Re-Use of Electric Vehicle Batteries for Smart Grid Energy Storage Systems

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1. Societal Need

Energy is a necessity and there is a projected **global reliance on fossil fuels** in 2035.

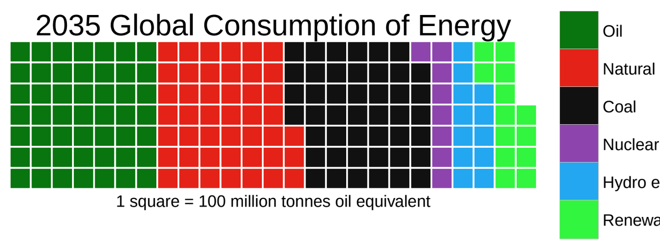


Figure 1: 2035 Global Projected Energy Consumption[1]

CO_2 from **burning fossil fuels** leads to a greenhouse gas (GHG) effect. Scientific evidence shows causality (through complicated correlation) between **GHG emissions & global warming**.

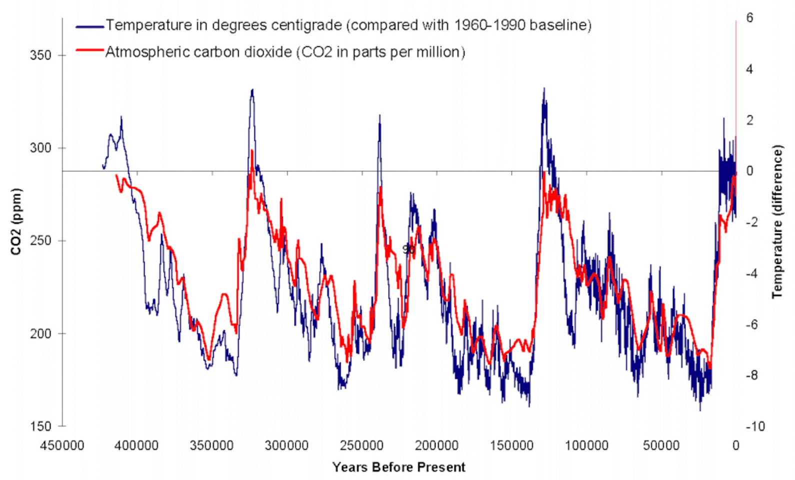


Figure 2: Observed Temperature and CO_2 Ice Core Records[2]

2. Problem

Utility companies rely on fossil fuels for peak demand energy generation since most renewable energy is intermittent and nuclear power is constant. The current **peak shaving** solution (i.e. time of use pricing) does not create true **load leveling**.

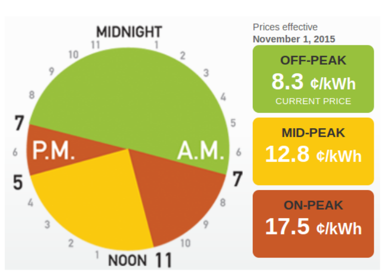


Figure 3: Ontario Time of Use Electricity Pricing[3]

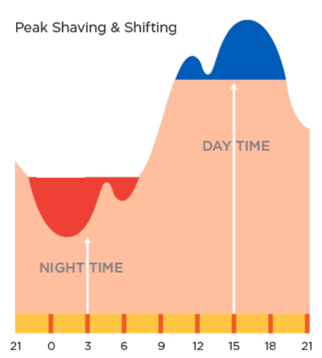


Figure 4: Peak Shaving

Also the increasing number of plug-in electric vehicles (EV) produces new **battery waste**.

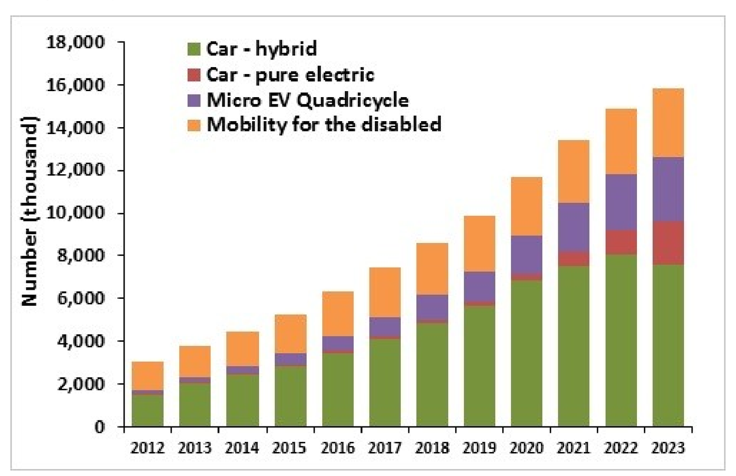
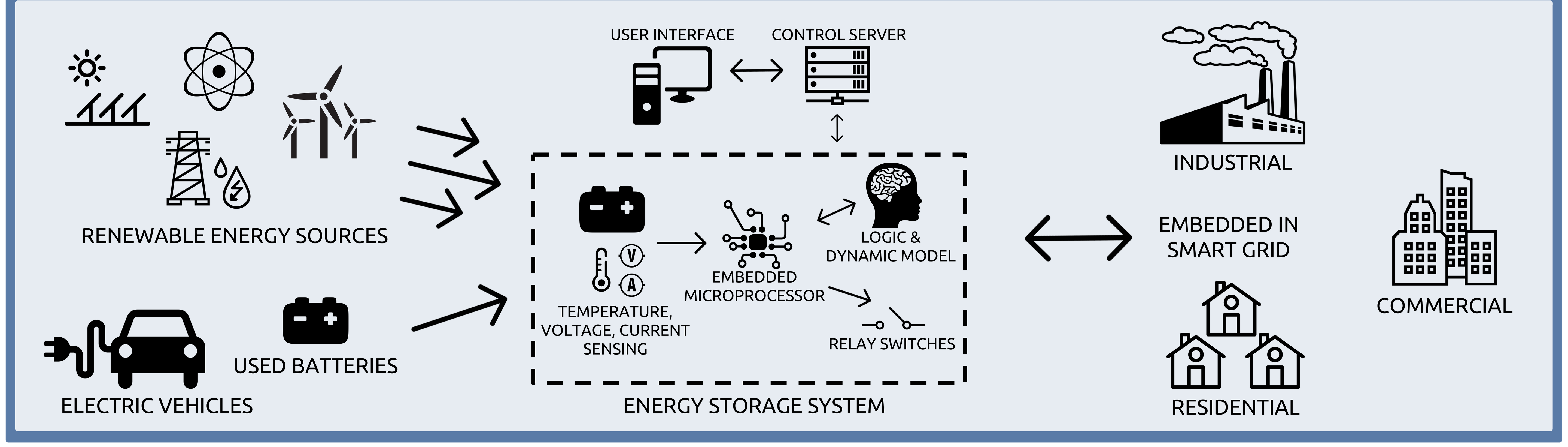


Figure 5: Forecasted EV sales [4]

3. Solution: Re-purposed Electric Vehicle Batteries for Energy Storage



3.1 Battery Modeling

EV batteries are disposed when they cannot meet the vehicle voltage requirements. Research shows that after an irreversible capacity fade, disposed batteries can still hold up to 80% of charge.

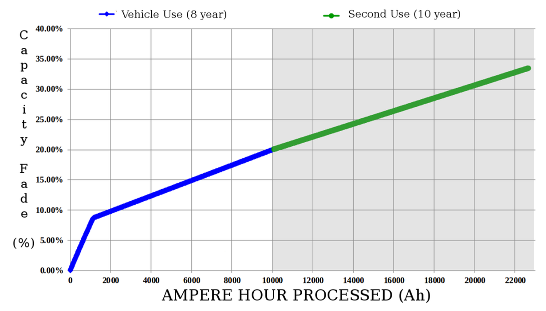


Figure 6: Capacity Fade on Battery[5]

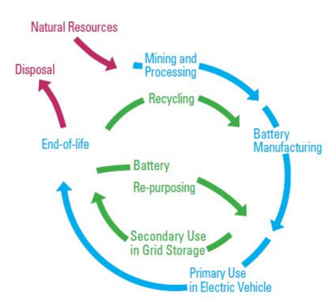


Figure 7: Proposed Battery Lifecycle[6]

The first step was to create and verify a system model of the re-purposed batteries.

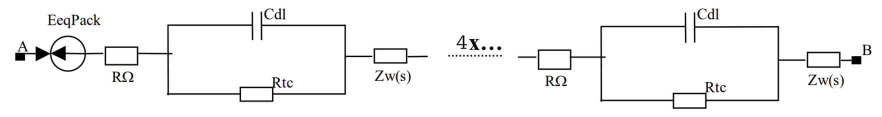


Figure 8: Battery Pack (Plant) Model

System Equations and Data Validation:
Voltage Response of Given Current:

$$v_{eqpack}(t) = E_{pack} + R_{\Omega}i(t)$$
$$+4\left[\mathcal{L}^{-1}\left(\frac{R_{tc}I(s)}{1+sR_{tc}C_{dl}}\right) + \mathcal{L}^{-1}\left(\frac{(1+s\tau_2)^{n_2}I(s)}{(s\tau_1)^{n_1}}\right)\right]$$

Energy Flow in Battery System:

$$e(t) = \int_{t=0}^{t} p(t)dt = \int_{t=0}^{t}\left[E_{eqpack} + 6\left(R_{\Omega}j(t) + \sum_{n=1}^{15} v_n(t)\right)\right] i(t)dt$$

Heat Generation (HG) in Battery System:

$$q = \dot{Q} = \int \delta Q/t = Q_{charged \to discharged}/t$$
$$q = (I(U-V) + I(T\frac{dU}{dT}))/t$$

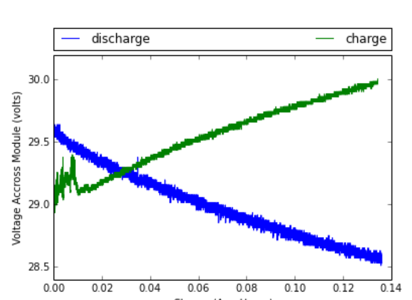


Figure 9: State of Charge (Coulomb Counting)

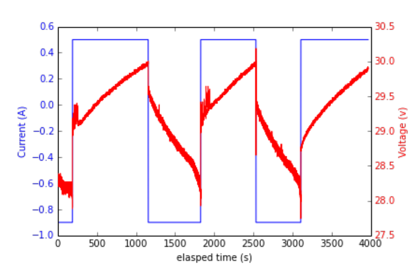


Figure 10: Voltage Response of Battery Cell to Current

3.2 Electrical Design

After bench-marking the batteries, an electrical system was designed and implemented to safely monitor and control the charging and discharging.

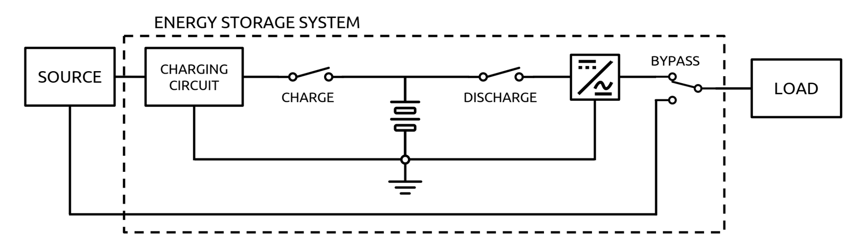


Figure 11: Simplified System Circuit

There were five parallel packs of four 7.2 V, 6.5 Ah Toyota Prius NiMH battery modules in series.
Useful Capacity: 480 Wh (see [7])
Nominal Voltage: 28.8 V

3.3 Mechanical Design

The enclosure was designed to securely house the batteries, allow for adequate temperature control and meet safety requirements.

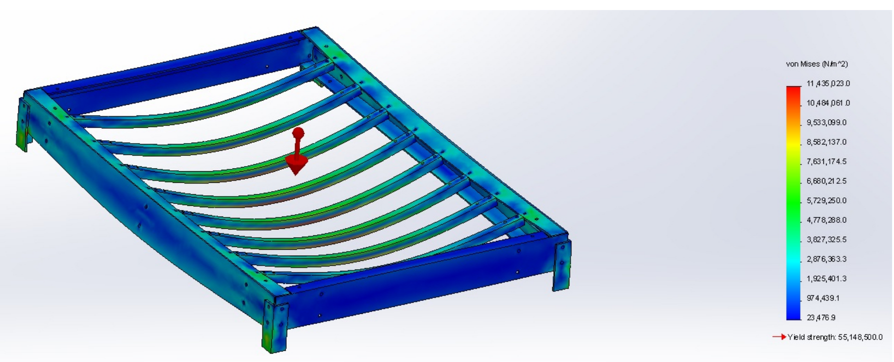


Figure 12: Bottom Frame Stress Analysis

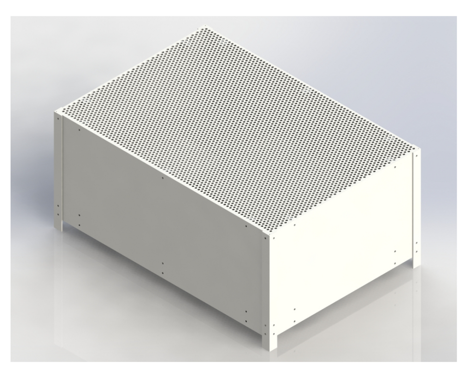


Figure 13: Full 3D Photo-realistic Render

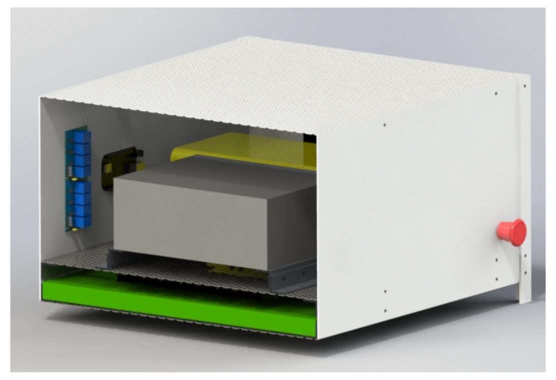


Figure 14: Cross Sectional View

3.4 Controls

Next, a closed loop control system was designed to meet specifications and requirements.

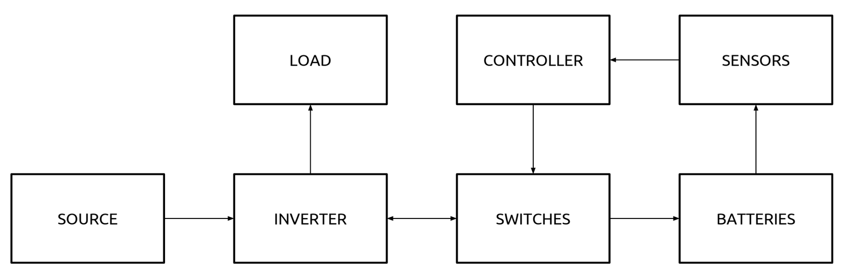


Figure 15: High Level System Block Diagram

State of the art non-linear control system:
Demand Forecasting (DF): Autoregressive Moving (Winter's) Triple Exponential Smoothing
State of Charge (SOC): Extended Kalman Filtering paired with Coloumb Counting
Remaining Useful Life (RUL): Support Vector Machine (non-linear) Charge Regression
Dynamic Temperature Control: Fuzzy rule-sets based upon HG, DF, SOC and RUL
Internet of Things (IOT):

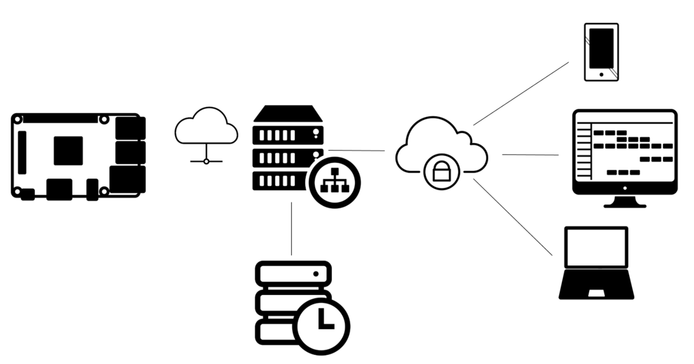


Figure 16: Internet of Things System Diagram

4. Results

In one winter month in Ontario, at the grid level, stationary energy storage can replace 788 GWh of demand normally supplied by natural gas, eliminating 143 Mt of CO_2 emissions[8]. A household may save \$50 on their monthly electricity costs.

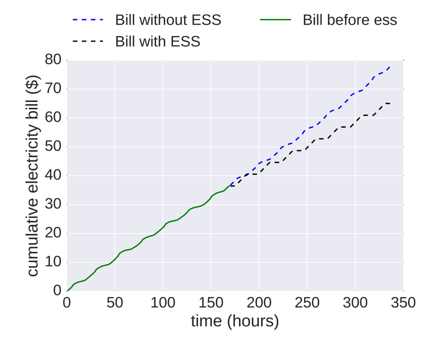


Figure 17: Monthly Savings with Energy Storage

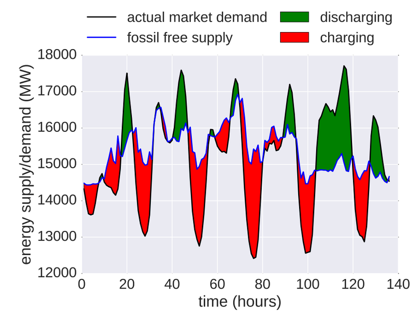


Figure 18: Grid Level Supply and Demand with Energy Storage

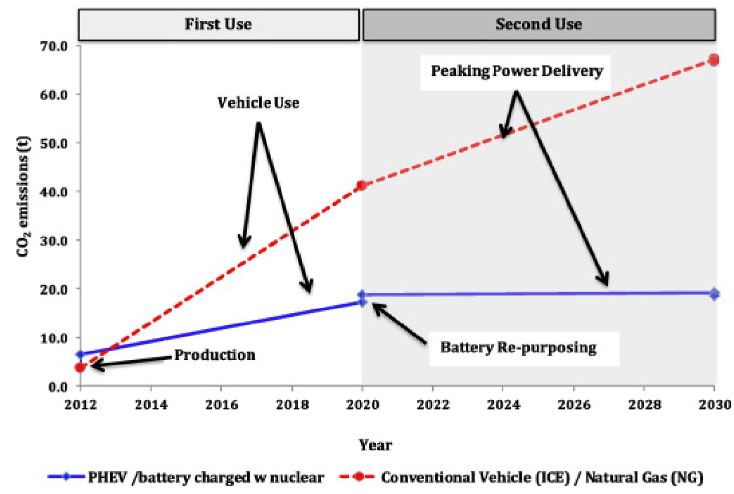


Figure 19: Simulation of CO_2 Emissions [6]

5. Conclusion

The prototype built successfully demonstrated the ability of re-purposing EV batteries for distributed stationary energy storage to create true load leveling in the energy grid.

References

[1] April 2015 BP statistical review of world energy.
[2] NOAA Paleoclimatology Program. Temperature change and carbon dioxide change.
[3] Ontario Energy Effective Winter Prices & Periods.
[4] Peter Harrop and Raghu Das. Hybrid & pure electric vehicles for land, water & air 2013-2023: Forecasts, technologies, players.
[5] Leila Ahmadi et al. Energy efficiency of li-ion battery packs re-used in stationary power applications.
[6] Leila Ahmadi et al. Environmental feasibility of re-use of electric vehicle batteries.
[7] Catherine Heymans et al. Economic analysis of second use electric vehicle batteries for residential energy storage and load-levelling.
[8] EIA Carbon Dioxide Emissions Coefficients.
[9] Sean B. Walker et al. Incentives for the reuse of electric vehicle batteries for load-shifting.