

EFFECT OF ELECTRIC VEHICLES ON DESIGN, OPERATION AND COST OF A 100% RENEWABLE POWER SYSTEM

BY

MATTHIAS FRIPP

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UNIVERSITY OF HAWAI'I AT MANOA 2424 MAILE WAY, ROOM 540 • HONOLULU, HAWAI'I 96822 WWW.UHERO.HAWAII.EDU

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Contents

Introduction	1
Optimal power system designs	3
EV charging infrastructure	6
Cost of electricity production and transport	7

Introduction

This report outlines the effect that electric vehicles could have on the cost of transport and electricity production in the context of a 100% renewable power system (RPS). Results presented here were produced using the SWITCH power system planning model,¹ configured to choose a least-cost plan to achieve 100% renewable power on Oahu by 2045, subject to a 5% limit on biofuel usage.

We considered two fleet scenarios and two charging scenarios. The fleet scenarios are

- 3.5% Electric Vehicle (EV) adoption by 2045 this continues the trend in 2010-16, with an increase of about 700 EVs per year
- 100% EV adoption by 2045.

The two fleet scenarios are shown in Figure 1. In both cases, the total number of vehicles in the Oahu fleet was held constant at 816,908, and vehicles drove an average of 8,706 miles per year. These values come from the 2014 DBEDT State of Hawaii Data Book (Tables 18.07 and 18.17), and exclude trailers and semi-trailers. Note that this is about 15% more vehicles than DBEDT shows in their Monthly Energy Trends product; the reason for the discrepancy is unclear, but the Hawaii Data Book appears to be more authoritative, drawing on vehicle inspection data and reporting both number of vehicles and total mileage.





The two charging scenarios are

 business-as-usual (BAU) charging – 1/3 of the fleet is charged at work and 2/3 is charged at home, with a mix of level 1.4 kW, 3 kW and 6 kW chargers; vehicles are fully recharged as soon as they reach their charging destination (based on nationally representative trip information for 200,000 vehicles in the 2009 National Household Transportation Survey); this charging scenario is shown in Figure 2

¹ http://uhero.hawaii.edu/products/view/508/

• optimal charging – vehicles obtain the same total amount of charge each day as in the BAU scenario, but they charge during the best hours each day (as chosen by SWITCH).



Figure 2. Business-as-usual EV charging profile (normalized to have mean value of 1.0)

In this study, we considered three load scenarios, defined as the combination of the two fleet scenarios with the two charging scenarios:

- 3.5% EV adoption with BAU charging
- 100% EV adoption with BAU charging
- 100% EV adoption with optimally timed charging

For each scenario, we used SWITCH to design a least-cost power system to achieve 100% renewable power by 2045, in compliance with Hawaii's Renewable Portfolio Standard, while serving traditional electricity loads and electric vehicles. These systems could include any combination of existing plants, wind and solar power, new thermal power plants, battery energy storage, pumped hydro energy storage and hydrogen energy storage (a hybrid facility with same-day storage of compressed hydrogen and multi-month storage of liquid hydrogen). A variety of fuels were also available, though only biofuels or hydrogen could be applied toward the RPS. In these scenarios, we also assumed that 30% of non-EV electricity loads could be rescheduled freely to a better time of day (price-based demand response). SWITCH then chose the optimal combination of resources to build and operate, subject to these opportunities and constraints.

Optimal power system designs

Figure 3 through Figure 5 show the optimal resource mix and hourly energy balance for several days in 2045 for the three EV fleet and charging scenarios considered in this study. (Text continues after figures.)



Figure 3. Hourly balance of 100% renewable power system, with 5% EV adoption (current trend) and business-as-usual EV charging



Figure 4. Hourly balance of 100% renewable power system, with 100% EV adoption and business-as-usual EV charging



Figure 5. Hourly balance of 100% renewable power system, with 100% EV adoption and optimally timed EV charging

By comparing Figure 3 to Figure 4, we can see that serving a 100% EV fleet requires a significant increase in wind and solar power production, to generate enough energy for the vehicles each day. With the BAU charging shown in Figure 4, additional storage capacity (hydrogen electrolyzer, fuel cell capacity and some grid-connected battery) must also be added; these expensive resources are used along with pumped storage hydro to provide power during some of the times when EVs recharge.

By comparing Figure 4 to Figure 5, we can see how the optimal power system design changes if the 100% EV fleet is charged at the best times of day (generally during sunny hours) instead of following the BAU charging profile. With optimally charged timing as shown in Figure 5, it becomes possible to reduce investments in wind power and increase investments in solar (wind is an expensive resource on Oahu). Optimally timed EVs also act as a substitute for short-term storage, and in the optimally timed scenario, the capacity of grid-connected batteries, hydrogen fuel cells and pumped storage hydro are reduced *below* the level used for the 3.5% EV scenario. The capacity investments in each scenario are shown in Table 1.

	3.5% EVs, BAU charging	100% EVs, BAU charging	100% EVs, optimal charging
Reciprocating engine power plants	0	113	39
Wind farms	643	1,030	625
Central tracking PV	1,606	1,954	2,228
Pumped storage hydro	150	150	122
Utility-scale batteries (grid-connected)	0	68	0
Hydrogen fuel cells (grid-connected)	290	456	237

Table 1. Power system generation and storage capacity (MW) added in 2021–45 under three EV fleet and charging scenarios

EV charging infrastructure

Figure 6 shows the amount of power used to charge EVs during each hour of the day under BAU and optimal charging scenarios. Optimal profiles are shown for twelve different sample days in 2045. The optimal-charging scenario concentrates charging primarily during the day, but the profile can differ significantly between different days. This suggests that attention should be given to development of workplace charging infrastructure and incentives for EV owners to charge at optimal times, such as dynamic marginal-cost pricing of electricity, with lower prices when power is abundant and higher prices when it is scarce.

The optimal charging scenario also concentrates charging during a smaller number of hours than the BAU profile; more study is needed to determine whether grid upgrades would be needed to support EV charging in districts with large numbers of commuter workplaces. The main daytime charging window is about 8 hours long, significantly longer than most vehicles would need to charge. During this time, the average power drawn per EV is about 600 W. These factors suggest that standard 1–6 kW chargers should be able to deliver enough power for each vehicle.



Figure 6. Hourly electricity consumption for charging EVs under three EV fleet and charging scenarios (816,908 EVs in 100% scenarios)

Cost of electricity production and transport

Table 2 and Table 3 show the effect of large-scale EV adoption on the cost of producing electricity and providing transport. For these cost estimates, we assume that in 2013, EVs and chargers cost each owner (or their workplace) \$1,000 more per year than an Internal Combustion Engine (ICE) vehicle, due to additional capital requirements for the higher-priced EV and for the charging station. We assume this extra cost declines linearly to \$200 per EV in 2045. We also assume that ICE vehicles have an efficiency of 23 miles per gallon of gasoline (mpg) in 2013, rising to 50 mpg by 2045. The cost of fuel for ICE's is based on forecasts by the U.S. Energy Information Administration.

Table 2 indicates that a 100% EV fleet (816,908 EVs) could save EV owners \$511 million in direct fuel expenditures in 2045, relative to a 3.5% EV fleet (28,617 EVs). Table 3 indicates that this is equivalent to \$648 per additional EV. However, under business-as-usual charging, a 100% EV fleet would raise the total cost of electricity production in 2045 by about \$400 million (\$502 per EV), reversing much of the fuel savings. If EVs and chargers have additional capital costs of \$200/year relative to ICE vehicles, then the 100% EV scenario with business-as-usual charging would have total costs for electricity and transport that are about \$54 more per year vehicle than the 3.5% EV scenario. It should be noted, however, that in this scenario, 100% of vehicles obtain their energy from 100% renewable sources.

Charging the 100% EV fleet at the best times of day could reduce the cost of electricity production in 2045 by nearly \$200 million per year compared to the 100% EV businessas-usual charging scenario (\$234 per vehicle). This is mostly due to reduced investments in grid-connected storage and a switch from wind to solar power, as discussed above. An optimally timed 100% EV fleet would raise the total cost of electricity production by about \$268 more per vehicle per year compared to a 3.5% EV fleet. With savings in direct fuel expenditures of \$648 per vehicle per year, this results in significant overall cost reductions. Even with extra capital costs of \$200 per year per vehicle, the total cost of electricity and transport in the 100% EV, optimally-timed scenario would be \$180 less per EV per year compared to the 3.5% EV scenario. In other words, each optimally charged EV added to the fleet reduces the total cost of electricity and transport by \$180 per year.

Table 2. Total cost of electricity production and transport (\$million) in 100% renewable power system, under three EV fleet and charging scenarios

	3.5% EVs, BAU charging	100% EVs, BAU charging	100% EVs, optimal charging
All electricity production (capital and fuel)	\$1,205	\$1,600	\$1,416
Extra cost of EV and charger vs. ICE	\$6	\$163	\$163
ICE fuel	\$511	\$0	\$0
Total annual cost	\$1,721	\$1,764	\$1,580

Table 3. Change in cost of electricity and fuel, per additional EV, for 100% EV fleet vs. 3.5% EV fleet, under two charging scenarios (difference between columns in Table 2, divided by difference in EV fleet size)

	BAU charging	optimal charging
Electricity production (capital and fuel)	+\$502	+\$268
Extra cost of EV and charger vs. ICE	+\$200	+\$200
ICE fuel	-\$648	-\$648
Total annual cost	+\$54	-\$180

Figure 7 shows the trend in total costs over the period from 2021 to 2045, as the power system transitions toward 100% EVs and 100% renewables (with RPS targets of 30%, 40%, 70% and 100% in the four periods shown). Higher EV shares appear to raise costs somewhat during the early years, but this effect is reduced in later years. By the time the system reaches 100% renewable power in 2045, the scenario with optimal charging of a 100% EV fleet has lower costs than the 3.5% EV scenario, and in fact has approximately the same cost as the 2021 system with 30% RPS and negligible EV adoption.



Figure 7. Total cost of electricity, electrification of vehicles (extra cost for EVs and chargers) and fuel, during transition to 100% renewable power, under three EV fleet and charging scenarios