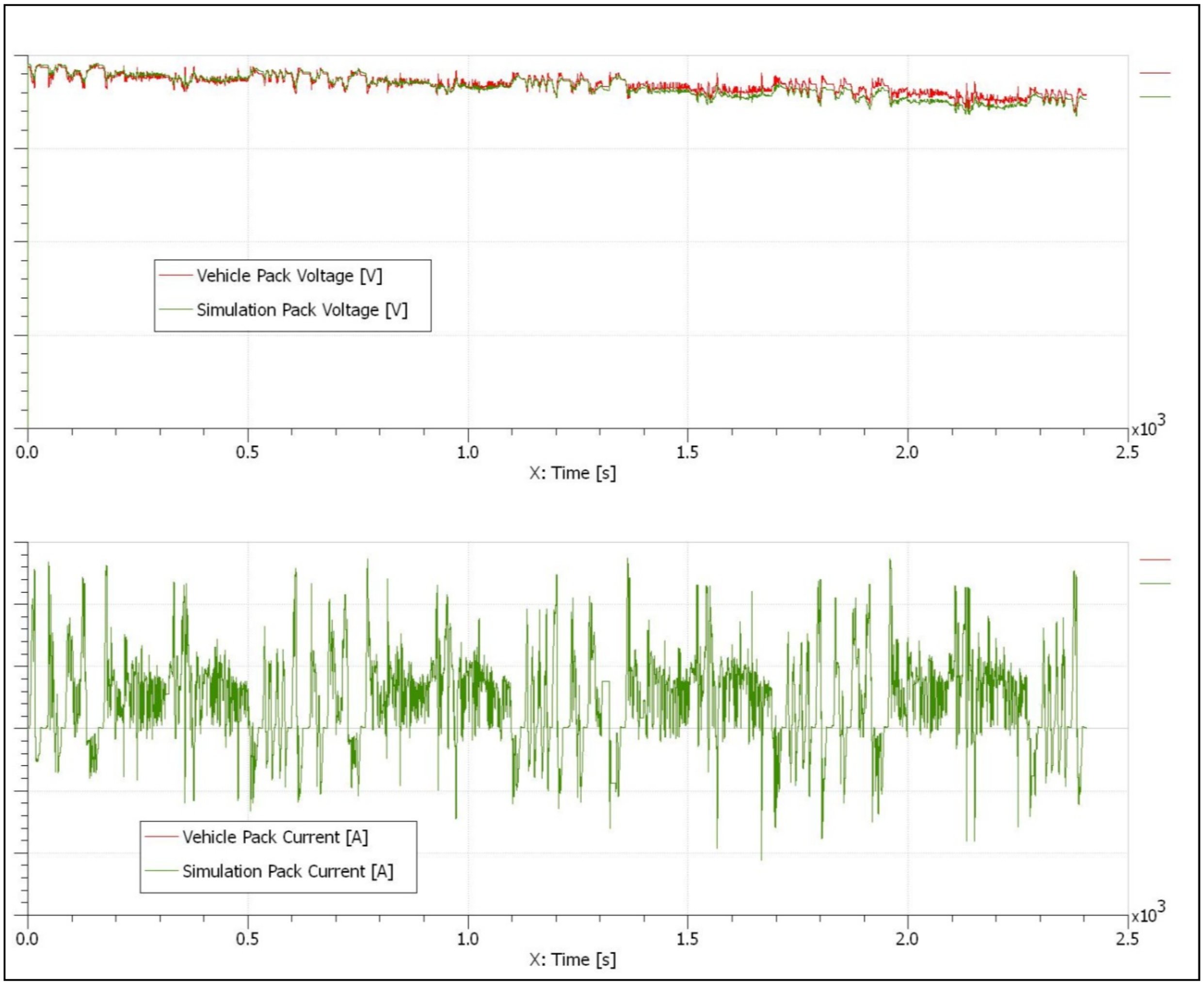


Figure 6: Battery Model Voltage and Current Output Matches Vehicle Test Data

Phase 2: Thermal System Simulation

When considering the design of the stand-alone thermal system, there were a set of given parameters that were fixed. The givens included:

- System is for Battery Electric Vehicle. (No fuel burning engine)
- Typical 50/50 LLC automotive coolant is used to cool the battery pack.
- Battery pack is attached under the vehicle floor. (Like the Fiat 500e)
- R-134a refrigerant is used.

The list of givens is based on the current Fiat 500e battery pack was used for this project. At the time of the project, R-134a was the main stream refrigerant used for vehicle air conditioning systems, however since the start of the project, there has been a shift in the industry to move to a lower GWP (Global Warming Potential) refrigerant. The industry seems to be adopting HFO-1234yf. The physical properties of HFO-1234yf happen to be very similar to that of R-134a. Therefore, it is not expected that the outcome of this project would be much different if HFO-1234yf was used instead of R-134a.

Identify Technology to Simulate

When looking at the thermal system, of course there are many different combinations of technology that could be applied. But, due to time constraints, this project focused on a stand along system using heat pump technology. Figure 7 ha a list of the 3 main systems that were evaluated compared to the base system. (Same as the Fiat 500 EV)

	Cooling Method	Heating Method	Comment
1	Refrigerant Chiller	Electric PTC Heater	Base Method (Same as F500 EV)
2	Refrigerant Chiller	Heat Pump	Improve COP
3	Refrigerant Chiller	Gas Injection Heat Pump	Improve low ambient temperature performance
4	Refrigerant Chiller + PCM	Heat Pump	Add passive heat adsorption

Figure 7: Technology Studied For the Thermal System

System 1 in Figure 7 is the base system that represents what is used in the production Fiat 500 EV. This consists of a vapor compression (R-134a) refrigerant system used to cool the vehicle cabin, and the battery chiller. For battery heating, an electric PTC (positive temperature coefficient) heater is used. The PTC efficiency (COP) cannot be any greater than 1; typically around 0.9. This means the amount of power put in, is about the same amount of heating that is applied. This method of heating is used in many PHEV and EV for not just heating the battery, but also for heating the cabin. In the Fiat 500 EV, there are two PTC heaters, one for the battery and one for the air entering the cabin. Figure 8 shows the various drive habits and ambient that was evaluated for each system.

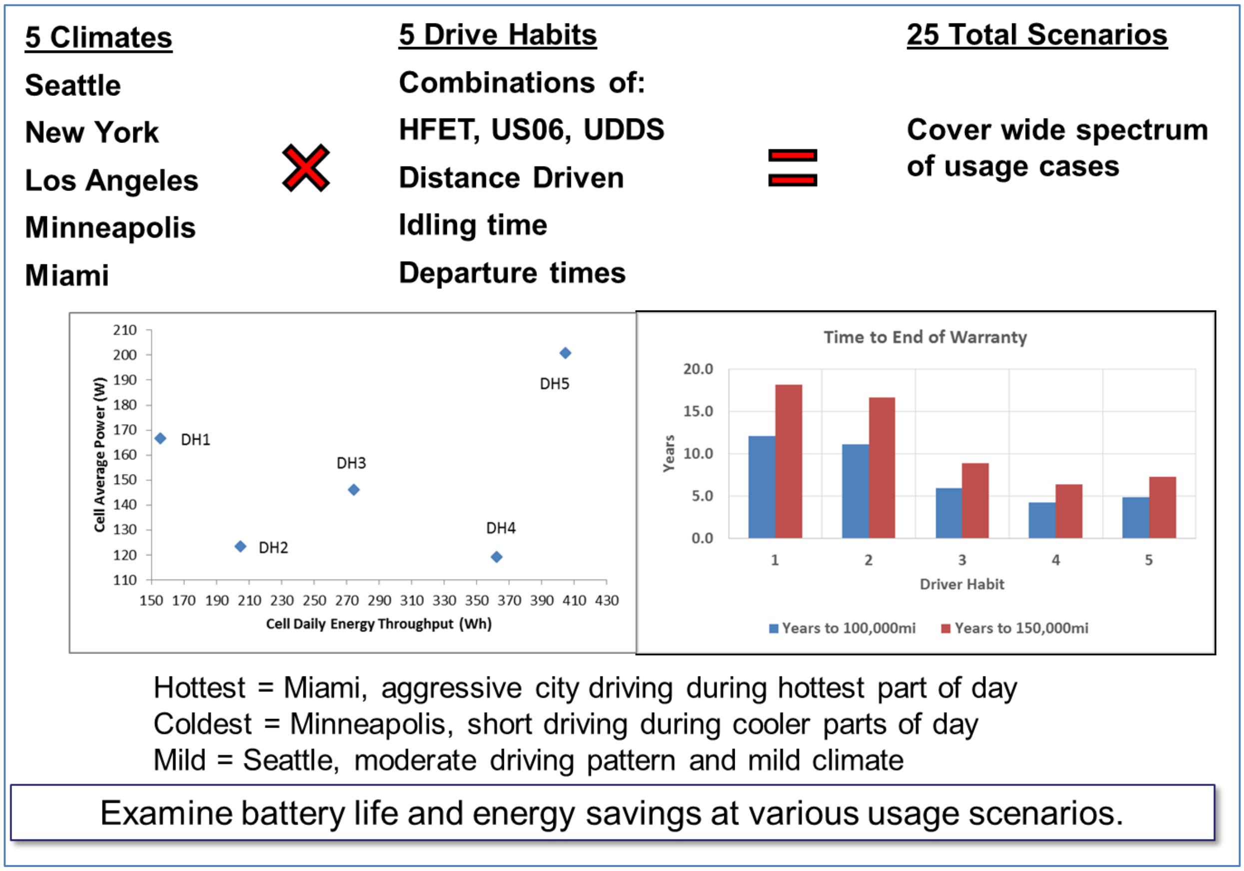


Figure 8: Drive Habits and Ambient Evaluated

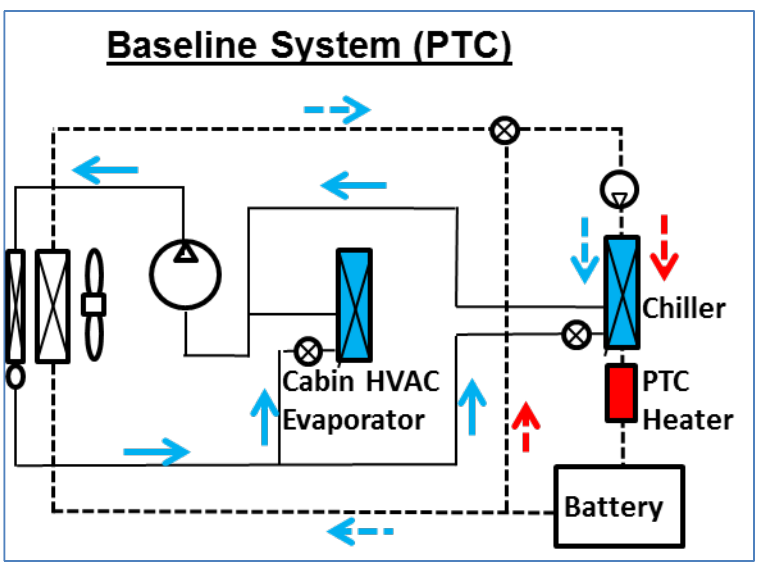


Figure 9: Base System Diagram (System 1)

The first system we will evaluate is an air conditioning system similar to that of the base vehicle, but dedicated only for the battery. This consists of an electric AC compressor, outside heat exchangers, expansion device, and a chiller to cool the coolant for the battery pack. The system can also be switched by using some refrigerant and water valves to change from using the vapor compression cycle for cooling to heating, operating as a heat pump. Figure 10 shows this system layout.

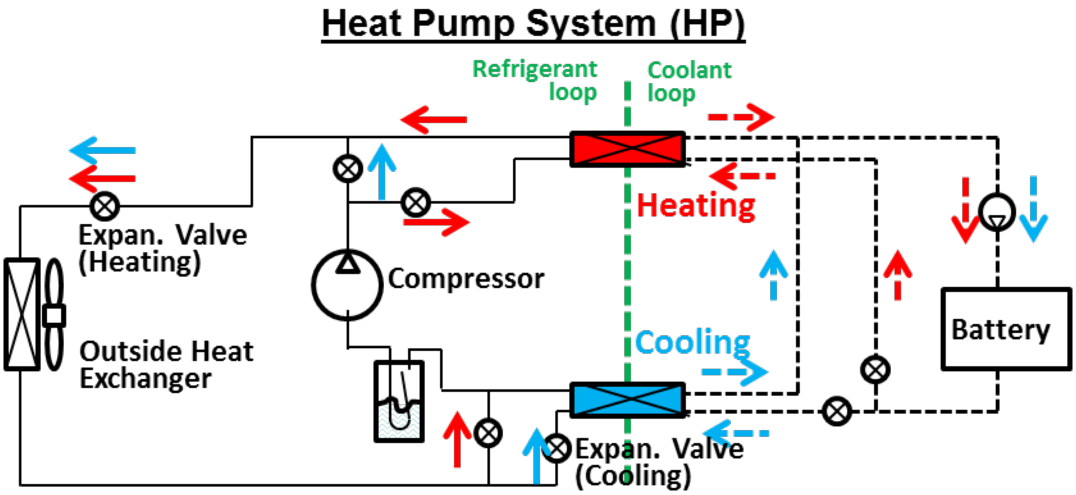


Figure 10: System 2 diagram; Stand Alone System with Heat Pump

There is another concept of heat pump that was tested, and this is what we call gas injection which is shown in Figure 11. Also known as a cascade type heat pump system, there are basically two compressors, or in this case, one compressor with two suction ports. One suction port is running at a higher suction pressure than the other. This allows for increase refrigerant flow rate through the condenser to improve heating performance at cold ambient.

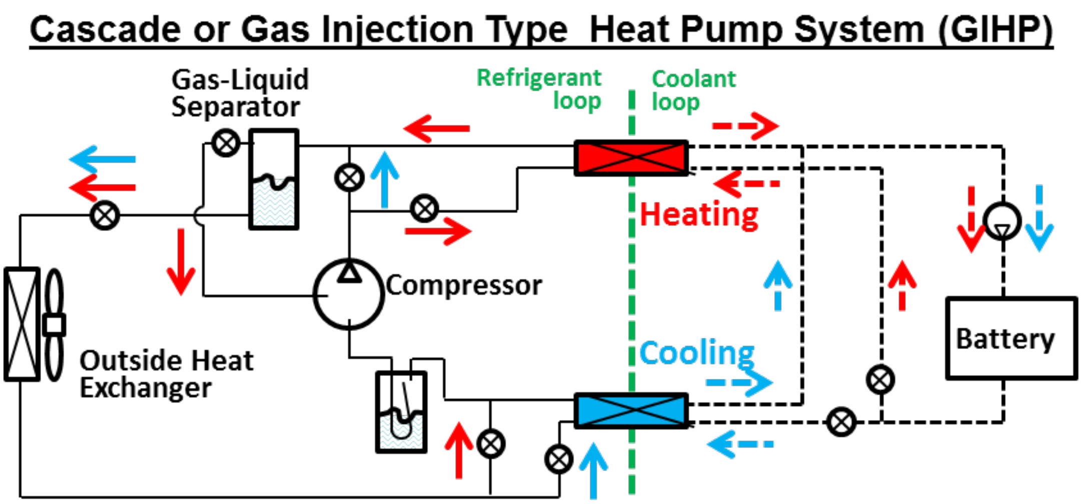


Figure 11: System 3 System Diagram (Gas Injection Heat Pump)

The final system that was simulated was a heat pump system as shown in Figure 10, but a PCM was added to the battery pack. The PCM (Phase Change Material) was used to help dampen the spikes in temperature from extreme hot. This occurs during high charge or discharge rates, and also when the car is parked, it can reduce the temperature spike results from heat load from the sun in the middle of the day. The phase change material used for this study has a melting temperature of 26°C. Figure 12 shows the system layout with the phase change material.

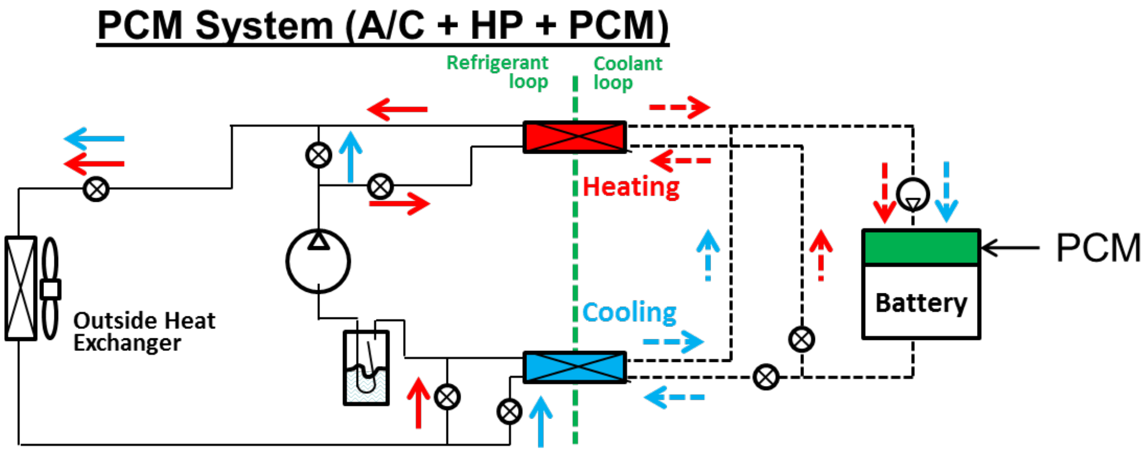


Figure 12: System 4 is a Heat Pump System with Phase Change Material

Figure 13 is a diagram of all three different refrigerant cycles to help understand the difference of each on a Pressure – Enthalpy diagram.

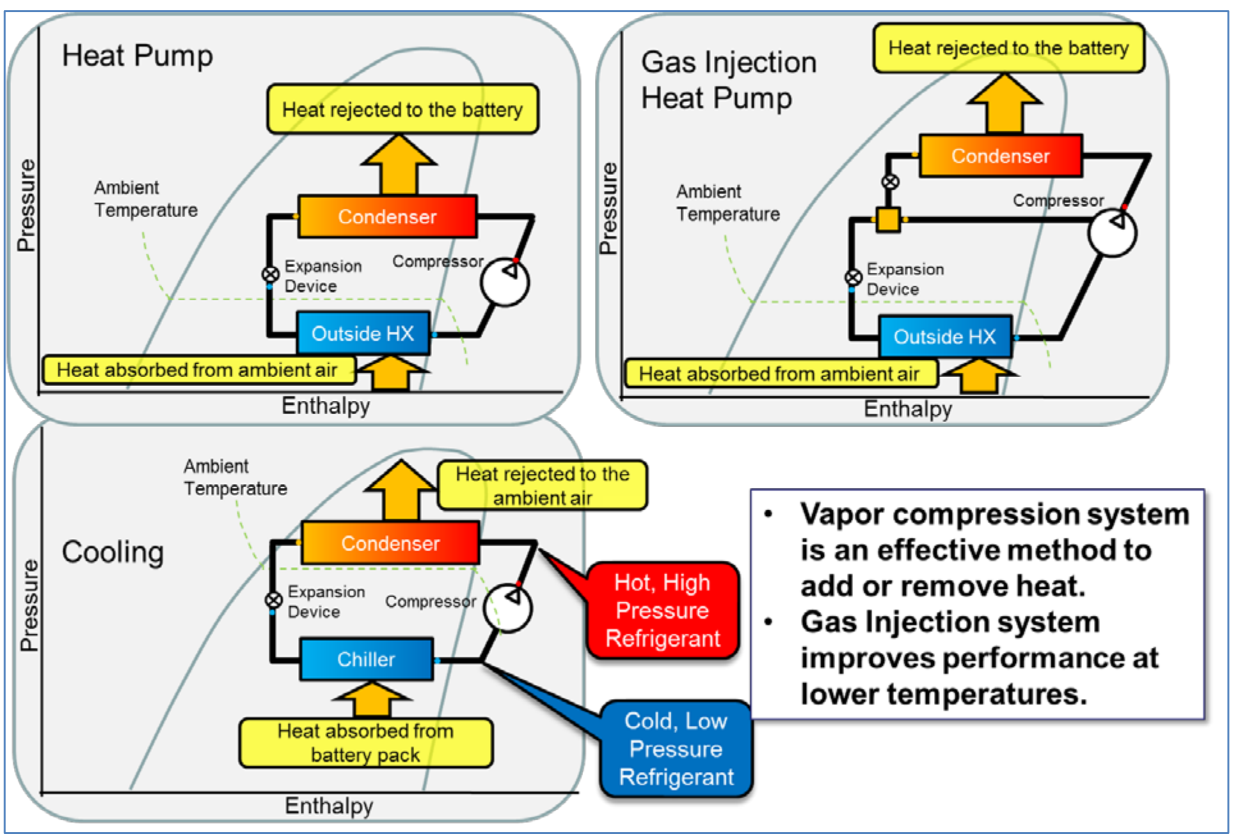


Figure 13: Pressure - Enthalpy Diagrams for each Refrigerant Cycle

Simulation Results

Battery Heating

The first simulation that was done is to warm the battery from a -30°C soak. The goal is to provide at least 2kW of heating power, while using the least amount of energy as possible. As mentioned before, the PTC heater has a COP of around 1, but a heat pump system has the ability to actually create more heating power than the power that is put into the compressor. At really cold temperatures like -30C, the heat pump can struggle to get "good" COP. Figure 14 shows the comparison of the PTC heater, regular heat pump (HP) and the gas injection heat pump (GIHP). In this study, the PTC heater used has an output of 2kW. As shown in Figure 14, at -30C, the heat pump actually cannot achieve 2 kW. However, with gas injection, the performance is almost the same as the PTC heater. As the ambient temperature rises, the heat pump performance increases. This is because the ambient is dictating the "evaporator" or OHX temperature shown in Figure13. When this temperature is very cold, the suction pressure is extremely low and it is very difficult for the compressor to move this refrigerant from a very low temperature and pressure, to a very high temperature and pressure. As the ambient temperature increase, this suction pressure increases and the compressor is able to move more refrigerant and create more pressure and heat on the high pressure side. Therefore, to reduce using too much power, the dashed lines in Figure 14 show what the heat pump would do if compressor speed was kept at maximum. Since only 2 kW is required, the solid lines show the heat pump performance as compressor speed is limited to keep 2 kW. However, it is allowed to go up to 3.5 kW at -20°C as it was determined this is a key temperature to target for heating. Most vehicles must operate at -20°C, however, at -30°C, it is questionable if the battery pack would provide enough power. So for this study we tried to improve heating at -20°C conditions.

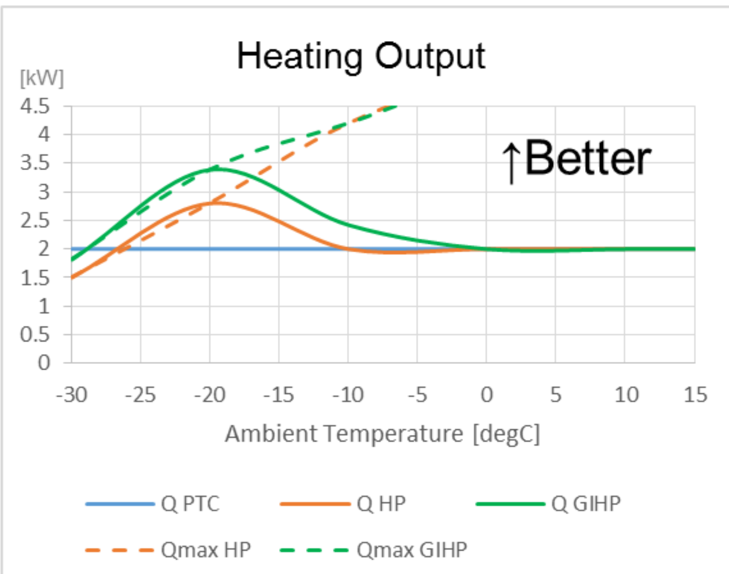
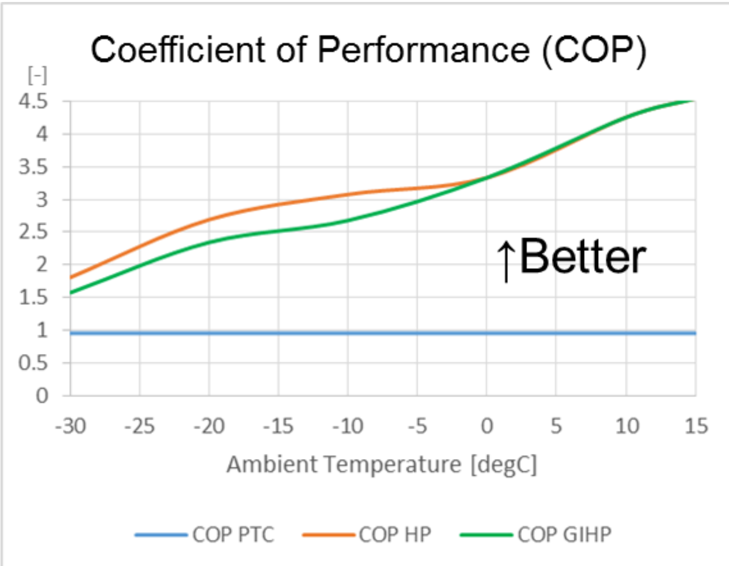


Figure 14: Simulated Heating Performance

Of course we need to think about not just providing the amount of heating required, but also doing so while using the least amount of energy as possible. Figure 15 shows the relationship in COP between the PTC heater, the regular heat pump and the gas injection heat pump at various ambient temperatures. As you can see, the heat pump keeps improving the COP as the ambient is increasing, and even at -30°C it has a COP of around 1.5, so it is still using less energy than the PTC heater.



$$\text{COP} = \frac{\text{Heating Output}}{\text{Power Input}}$$

Figure 15: Heating Coefficient of Performance at Various Ambient Temperatures

To really understand what this means, figure 16 shows the system power consumption; PTC heater compared to the compressor power of the heat pump systems. The conclusion is the heat pump could provide the same heating as a 2kW PTC heater, but use half the amount of power at ambient temperatures above -20°C.

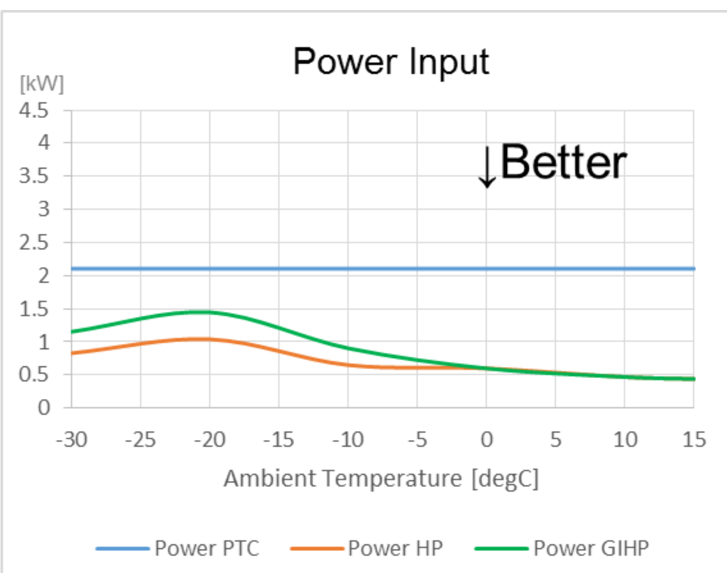


Figure 16: Heating Power Consumption for Various Ambient Temperatures

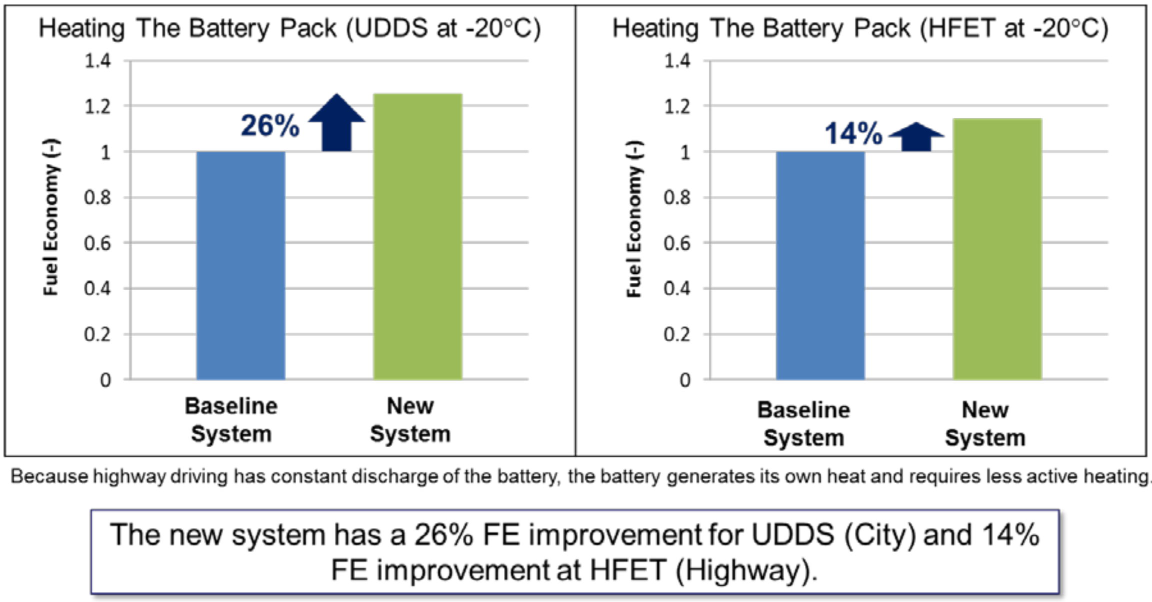


Figure 17: Fuel Economy Savings in Heating Mode

Figure 17 is a study to compare the gas injection system to the baseline PTC heater in drive cycles at cold ambient. The GIHP is able to provide a 26% and 15% improvement. During highway, the improvement is reduced because there is a constant discharge on the battery so it is able to do some self-heating.

Results of Phase Change Material

The purpose of the phase change material is to reduce the temperature spikes that occur every day. This happens as the car is parked and the temperature rises through the day, with the influence of solar heat from the sun on the car. Hot air from inside the cabin can conduct heat to the battery pack through the floor panels. Figure 18 shows the results of this projects PCM study.

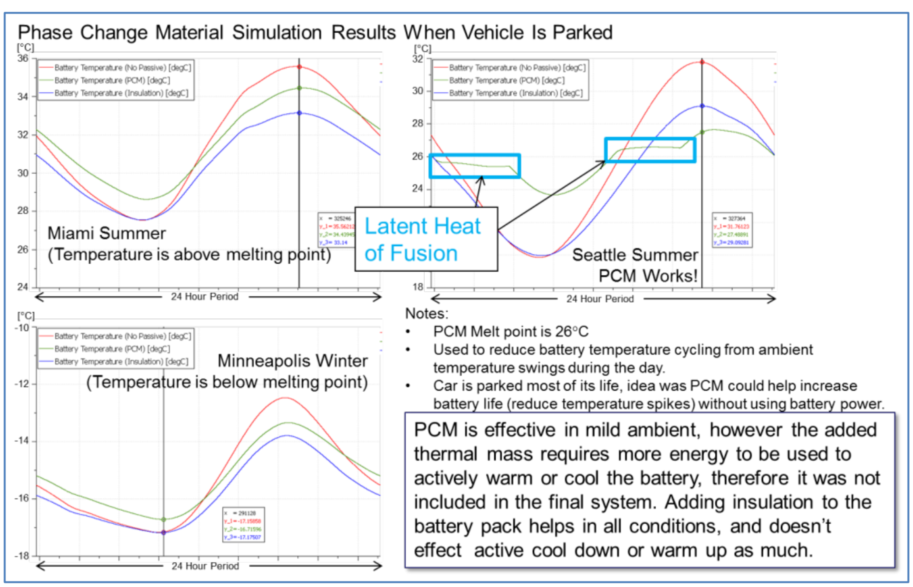


Figure 18: Phase Change Material Simulation Results

The PCM simulation results show that in an area like Miami, the average temperature of the battery pack stays above 26°C, which is the melting temperature of the PCM material. And in Minneapolis winter day, the battery pack temperature stays well below the melting temperature. Therefore, the only area a benefit was found is in mild temperatures like a Seattle summer day. In this case, the PCM works great at reducing the spike in temperature from the heat of the day. But, we found there are other negative issues. This PCM has a very high thermal mass, so if we are in Miami and the battery pack is hot and needs to be cooled, now the system must not only cool off the battery pack, but also the large thermal mass of the PCM material. We found this actually hurt our overall energy usage in an annualized basis across the United States. Perhaps more work can be done on tuning the melting temperature, or making a hybrid PCM that has a large range of melting temperature.

Cooling the Battery Pack

Because the thermal system used to cool the pack is basically the same as the base system, from an energy usage point, there is no change from the base system to the new system. Advantages will be studied later when we adjust the pack target temperature. Figure 19 shows the simulation that there is basically no change in energy for cooling the battery from the base system to the new system.

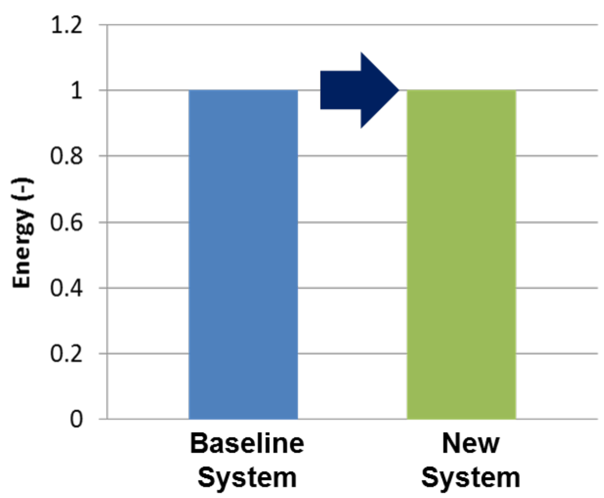


Figure 19: Cooling the Battery Pack from 43°C to 30°C

Conclusion from the simulations is to continue the study using the Gas Injection heat pump system. The next step was to analyze what the energy savings would be and how much size could the battery pack be reduced.

Effect on Driving Range in Various Scenarios

After deciding the system to continue with the study, which is the gas injection system, simulation was done to learn what exactly the impact is on "Fuel Economy" by using this dedicated thermal system compared to the base system. This involved evaluating at all the conditions shown in Figure 8. Figure 20 shows the effect of the new Gas Injection heat pump system compared to the base system considering different driving habits and environments. Because the only efficiency gain was in heating mode, there is only 0-2% improvement in Miami, but in Minneapolis it is calculated that the GIHP system will improve fuel economy by 5-18%, depending on the driver habits. The driver habits were based on information provided by FCA, so the details cannot be shared; however an example is some drivers drive short distances, with limited stops, some drive short distance, with a lot of stops with aggressive acceleration and deceleration, and others are longer drives with no stops. It is assumed that all drivers drive to work, stop to make an errand on the way home, and then continue home to park for the night and plug in. We assume the vehicle is not driven on the weekend. Note that in Figure 20, he box for system control shows there are specified values for when to turn the heating or cooling on based on the battery temperature. (The temperature range the battery pack is kept.) In Figure 21, we changed those values to run the battery at cooler temperatures.

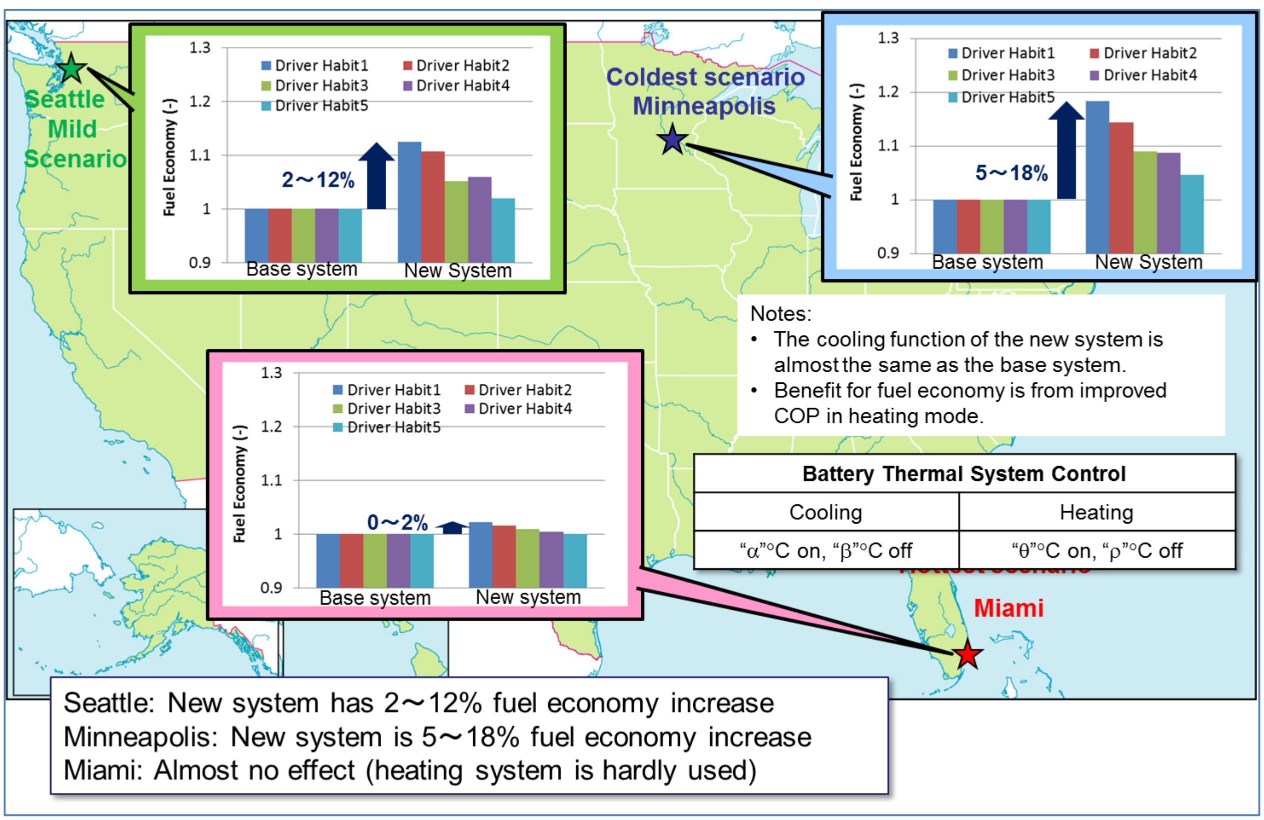


Figure 20: Effect on Driving Range at Various Scenarios (Baseline & GIHP)

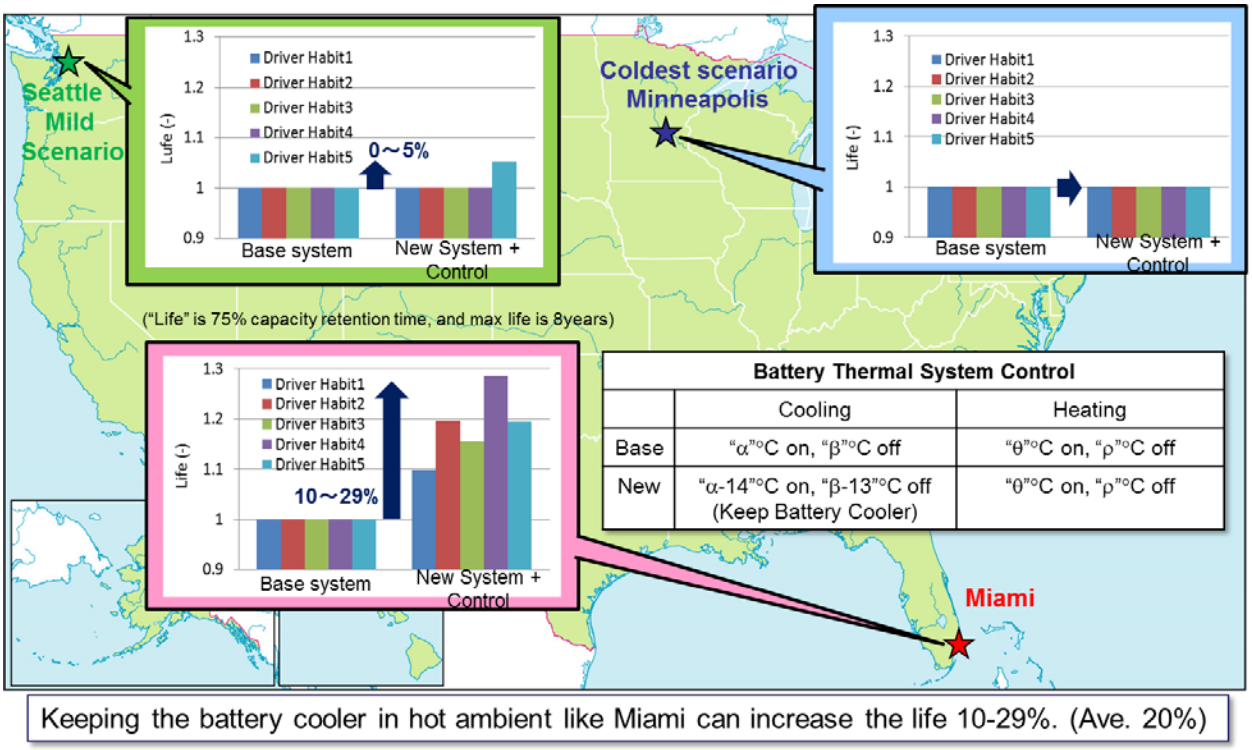


Figure 21: Battery Life of GIHP System & GIHP System with Modified Temperature Controls

In Figure 21, it is shown that by keeping the battery temperature lower, there is a large impact to battery life in areas like Miami. However, in Seattle or Minneapolis, there is little to no effect. This means that keeping the battery cooler helps for vehicles being used in warm climates. But, does keeping the battery cooler affect the driving range (Fuel Economy)? To answer this, Figure 22 shows there is little impact to driving range from reducing the operating temperature of the battery pack.

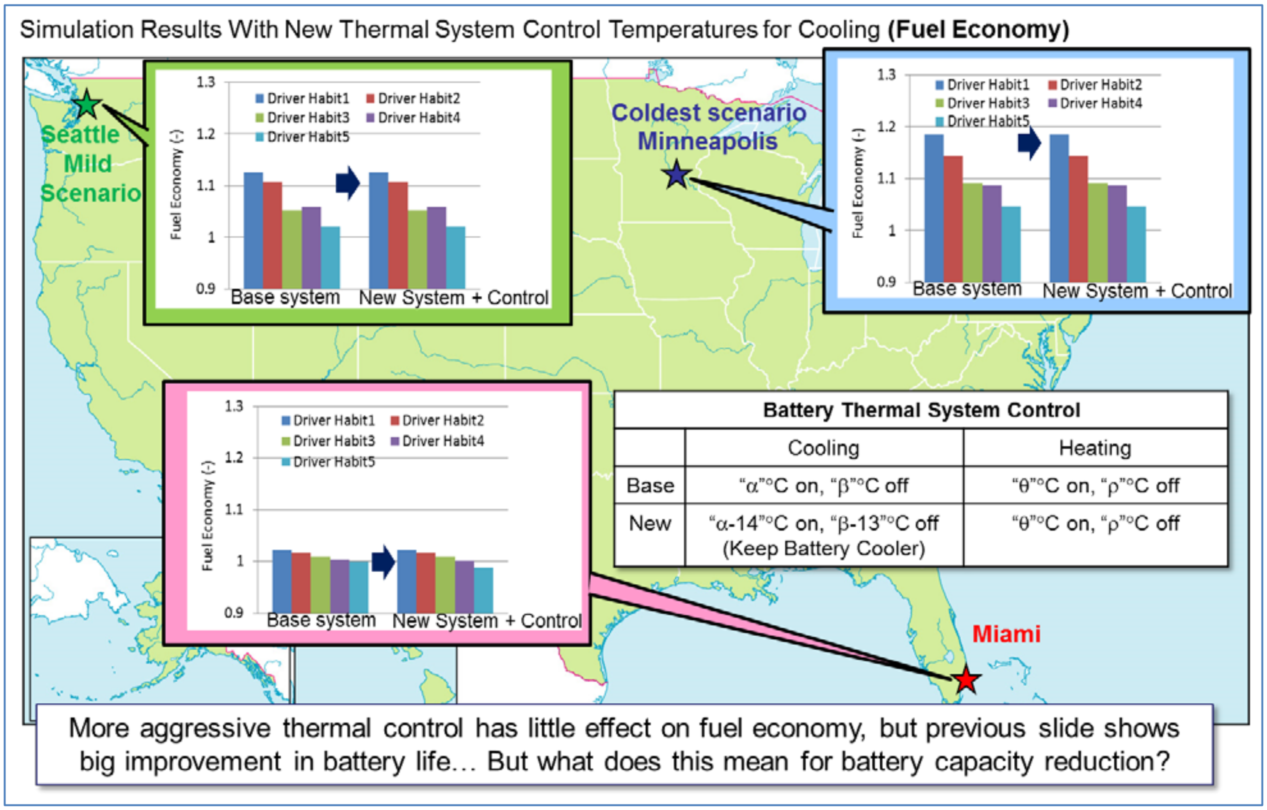


Figure 22: Fuel Economy (drive range) with controls to keep the battery cooler

Simulation for Battery Size Reduction (Battery Life)

Based on the above, simulation was done to determine how much battery capacity could be reduced and meet the battery life requirements. The key parameters to look at when studying the battery pack life is the resistance increase and capacity fade over time. For this project, the maximum battery resistance that was allowed is 1.3 more than the new battery cell. And the minimum capacity for the battery cell is 75% of the original capacity. This means that if a battery cell resistance is 1.3 times more than the original, or capacity is 75% of the original, the battery is considered at the end of life. The goal is to prevent these two from occurring while the battery is still covered by the vehicle warranty, which in this case was 8 years. And of course driving habit has an impact to this because of the cycle rates. If the battery is deeply discharged and charged again in a high frequency, it will reach the end of life faster than if the battery SOC (state of charge) is kept high or frequency is low. Figure 23 shows the comparison of resistance and capacity of the battery with the base system, and with the new system. (Again, new means GIHP with controls to keep the battery cooler.) These results were from Miami conditions, where battery life was the worst.

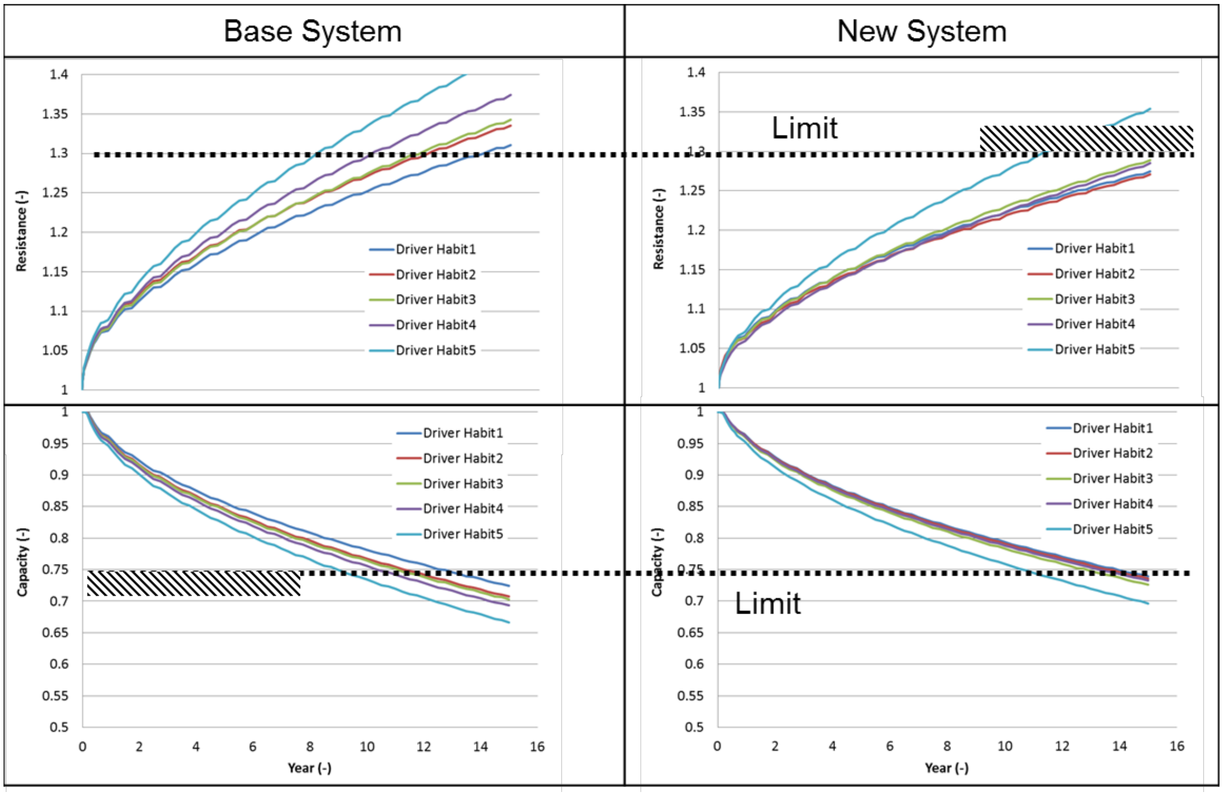


Figure 23: Comparison of Battery Resistance and Capacity (battery life) for Base System and New Thermal System with Updated Controls

Based on Figure 23, it is clear that driver habit 5, in Miami, is the worst case for battery life. To understand how much the battery could be reduced Figure 24 shows the battery capacity of drive habit 5, with new system, and reducing the starting point down until the capacity intersects 75% at the 8 year point. By doing this, we can see we can reduce the initial battery capacity by 5%. Another way to look at this is if the original battery capacity was not reduced, then the battery life could be increased by almost 2 years. This could lead to higher used vehicle value or allow the OEM to provide a 10 year instead of a 8 year battery warranty. Figure 25 shows the increase in battery life, comparing the base system capacity and the new system capacity fade over time.

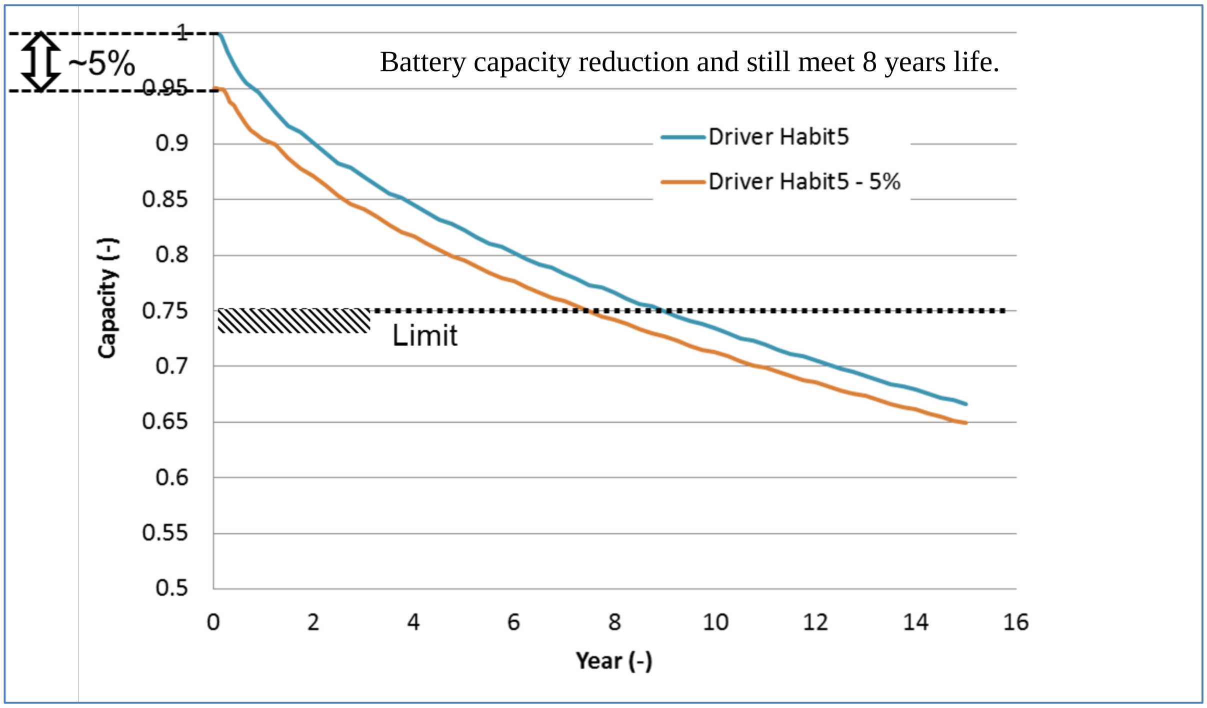


Figure 24: Battery Capacity can be Reduced ~5% and Still Satisfy ≥75% at 8 years.

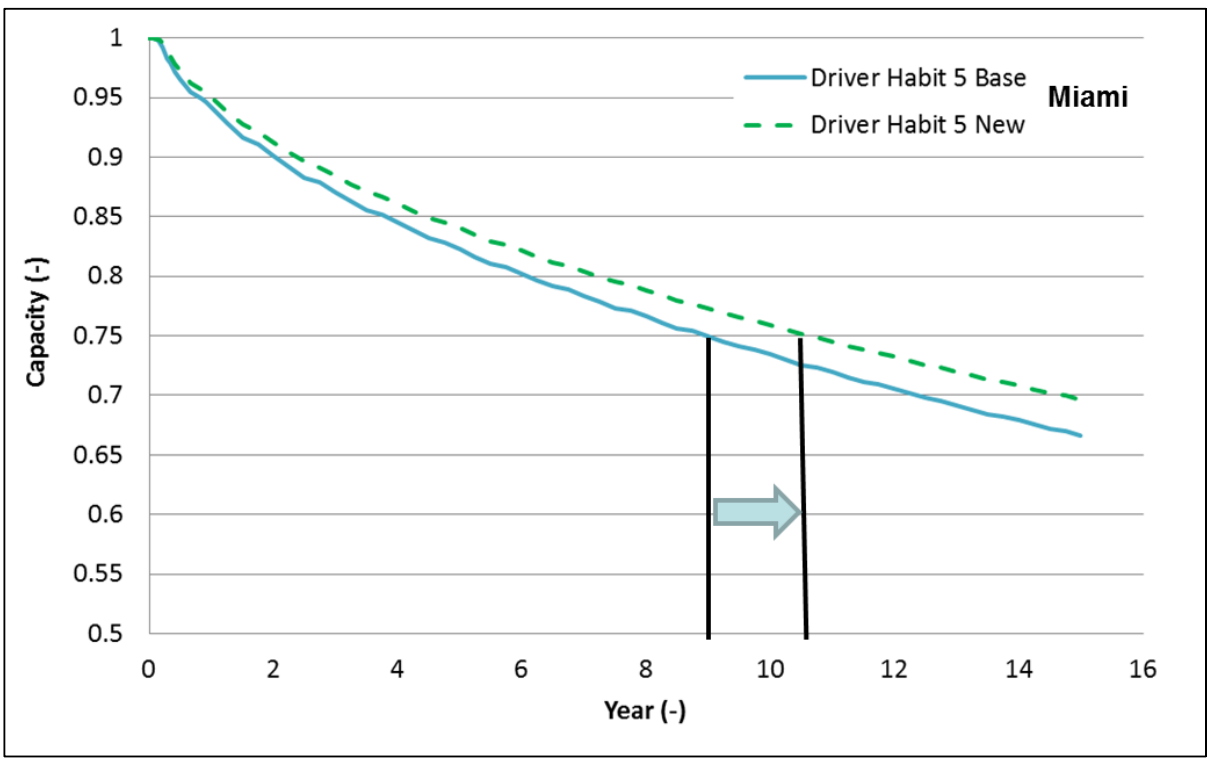


Figure 25: Battery Life Could Be Extend ~2 Years by keeping the Same Beginning of Life Capacity.

It should be noted again that the NREL battery life model was used for these calculations. Also, this is very reliant on the sensitivity to the battery chemistry and cycles and just decay over time. We found that even if the battery was maintained at 20°C for its entire life, the battery pack still has a pretty constant capacity reduction over time. This was something that was not considered when the original 20% battery pack size reduction target was set, is that 15% of that is just the effect of the battery chemistry degrading over time and number of cycles.

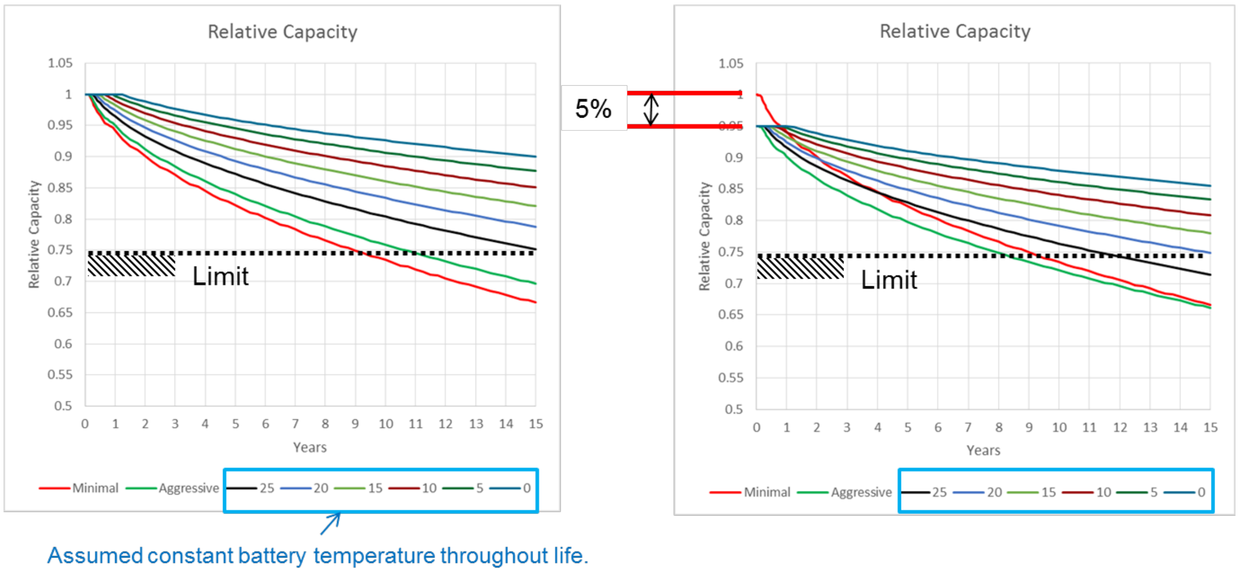


Figure 26: Minimal (base) Thermal Management and New Thermal Management Controls, compared to keeping constant battery temperature for its entire life.

Cost Analysis

Based on the above numbers, it is found that the battery pack size could be reduced by 5% and still keep the required life of the battery. Based on this, an analysis was done to roughly estimate the cost savings by using the stand alone system. To make this estimation, some assumptions had to be made about the battery pack capacity, cost of the battery pack, and the cost of the thermal system components.

Cost Analysis Assumptions	
Baseline Battery Pack Size	24 kWh
New Battery Pack Size (5% Downsize)	22.8 kWh
Battery Pack Cost (based on industry data)	$250 / kWh
Base Thermal System Cost (chiller + electric PTC Heater)*	$450
Stand Alone System Cost* (see figure 28 for component list)	$800
System Cost Integrated into Vehicle A/C*	$450

Figure 27: Assumptions for Cost Analysis

*Engineering Estimates

The list of components used to determine the costs of the stand-alone system are in Figure 28. Base system components consist of only the battery chiller and PTC heater since the rest of the vapor compression cycle is part of the vehicle AC system.

Stand Alone System Component List
Compressor
Water - Refrigerant Heat Exchanger
Electronic Expansion Valves
Gas Liquid Separator
Refrigerant Solenoid Valves
Water Valves
Pipes
Outside Heat Exchanger

Figure 28: Component List Used for System Cost Analysis

Based on the assumptions in Figure 27, Figure 29 shows the cost analysis results. The results show that even though the battery pack size was reduced 5%, the cost of the smaller battery pack, plus the cost of the stand-alone system are actually $50 more than the base system which has a larger battery pack, but smaller (cheaper) thermal system. Because of this, it is recommended to convert the vehicle air conditioning system to a heat pump, and basically integrate the new system into the vehicle AC system. This reduced cost by only have one refrigerant compressor. When this is done, we can achieve a 5% cost down from the base system.

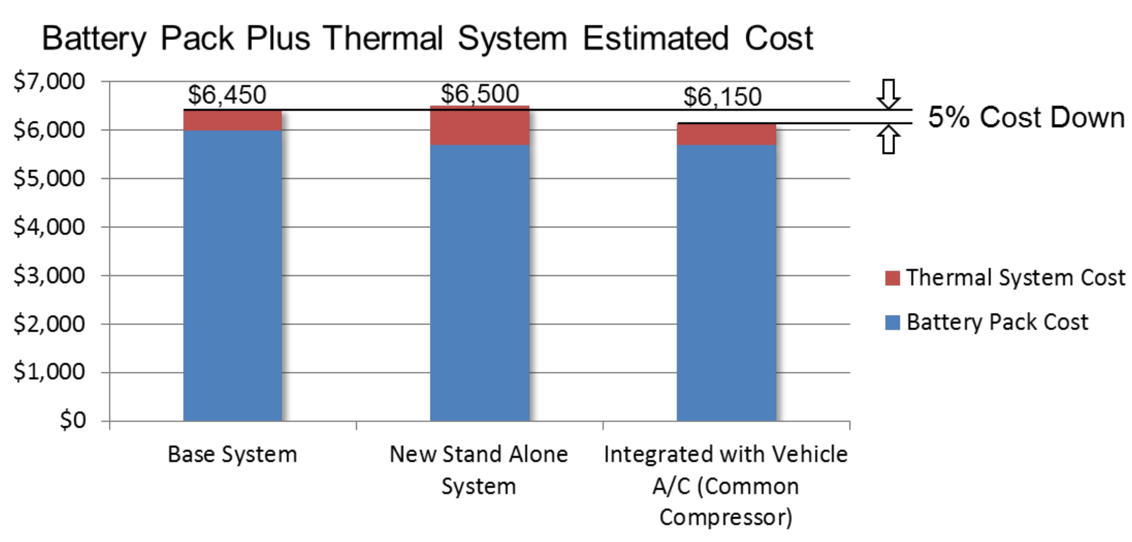


Figure 29: Results of the Cost Analysis

Phase 3: Actual Bench Testing

To confirm the simulation results, the stand alone thermal system was constructed in a test bench at DENSO International America. It was connected to the Fiat 500 EV battery pack. The system set up looked like Figure 11. The battery was in a room separate from the rest of the stand-alone system. This was simply because one room wasn't big enough to put all the test equipment in. Both rooms have the ability to run at temperatures from -40°C to 80°C.

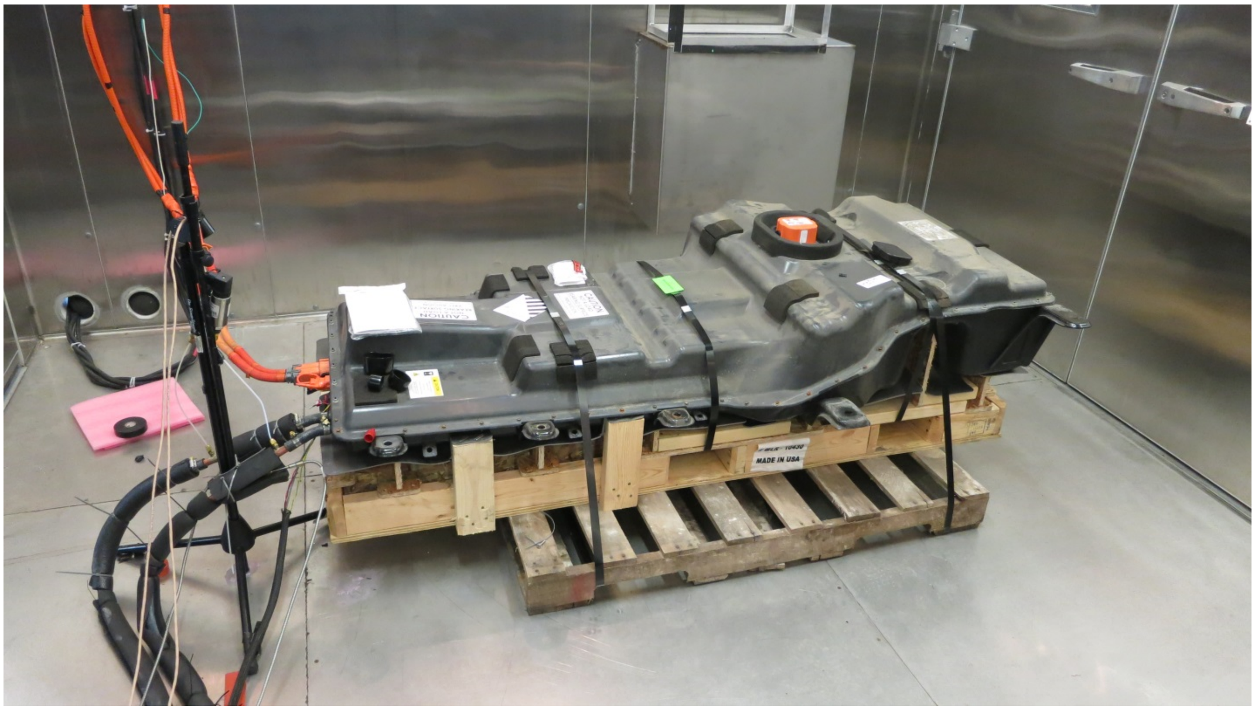


Figure 30: Photo of Battery Pack Installed In Thermal Test Chamber at DENSO

Test Equipment List

- Arbin BT2000-PWM (600V, 300A)
- Arbin MITS Pro Testing Software (Charge and discharge the battery at specified rates)
- CANalyzer from Vector for communication with the battery management system.
  - Read internal temperatures
  - Communicate with battery to turn the high voltage circuit on or off.
- RTD Probes for coolant, air and refrigerant temperatures
- Honeywell 440 Pressure Transducers (Coolant and refrigerant pressures)
- Campbell Scientific CR9000 for measuring all system temperatures, pressures, flows and recording in Microsoft Excel for data acquisition.

Test Data

The first tests that were done was simply warming up the battery pack from -20°C and cooling the battery pack off from 43°C. There was no current draw from the battery pack, so this is only heating and cooling the mass of the battery pack. The purpose of this is to confirm the thermal mass value that was used in the simulation model. If the thermal mass value in the simulation is incorrect, then the values report would not be accurate as more or less energy would be required to change the temperature of the battery pack. As shown in Figure 31, the data for warming the battery pack up from -20C to 0C has very close correlation. The Bench Data is in steps because this is the resolution of the actual battery cell temperature from the battery CAN data. Figure 31 is a similar test, but going the other way and cooling the battery pack off from 43C soak to 30C soak. Again good correlation is shown. At the start of the cooldown, it is noted that the simulation shows the cell temperature dropping before the actual bench testing, but this is believed to be somewhat related to the resolution and location of the battery cell temperature sensor located in the actual battery pack. The important fact is the slope or rate of change is almost the same.

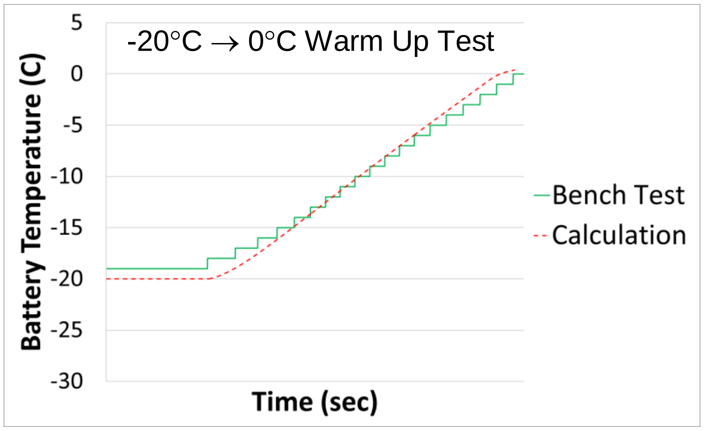


Figure 32: Comparing simulated battery warm up and actual bench testing battery warm up

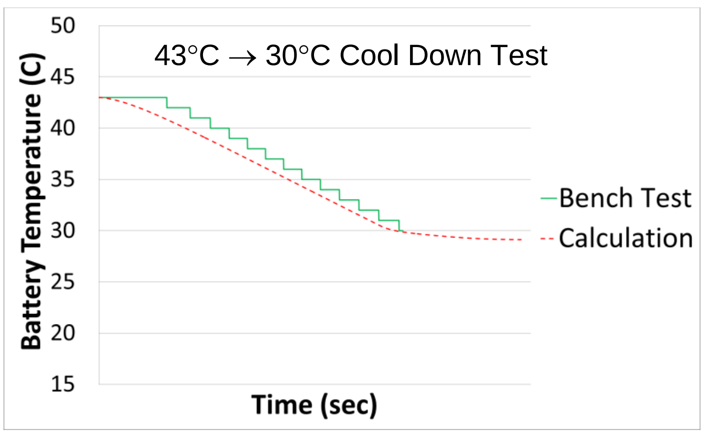


Figure 31: Comparing simulated battery cool down and actual bench testing battery cool down

The next testing that was done on the bench was evaluating the temperature of the battery pack at typical automotive drive cycles. In this case, the US06 drive cycle was used after soaking the battery and thermal system at 43°C, and Davis Dam was tested also after soaking the battery pack and system at 43°C. The US06 is an US EPA drive cycle and drive pattern is well published on EPA web sites. The US06 represents aggressive driving pattern which consist of high charge and discharge rates on the battery pack. (thus creating heat in the battery) The Davis Dam is not an EPA test, but is commonly used in the automotive industry for evaluating the performance of powertrain cooling systems and is reflected in J2807 "Highway Gradeability" test. Conditions are an 11.4 mile long road which starts at an elevation of 550ft, and ends at an elevation of 3,500 ft., with ambient temperature of at least 38C (100F) and the vehicle must maintain speed of roughly 40-50 miles per hour. This test puts a constant, high current discharge rate on the battery pack for a long length of time in very high ambient temperature. Figures

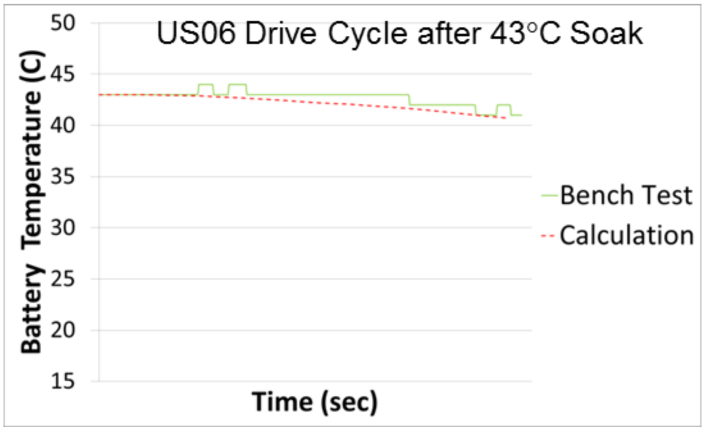


Figure 33: Comparing Simulation and Bench Data During US06 Drive cycle at 43°C

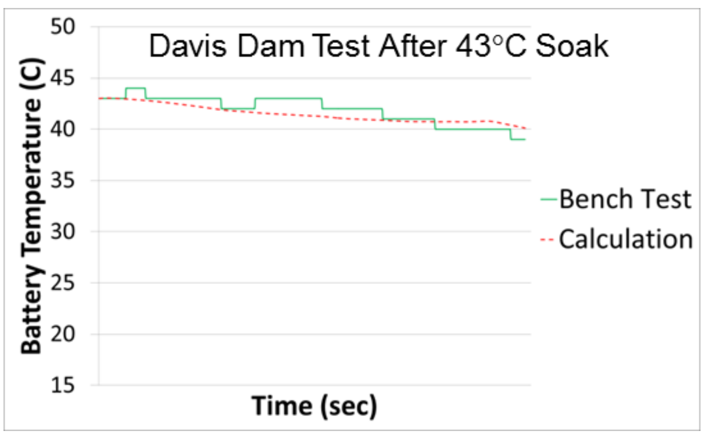


Figure 34: Comparing Simulation and Bench Data During Davis Dam Drive Cycle at 43°C

The following pages document the detailed data that was gathered for each of the tests listed above.

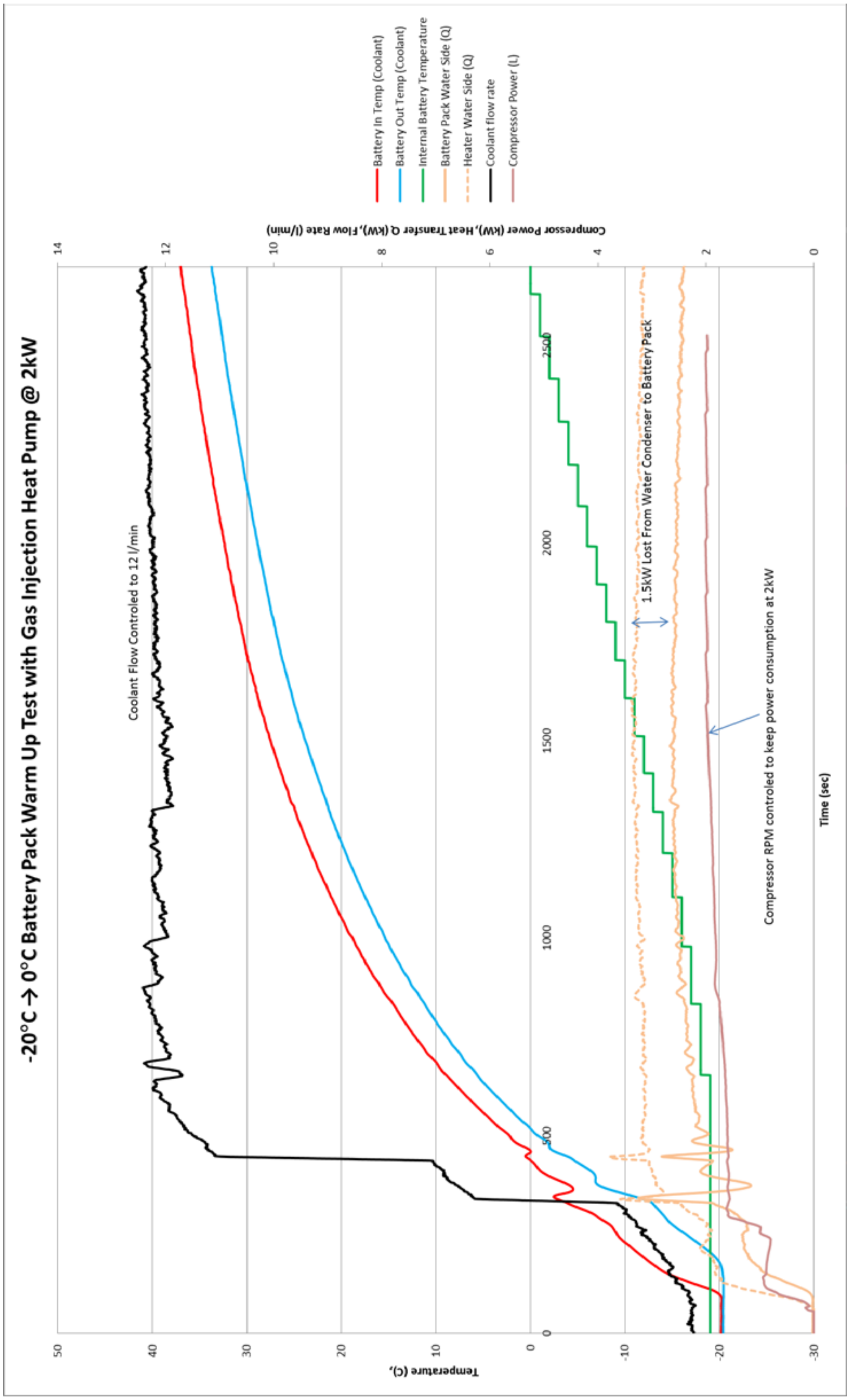


Figure 35: Detailed Data From -20°C -> 0°C Warm Up Test

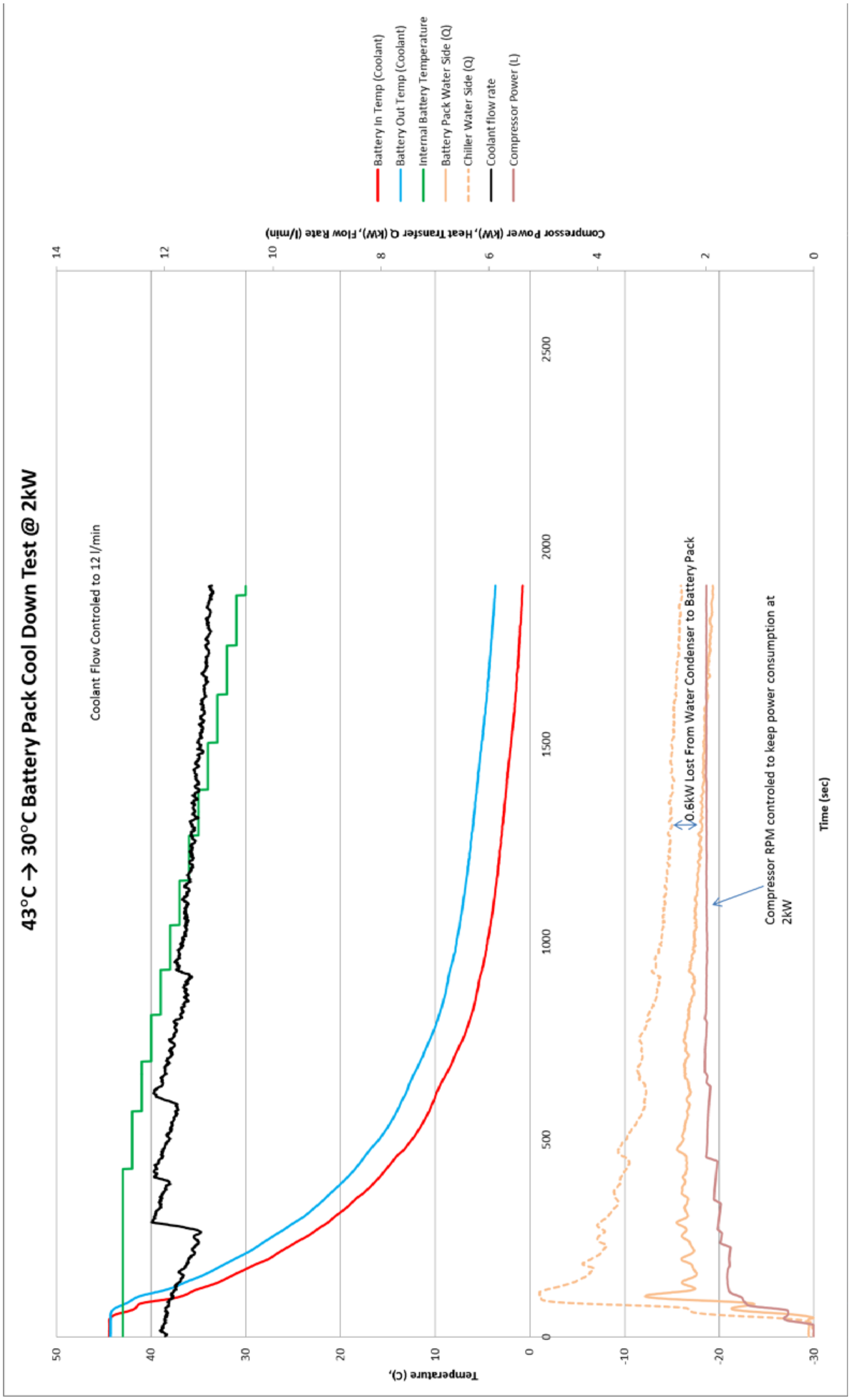


Figure 36: Detailed Data from 43°C to 30°C Battery Cool Down

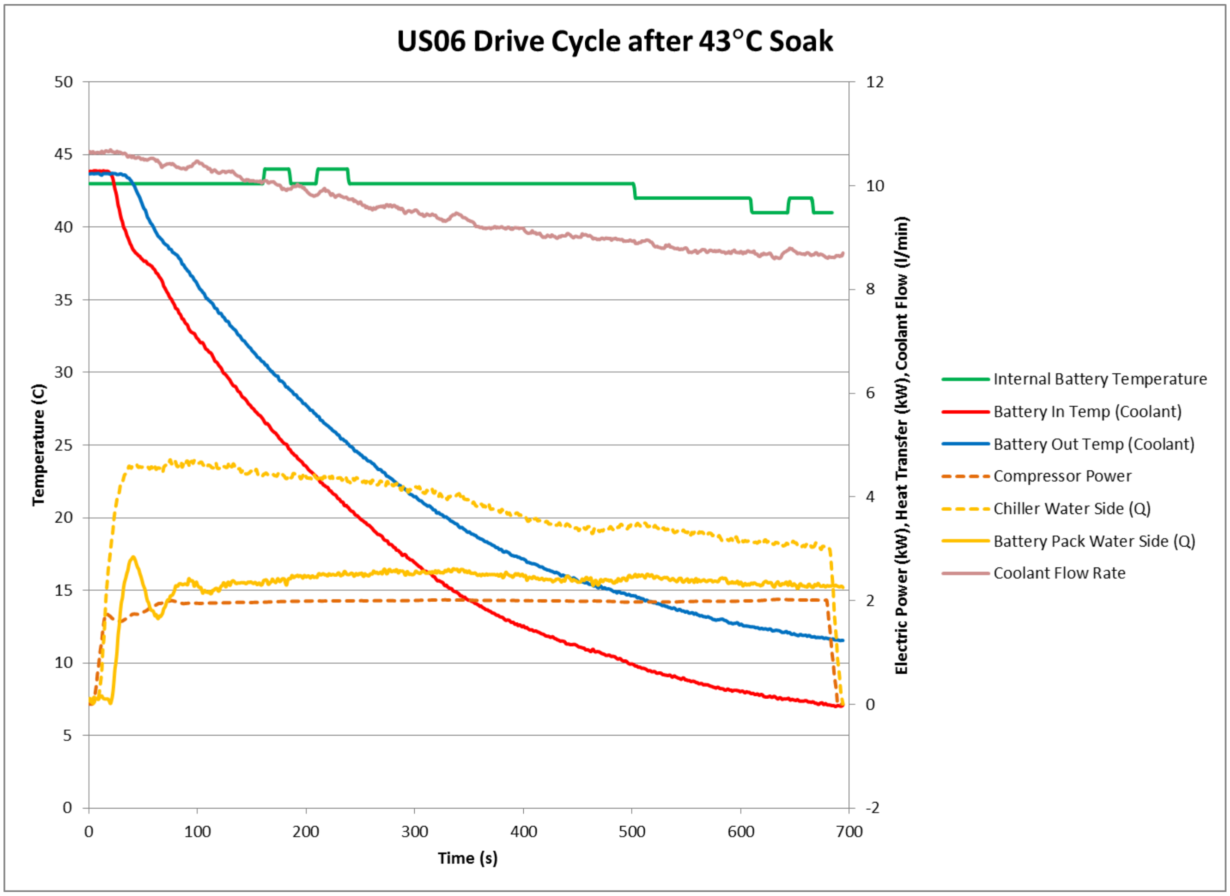


Figure 37: US06 Drive Cycle Bench Test Detailed Data

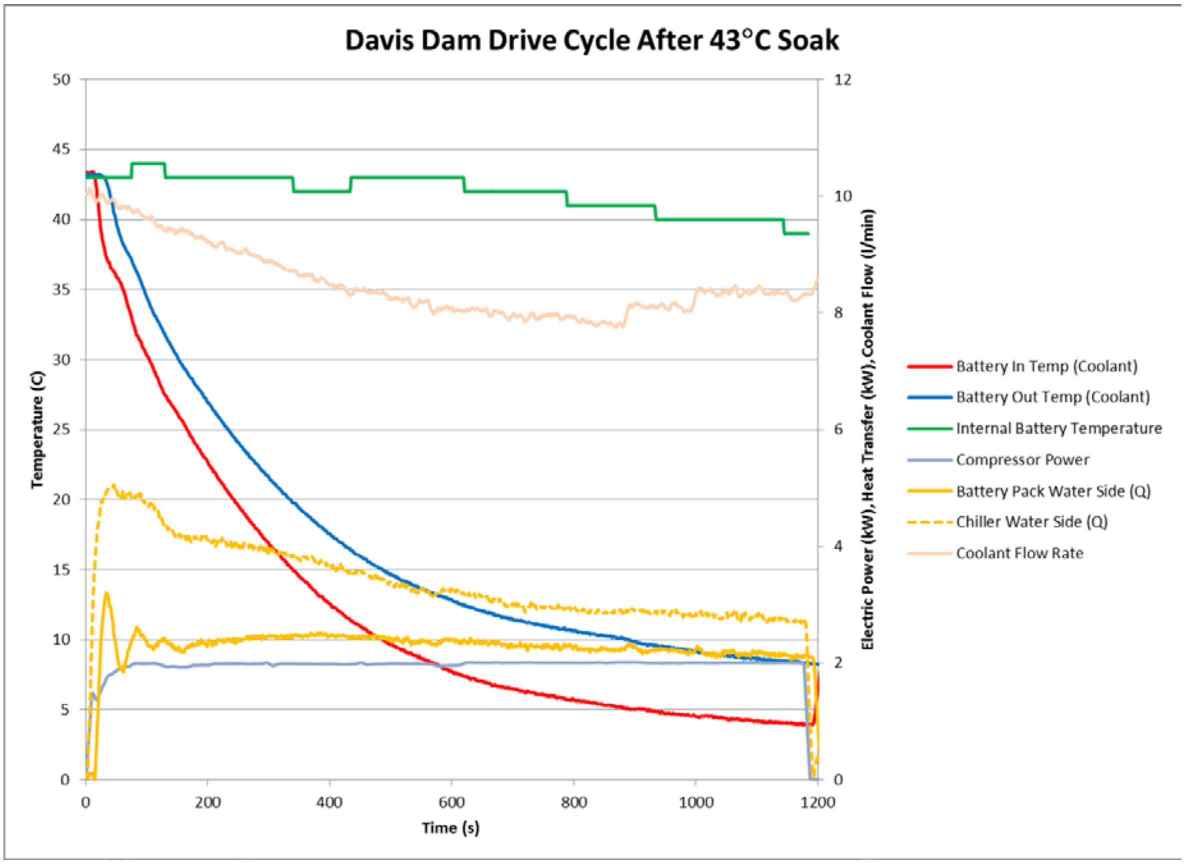


Figure 38: Davis Dam Detailed Bench Test Data

Due to time constraints, it is not possible to test every driver habit and condition that was done during the simulation stage. However, the data above that compares the data from the simulation model to that of actual bench testing shows the thermal mass of the battery is correct from the cool down and warm up tests. Also, the heat rejection and performance of the thermal system is confirmed in the US06 and Davis Dam tests when the battery pack is actually charges / discharged with the thermal system working to cool the battery.

The final stage and "check" is for the complete battery pack and thermal system to be sent to NREL for verification of the test results, and further study of the battery thermal behavior. The testing we done at the NREL Golden Colorado using a thermal chamber to heat or cool the battery pack for simulating hot or cold ambient conditions. Due to lab restrictions, the thermal system was located in the lab area outside the thermal chamber, at room temperature. Therefore, the results could not be compared directly; however it does confirm the heating / cooling rates and thermal mass of the battery pack. The NREL results are shown in figures 39 and 40.

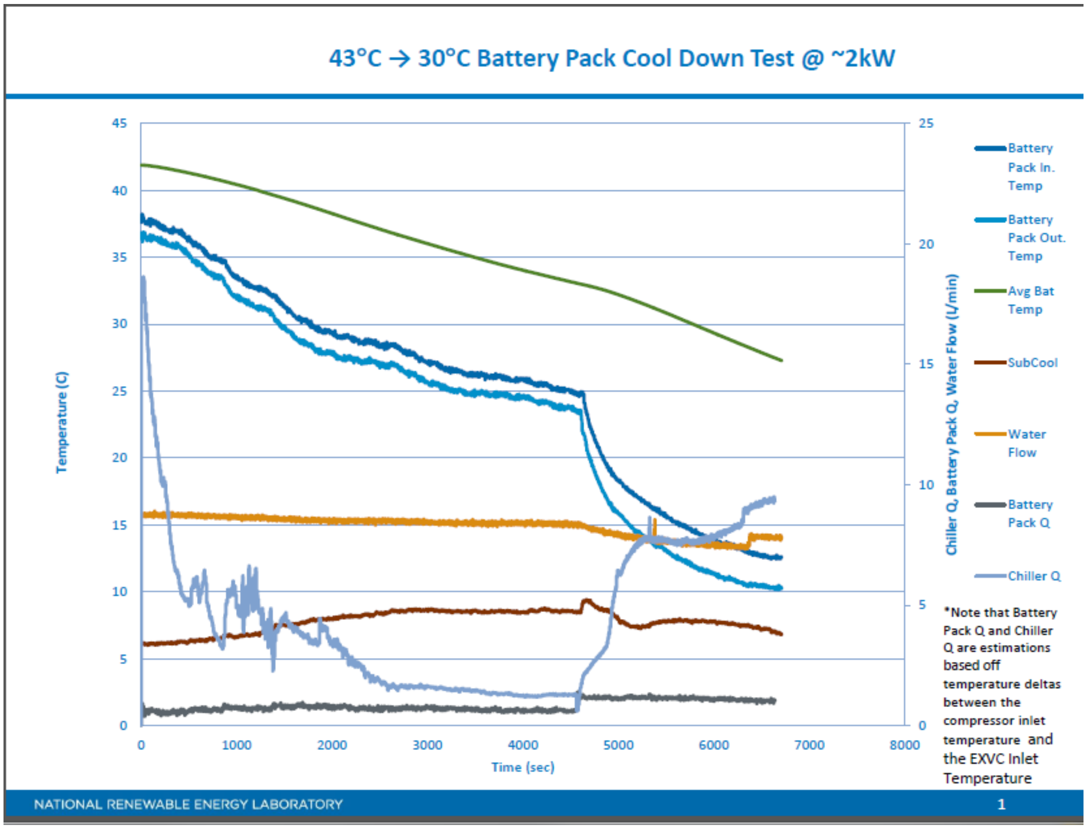


Figure 39: Battery Cool Down Data from NREL

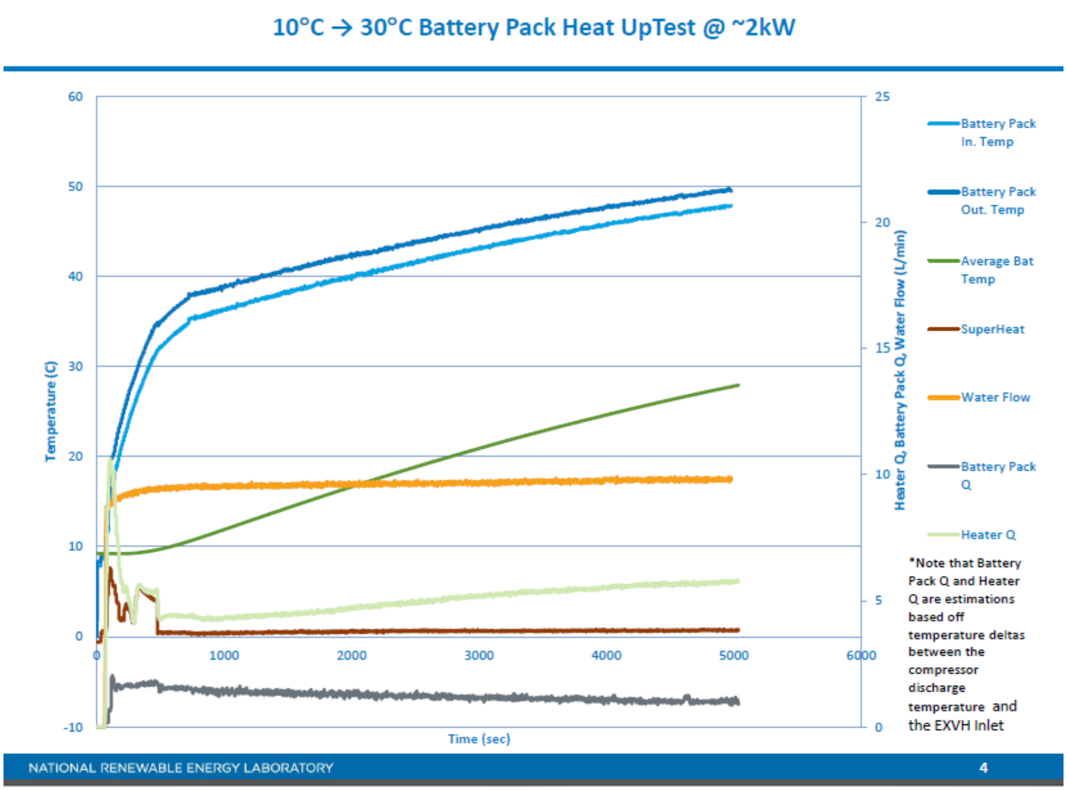


Figure 40: Battery Pack Warm Up Data from NREL

Conclusion

During this project, as battery pack simulation model was created in AMEsim. The model was linked to other simulation tools to calculate battery life and thermal system performance. The results show that for the stand alone system, the heat pump system can improve driving range, or “fuel economy” by 12% compared to using a traditional PTC heater. Also, by keeping the battery cooler in hot ambient, the battery capacity could be reduced by 5%, or the life of the battery pack could be increased by 2 years. However, the additional cost of the stand-alone system is larger than the cost savings from the 5% reduction in battery pack capacity. Therefore, it is recommended that the battery thermal system be integrated with the vehicle cabin air conditioning system. By doing this, overall system cost can by reduced by 5%. It is recommended for future work that more studies be done on the potential energy savings of integrating the heat pump to heat not only the battery, but the vehicle cabin. There is potential for a large amount of energy savings which can improve driving range in cold weather.

Glossary

AC or A/C = Air Conditioning

COP = Coefficient of Performance

FCA = Fiat – Chrysler Automotive LLC

GIHP = Gas Injection Heat Pump

HP = Heat Pump

OEM = Original Equipment Manufacture

PTC = Positive Temperature Coefficient (Type of electric heater)

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R. Kroeze, P. K. (2008). Electrical Battery Model for Use in Dynamic Electric Vehicle Simulations. *39th IEEE Power Electronics Specialist Conference.*

Kim, G.H. (2008). Three-Dimensional Lithium-Ion Battery Model. *4th International Conference Symposium on Large Lithium Ion Battery Technology and Application* (p. 34). Tampa, FL: National Renewable Energy laboratory.

Publications

<u>Effect of a Stand Alone Battery Thermal System on Lithium Ion Battery Life and Driving Range,</u> Advanced Automotive Battery Conference, June 16, 2015, Detroit, MI