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The Importance of Grid Integration for Achievable GHG Emissions Reductions from Alternative Vehicle Technologies

Assessment and results produced by the Advanced Power and Energy Program (APEP) at UC Irvine

A shorter version of this study was published in the peer-reviewed scientific journal *Energy* and can be found here:
http://www.sciencedirect.com/science/article/pii/S0360544215005460

Preface

Advanced alternative vehicles such as Plug-in Hybrid Gasoline Electric (PHEVs), battery electric vehicles (BEVs), fuel cell electric vehicles (FCEVs), and plug-in fuel cell hybrid vehicles (PHFCVs) must utilize renewable resources to charge vehicles or produce hydrogen in order to provide significant greenhouse gas emission reductions. The 2014 APEP Well-to-Wheels greenhouse gas emissions study examined the greenhouse gas intensity of different vehicle types assuming BEV and FCEV pathways are capable of **fully** absorbing variable renewable generation on the electric grid. While the efficiencies of these pathways as well as that for PHEVs and PHFCVs are different, the charging/fueling infrastructure for each of these vehicle types can be configured and managed in many different ways. These in turn determine how well vehicle fleets composed of these types can interface with the electric grid and absorb renewable generation, thereby affecting achievable greenhouse gas emissions reductions. In addition to the well-to-wheels factors, factors such as the temporal variability of renewable generation, consumer travel and refueling patterns, and performance limitations of electric grid load-balancing resources must be taken into account to determine achievable GHG emission reduction potential.

The following is a summary of the results from an extensive APEP study which integrates detailed models of electric grid operations and the light duty transportation sector. These results display the **combined** annual GHG emissions of the electric grid and light-duty transportation fleet including upstream emissions for fuel processing and mining during the year 2050 in California. This includes grid emissions from generation used to meet the non-transportation load demand as well. Different vehicle charging/fueling infrastructure configurations are examined while taking into account grid interface factors, vehicle population, and electric load growth due to population growth. Additionally, the year 2050 greenhouse gas emissions goal dictated by Executive Order (EO) S-21-09 of 80% below 1990 levels [1] for the combined system is labeled in order to understand which vehicle pathways are able to meet this goal.

This report is organized as follows. An Executive Summary contains the summary of the study approach, key findings, and conclusions. In the main body of the report, the results for the intermediate installed renewable capacity of 325 GW are presented first to provide general observations regarding the performance of different vehicle pathways, some of which apply across all renewable capacity levels. Afterwards, the sensitivity of these results to both the lower (205 GW, 255 GW) and the higher (375 GW, 425 GW) installed renewable capacity levels will be presented and described. The key conclusions and takeaways from the overall study are presented in the last main section. Finally, a brief description of the vehicle types, scenarios, and major study parameters are presented in Appendix A, and supplementary results which help to explain the main results are presented in Appendix B.

Direct links to different sections of the report are provided here for reader convenience.

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        - Sensitivity Results: Lower Renewable Capacities (255 GW RE, 205 GW RE)
        - Sensitivity Results: Higher Renewable Capacities (375 GW RE, 425 GW RE)

    - **Key Conclusions and Takeaways**

- **Appendices**
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Executive Summary

Summary of Approach

Five different renewable capacity installation levels (205, 255, 325, 375, and 425 GW) are examined for each case to understand the scale of renewables needed for different vehicle supply chains to meet the EO S-21-09 goal projected for 2050. This study includes vehicle emissions, electric grid emissions, and upstream emissions for fuel extraction and processing. Note that this study does not include vehicle manufacturing. For these aspects, the EO S-21-09 goal for these combined sectors is calculated to be 50.7 Million Metric Tons (MMT) per year. The electric load is scaled up by population projections to represent the year 2050.

The light duty vehicle fleet size is scaled up according to population to represent the year 2050. The fleet is composed of 90% alternative powertrain vehicles, with the remaining 10% being advanced gasoline hybrid vehicles. Note that 90% of the vehicle fleet does not necessarily correspond to 90% of the vehicle miles traveled served. If a certain vehicle type is unable to satisfy all of the vehicle trips required by consumer travel patterns due to range limitations (i.e. BEVs with 100 mile range), gasoline vehicles will need to be used.

Vehicle efficiency characteristics were determined for representative vehicle classes for each powertrain type: automobiles, small trucks/SUVs, and large trucks/SUVs using the NREL FastSim [2] and NREL ADVISOR [3] vehicle modeling tools and available data for currently released models. Note that different powertrains were simulated on similar vehicle platforms in each class: different powertrains shared a common vehicle platform. For example, a Ford Escape, which is one of the vehicles in the light SUV/truck class, was simulated with ICV, FCEV, PHEV, BEV, and PHFCV powertrains. This is to isolate the impact of the powertrains on the vehicle characteristics with regard to weight and efficiency. This also indicates that each powertrain type is scaled to the same peak system power output as its gasoline counterpart for a common vehicle. This process is repeated for multiple vehicles within a class, and the average effect is determined to represent the fleet of that vehicle class.

Peak power levels calculated for the average vehicle by class is 172 hp for passenger cars, 179 hp for light SUVs/Trucks, and 254 hp for heavy SUVs/Trucks. Fleetwide average vehicle efficiency factors for each vehicle type were determined from knowledge of the vehicle-miles-traveled by each vehicle class from the CARB EMFAC data [4]. Battery energy densities for electric drive are represented by that for the Tesla Model S 85 kWh model [5]. Additionally, note that this study uses current state-of-the-art technologies to characterize vehicle powertrain characteristics, and does not speculate regarding the technical improvement of one technology or another in its model simulations. Some discussion on the potential effects of technology improvements are presented after the conclusions. The year 2050 is represented primarily by population growth to 2050 levels.

Once fleet-wide vehicle characteristics are determined for each class, these parameters are used in the Holistic Grid Resource Integration and Deployment (HiGRID) tool [6], which simulates the response of the electric grid to vehicle interaction. Electric vehicle charging is simulated by a model developed by Zhang [7] which takes into account vehicle travel patterns from the National Household Transportation Survey [8] in terms of trip length, vehicle location, dwelling time, and charging strategy. Hydrogen infrastructure GHG emission performance is simulated by the Preferred Combination Assessment (PCA) tool [9], both of which interact with HiGRID. Aggregate emissions performance is then calculated. This process is repeated for each renewable capacity installation level.

More details are presented in Appendix A of the report.

Primary Results, Key Points, and Conclusions

The following presents the primary results (325 GW) for combined GHG emissions, key points regarding vehicle performance, and the key takeaways and conclusions. The sensitivity results for different renewable capacities are presented in the main report. More details on supplementary results are presented in the main body and Appendix B of the report.

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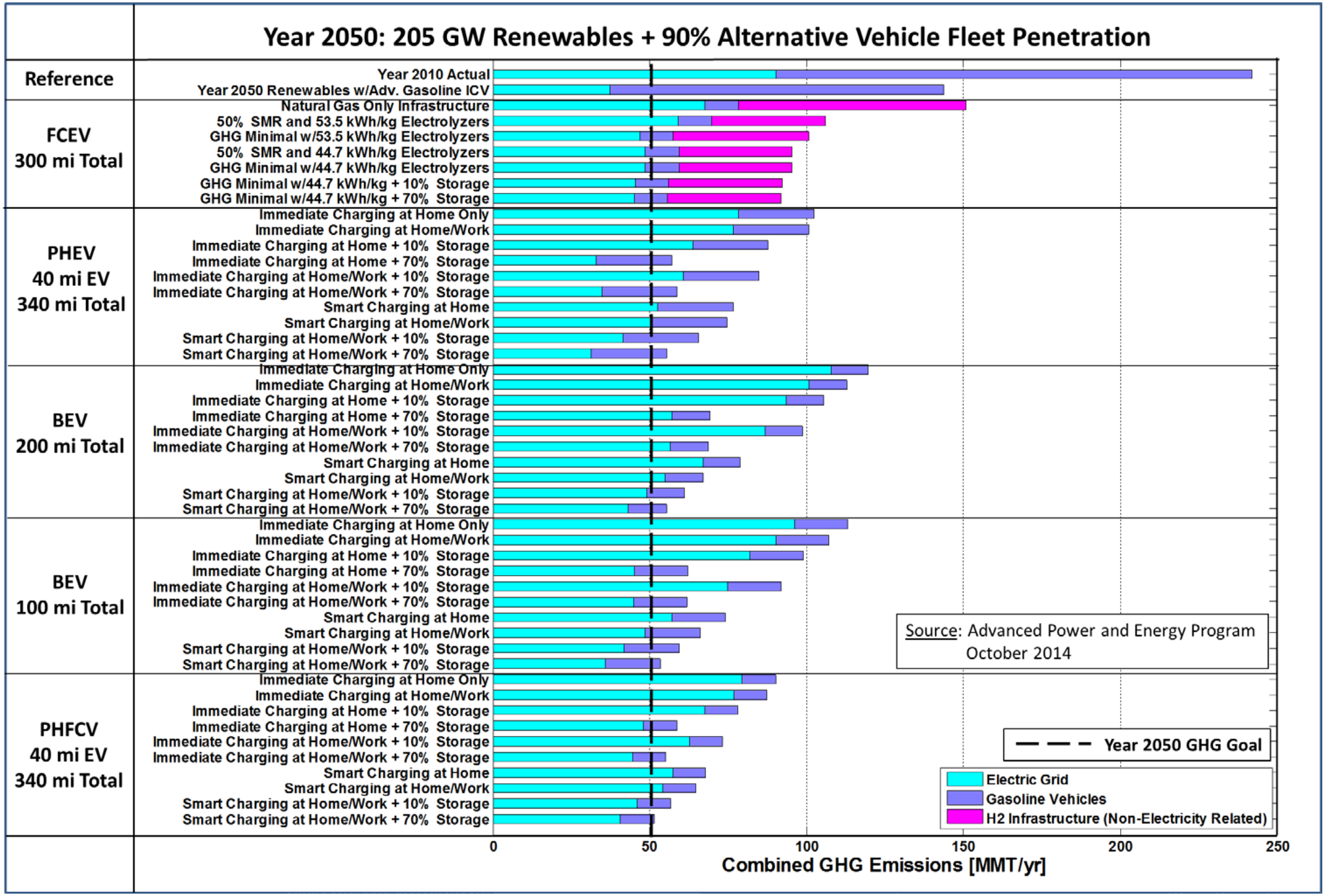
Summary of Results – Vehicle Pathway Greenhouse Gas Emissions at 205 GW RE



Source: Advanced Power and Energy Program October 2014

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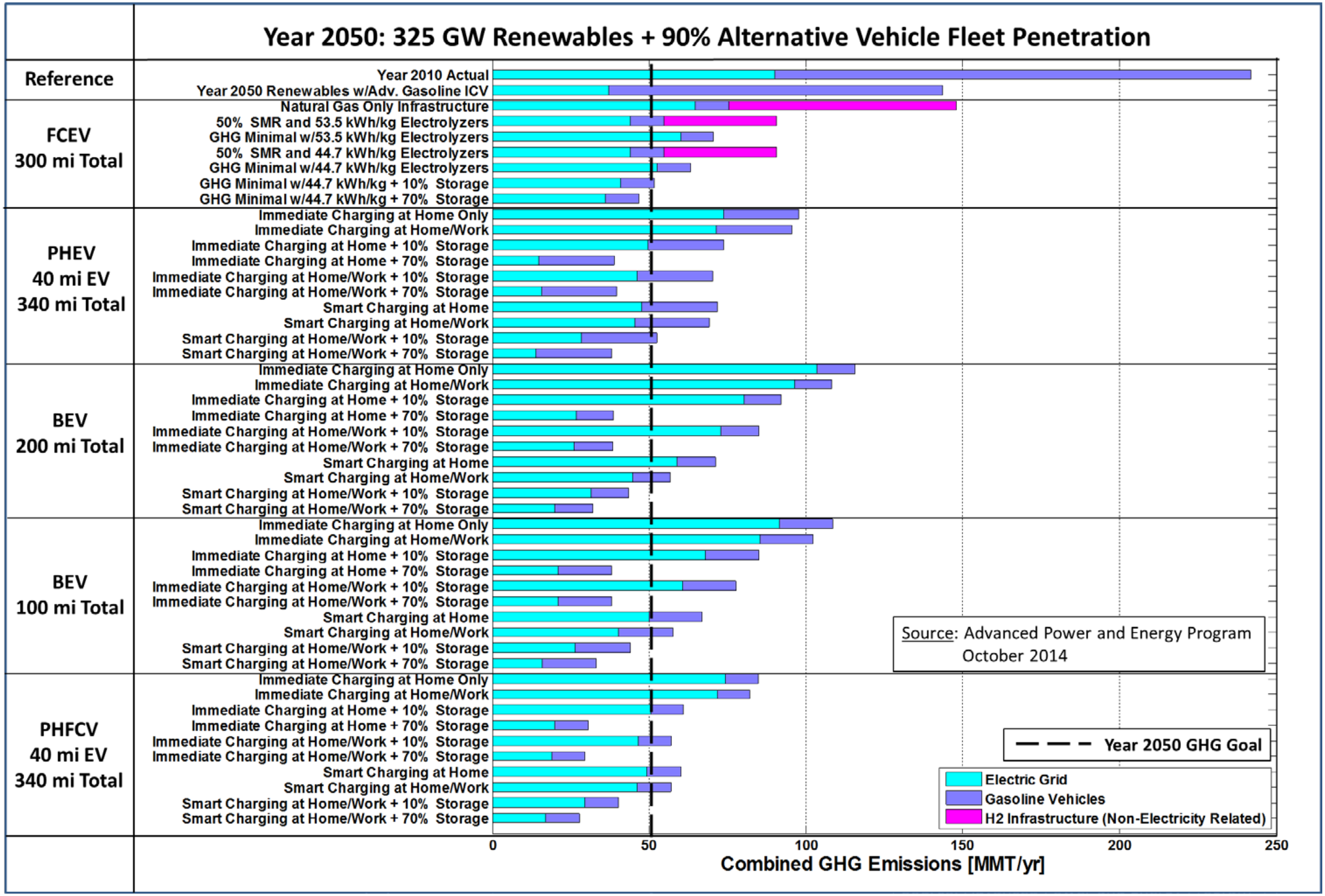
Summary of Results – Vehicle Pathway Greenhouse Gas Emissions at 325 GW RE



Source: Advanced Power and Energy Program
October 2014

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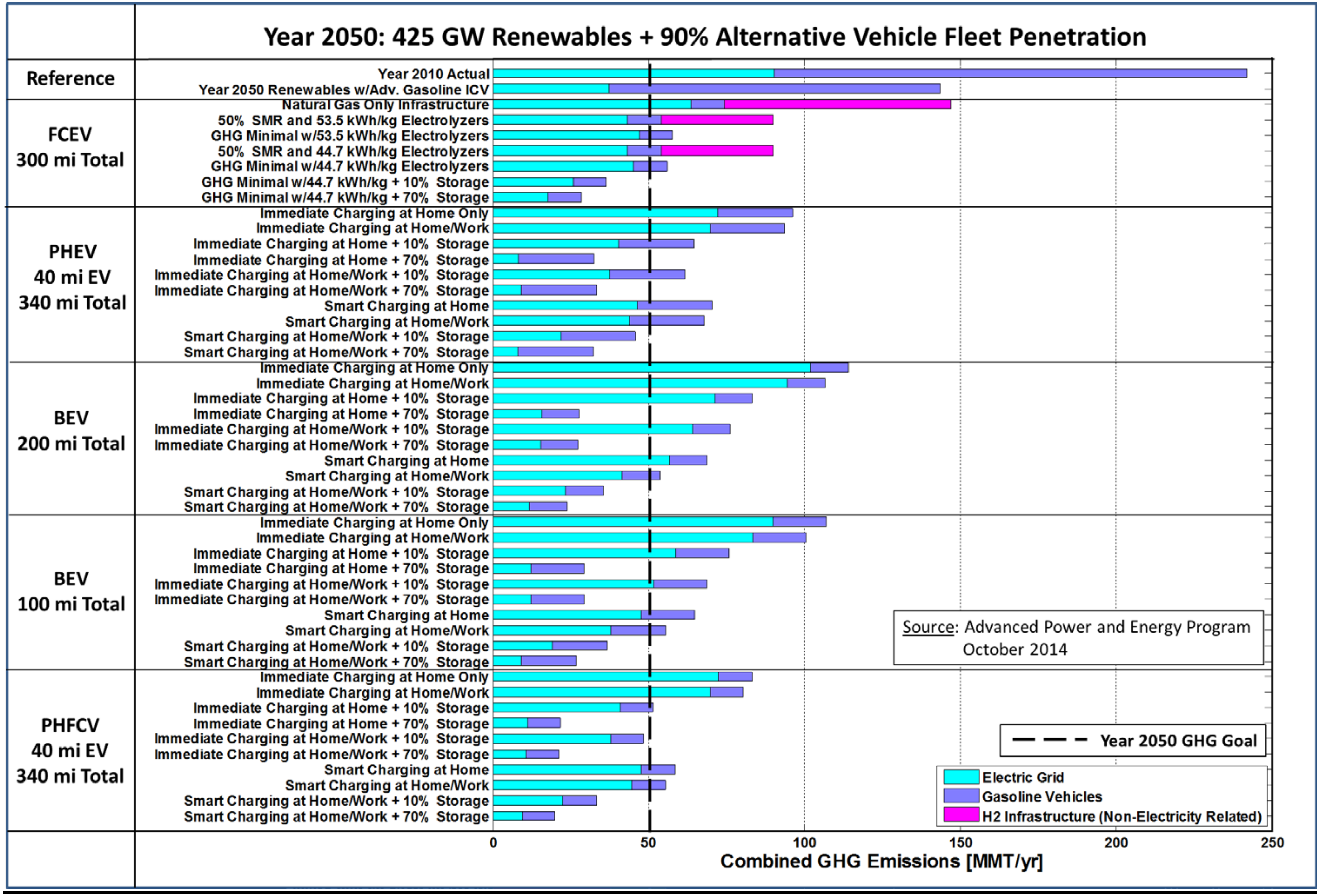
Summary of Results – Vehicle Pathway Greenhouse Gas Emissions at 425 GW RE



Source: Advanced Power and Energy Program
October 2014

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Summary of Greenhouse Gas Emissions Performance by Vehicle Type

The following table summarizes key points related to the greenhouse gas emissions reduction potential of each vehicle type.

Vehicle Type	**Key Highlights**	**Potential Disruptive Factors**
Advanced ICV	• Even with efficiency improvements, there is a limit on GHG emissions reductions with vehicles that are 100% dependent on gasoline	N/A
FCEV 300 mi H2	• Significant GHG emissions reduction possible, but requires higher renewable capacities compared to other alternative vehicle types. • Sufficient range to satisfy 100% of consumer vehicle mileage in one vehicle • Electric load is freely flexible to absorb renewable generation. • Production mix must be optimized for the amount of excess renewable generation. • Worst case does not reduce GHG emissions more than advanced ICV. • Fuel cell becomes heavy in larger vehicles with higher power requirements. • High efficiency pathway (NG SMR) has direct emissions, cannot use renewable elec. • Pathway which uses renewable electricity (Electrolysis) has a low overall efficiency.	• Use of biogas can allow the SMR to be carbon neutral, but biogas potential in CA is currently limited but advanced biogas production technologies can potentially support a large FCEV penetration. • Low natural gas prices producing cheap hydrogen make the worst case to be the most economical at the moment.
PHEV 40 mi EV 340 mi Tot.	• Meets 86% of consumer vehicle mileage on electric drive. • Still requires gasoline usage for longer trips (14% of vehicle mileage). • Smaller batteries keep vehicle weights down and electric drive efficiencies high. • Smaller IC engines used as range extenders are light and also keep weight down. • Smart charging and/or energy storage is required for significant GHG reductions	• Lack of smart charging (consumer behavior cooperation) or energy storage severely limits GHG reduction potential.
Pure BEV 200 mi EV	• Meets 98.5% of consumer vehicle mileage on electric drive. • Low energy density requires high battery weights for 200 mile range • Large battery weights reduce electric drive efficiencies, especially in larger vehicles. • Smart charging and/or energy storage is required for significant GHG reductions • Worse than PHEVs and best FCEV cases if immediate charging is used w/o storage	• Breakthroughs in battery energy density can reduce battery weights and keep efficiencies high • Lack of smart charging or energy storage severely limits GHG reduction potential.
Pure BEV 100 mi EV	• Meets 93% of consumer vehicle mileage on electric drive. • Still requires non-trivial gasoline usage and therefore ownership of a gasoline vehicle • Smart charging and/or energy storage is required for significant GHG reductions • Smaller batteries relative to BEV200 keep weights down allow electric drive efficiencies to remain high, especially in larger vehicles. • Worse than the best FCEV cases if immediate charging is used w/o storage.	• Breakthroughs in battery energy density can significantly increase electric drive efficiencies. • Lack of smart charging (consumer behavior cooperation) or energy storage severely limits GHG reduction potential.
PHFCV 40 mi EV 340 mi Tot.	• Meets 100% of consumer vehicle trips in one vehicle, 86% on pure electric drive. • Hydrogen meets 14% of consumer trips, significantly reducing the hydrogen demand and allowing it to be met in a carbon-free manner with lower renewable capacities. • Fuel cell acting as a range extender does not have to provide total system power output, allowing a low-weight fuel cell. • Smaller batteries reduce weight and keeps electric drive efficiencies high. • Smart charging and/or energy storage is required for significant GHG reductions	• Requires development of both H2 fueling and EV charging infrastructure (albeit to smaller scale than pure pathways) • Dual novel powertrain potentially costly. • Lack of smart charging (consumer behavior cooperation) or energy storage severely limits GHG reduction potential.

Conclusions: General Observations

- **Minimizing greenhouse gas emissions for FCEVs requires optimization of the production mix based on available excess renewable generation.**
    - The two primary pathways for producing hydrogen are through steam methane reformation and hydrogen electrolysis. The former is higher efficiency but emits direct emissions, while the latter is low efficiency but can use renewable generation. The share of each method in the hydrogen production mix must be selected to minimize GHG emissions.
    - While not evaluated here, the availability of sufficient biogas resources could contribute a carbon neutral source of hydrogen through a high efficiency pathway. Determining the amount of available biogas resources and its impact on emissions is a topic of future work.

- **Relying purely on natural gas for hydrogen production in fueling FCEVs does not provide greenhouse gas emissions benefits compared to state of the art gasoline hybrid vehicles.**
    - Hybrid gasoline vehicles have reached a point where their efficiencies are very high. Combined with upstream emissions for gasoline production being low compared to that for natural gas mining, a strong reliance on natural gas for FCEVs can produce as much life cycle GHG emissions compared to that for state of the art gasoline hybrids.

- **Lack of load dispatchability for plug-in vehicles (BEVs, PHEVs, and PHFCVs) can limit their potential greenhouse gas benefits.**
    - All of the cases using immediate charging without energy storage for plug-in vehicles did not reduce greenhouse gas emissions below a certain level even with increasing renewable capacities while the FCEV cases using electrolysis could achieve lower GHG emissions as a result of the large dispatchable electrolysis load.
    - Consumer travel behavior places the electric vehicle charging load during times when renewable generation is relatively low, causing it to be met with natural gas generation and limiting the use of renewable generation without grid-responsive charging management.

- **Smart charging and/or energy storage are required for significant greenhouse gas emissions reductions from plug-in vehicles (BEVs, PHEVs, and PHFCVs).**
    - When consumers are unwilling to schedule their travel patterns into the grid and allow grid operator control of vehicle charging (immediate charging), a large amount of energy storage must be installed to compensate and shift renewable generation to occur at the time of the vehicle charging load.
    - Alternatively, allowing grid operator control and providing knowledge of one's travel patterns allows the electric vehicle charging load to better use renewable generation.

- **Fuel cells as a range extender for plug-in electric vehicles (e.g., PHFCV) provided the lowest emissions of all vehicle types considered with currently available, state-of-the-art technologies.**
    - The characteristics of FCEVs pose challenges for the use of fuel cells as the sole vehicle powertrain due to low carbon-free pathway efficiency and high weight for vehicles with high power outputs. High availability of biogas resources can alleviate the first issue and improvements in fuel cell power density can alleviate the second, but it remains to be seen whether these will occur.
    - The characteristics of BEVs pose challenges regarding the weight of batteries impacting vehicle efficiency when scaled to provide sufficient range with current energy densities, especially in larger vehicle types. A breakthrough in battery energy density could alleviate this issue, but it remains to be seen whether this will occur.
    - With current state-of-the-art technologies, PHFCVs have the following benefits relative to other alternative vehicle types:
        - Using a relatively small battery compared to BEVs, which keeps weight down and increases efficiency especially for larger vehicle classes, keeping efficiencies higher.
        - Using the fuel cell as a range extender allows it to remain light since it does not need to meet total system power output alone, keeping vehicle efficiencies higher.
        - Using renewable hydrogen instead of gasoline to meet longer vehicle trips. By having hydrogen fuel only meet 14% of the miles traveled per vehicle (vs. 100% for FCEVs), the hydrogen demand is significantly smaller, reducing the requirement for excess renewable generation.

Conclusions: Meeting the 2050 EO S-21-09 GHG Emissions Reduction Target

- **Energy storage is required to meet the long-term greenhouse gas emissions goal regardless of vehicle type.**
  - For most of the renewable capacity levels considered, only the cases which utilized energy storage were able to meet the EO S-21-09 goal **regardless of vehicle type.**
  - Meeting the transportation load with renewable generation but only allowing the stationary load to use renewable generation at the time of occurrence does not enable enough offset of carbon-based power to meet the EO S-21-09 goal, even with increasingly high installed renewable capacities.
  - Excess renewable generation from high generation periods must be captured and used to meet the stationary load during times when renewable generation is low to provide enough emissions reductions.

- **FCEVs can meet the long-term greenhouse gas emissions goal, but require larger renewable capacities to do so compared to the other vehicle types.**
  - Due to the lower efficiency of the renewable hydrogen supply chain, FCEVs require more excess renewable generation to produce hydrogen in a carbon-free manner.
  - The best FCEV case was able to meet the EO S-21-09 goal within a small margin at a renewable capacity of 325 GW, compared to 255 GW for the best PHEV 40 / BEV 200 cases, and 205 GW for the best BEV 100 / PHFCV 40 case.

- **A minimum of 205 GW of installed nameplate renewable capacity is required to meet the long-term greenhouse gas emissions goal.**
  - Only the BEV 100 and PHFCV 40 were close to meeting the goal at 205 GW.

  - All other cases resulted in insufficient emission reduction due to either a lack of dispatchability and/or lack of sufficient excess renewable generation.

- **Smart charging for plug-in vehicles allows the use of smaller energy storage systems in meeting the long-term greenhouse gas emissions goal.**
  - With immediate charging, much of the capacity of the energy storage system is used to compensate for the mismatch between renewable generation profiles and vehicle charging profiles.
  - With smart charging, some cases were able to meet the EO S-21-09 goal with an energy storage system sized to 10% of the renewable capacity and average daily renewable generation.
  - With smart charging, the vehicle charging profile is more closely aligned with renewable generation profiles, the energy storage system can be operated to focus on capturing excess renewable generation to meet the stationary load and offset natural-gas power plant generation.

Report

Description of Results

This section presents and describes the performance of different vehicle pathways and infrastructure configuration with respect to combined greenhouse gas performance at different installed renewable capacity levels.

The results for 325 GW installed renewables are presented first, and general observations with respect to vehicle pathway behavior, interface with the electric grid, and relative combined greenhouse gas emissions which may apply across all renewable capacity increments. The results specific to the 325 GW renewable capacity and the EO S-21-09 goal are then presented.

The sensitivity of the primary results relative to the EO S-21-09 goal to renewable capacity is then presented, with a description of the differences in vehicle pathway performance. Lower renewable capacities of 205 GW and 255 GW are examined first, with higher renewable capacities of 375 GW and 475 GW are presented afterwards.

Summary of Approach

All of the cases are examined at five different renewable capacity installation levels (205, 255, 325, 375, and 425 GW) to understand the scale of renewables needed for different vehicle pathways to meet the EO S-21-09 goal projected for 2050. This study includes vehicle emissions, electric grid emissions, and upstream emissions for fuel processing and mining. Note that this study does not include vehicle manufacturing. For these aspects, the EO S-21-09 goal for these combined sectors is calculated to be 50.7 Million Metric Tons (MMT) per year. The electric load is scaled up by population projections to represent the year 2050.

The light duty vehicle fleet size is scaled up according to population to represent the year 2050. The fleet is composed of 90% alternative powertrain vehicles, with the remaining 10% being advanced gasoline hybrid vehicles. Note that 90% of the vehicle fleet does not necessarily correspond to 90% of the vehicle miles traveled served. If a certain vehicle type is unable to satisfy all of the vehicle trips required by consumer travel patterns due to range limitations (i.e. BEVs with 100 mile range), gasoline vehicles will need to be used.

Vehicle efficiency characteristics were determined for representative vehicle classes for each powertrain type: automobiles, small trucks/SUVs, and large trucks/SUVs using the NREL FastSim [2] and NREL ADVISOR [3] vehicle modeling tools and available data for currently released models. Note that different powertrains were simulated on similar vehicle platforms in each class: different powertrains shared a common vehicle platform. For example, a Ford Escape, which is one of the vehicles in the light SUV/truck class, was simulated with ICE, FCEV, PHEV, BEV, and PHFCV powertrains. This is to isolate the impact of the powertrains on the vehicle characteristics with regard to weight and efficiency. This also indicates that each powertrain type is scaled to the same peak system power output as its gasoline counterpart for a common vehicle. This process is repeated for multiple vehicles within a class, and the average effect is determined to represent the fleet of that vehicle class.

Peak power levels calculated for the average vehicle by class is 172 hp for passenger cars, 179 hp for light SUVs/Trucks, and 254 hp for heavy SUVs/Trucks. Fleetwide average vehicle efficiency factors for each vehicle type were determined from knowledge of the vehicle-miles-traveled by each vehicle class from the CARB EMFAC data [4]. Battery energy densities for electric drive are represented by that for the Tesla Model S 85 kWh model [5]. Additionally, note that this study uses current state-of-the-art technologies to characterize vehicle powertrain characteristics, and does not use any speculation regarding the technical improvement of one technology or another in its model simulations. Some discussion on the potential effects of technology improvements are presented after the conclusions. The year 2050 is represented primarily by population growth to 2050 levels.

Once fleet-wide vehicle characteristics are determined for each class, these parameters are used in the Holistic Grid Resource Integration and Deployment (HiGRID) tool [6], which simulates the response of the electric grid to vehicle interaction. Electric vehicle charging is simulated by a model developed by Zhang [7] which takes into account vehicle travel patterns from the National Household Transportation Survey [8] in terms of trip length, vehicle location, dwelling time, and charging strategy. Hydrogen infrastructure performance is simulated by the Preferred Combination Assessment (PCA) tool [9], both of which interact with HiGRID. Aggregate emissions performance is then calculated. This process is repeated for each renewable capacity installation level.

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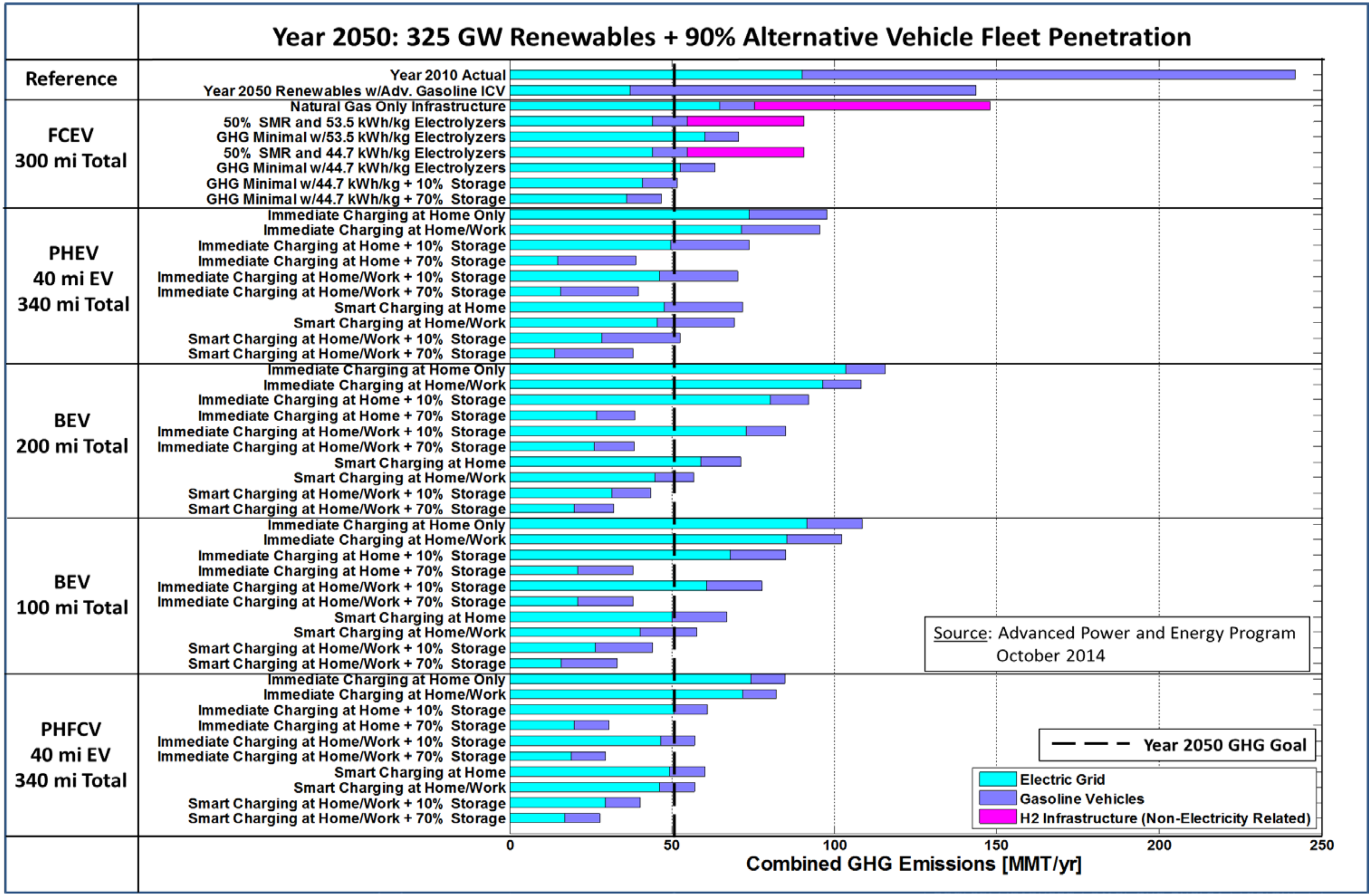
Primary Results and General Observations

325 GW Installed Renewable Capacity



Source: Advanced Power and Energy Program
October 2014

General Observations

This section describes the behavior that gives rise to the performance of each vehicle pathway scenario relative to each other. The performance relative to the AB32 goal and specific to this renewable capacity is presented in the "Specific Observations" section which follows.

Reference Cases

The current trend of hybridization of gasoline vehicles and the growing trend of installing renewable resources are already providing means to significantly reduce combined sector greenhouse gas emissions from current levels. Installing this capacity of renewables and converting the entire light duty fleet to state-of-the-art hybrid gasoline vehicles already cuts combined sector emissions to about 144 MMT/yr, a reduction of 42.9% compared to year 2010 levels even without any alternative powertrain vehicles. This sets the baseline, however, against which alternative vehicle pathways must be compared against.

Fuel Cell Electric Vehicles

The greenhouse gas emissions from a FCEV-based vehicle pathway depend strongly on the configuration of its fueling infrastructure, which determines its pathway efficiency and its ability to utilize renewable generation. If this infrastructure is not configured to minimize greenhouse gas emissions, the potential benefit of using FCEVs can be diminished or absent altogether. For example, relying completely on steam methane reformation for hydrogen production and the current paradigm of liquid hydrogen delivery through trucks does not provide any greenhouse gas emissions benefit compared to an advanced hybrid gasoline fleet (although air quality benefits will still be present). This configuration does not allow the system to take advantage of renewable generation, other than indirect use by non-dispatchable liquefaction and processing loads. This behavior is exemplified in Figure 1:

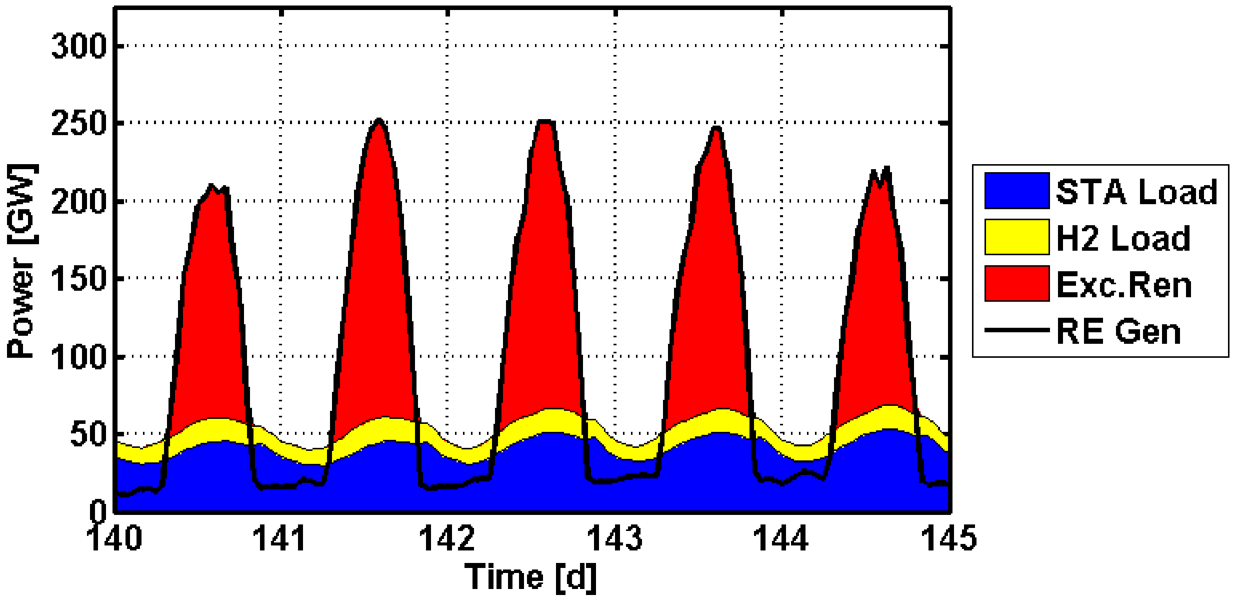


Figure 1 - Sample Timeseries of FCEVs with a Natural Gas Only Infrastructure at 325 GW Installed Renewables

STA Load refers to the stationary (non-transportation fueling related) electric load demand, H2 Load refers to the electric load associated with the hydrogen infrastructure, and "Exc. Ren" refers to unutilized renewable generation. The black line represents the total renewable generation profile.

For FCEV pathways to garner emissions reductions, the infrastructure must be configured to take advantage of renewable generation through dispatchable electrolysis. Since FCEVs operate similar to gasoline vehicles, the timing of fuel production and vehicle refueling is only loosely coupled, allowing electrolyzers the flexibility to absorb variable renewable generation. On the other hand, however, the pathway efficiency of electrolysis is low, meaning that a relatively large amount of renewable energy must be available to produce a unit of hydrogen fuel.

To minimize greenhouse gas emissions for FCEV pathways, the hydrogen production mix must be configured such that it meets as much of the hydrogen demand as possible for a given amount of available excess renewable generation. This is shown by comparing the 50% SMR vs. the GHG minimal cases. At this renewable capacity as an example, there is enough excess renewable generation to meet more than 50% of the hydrogen demand, so constraining the hydrogen production mix to 50% from electrolysis does not yield the lowest greenhouse gases. For this renewable capacity specifically, 100% of the hydrogen demand can be met with excess renewable generation, and the GHG minimal cases use 100% electrolysis as a result.

The implementation of energy storage for FCEV pathways reduces greenhouse gas emissions further, but only to a limited extent. This occurs since the hydrogen electrolysis load in the GHG minimal case has used most of the excess renewable generation due to its low pathway efficiency. Therefore, there is not much additional excess renewable generation that can be captured and used to meet the stationary load demand. This behavior is exemplified in Figure 2:

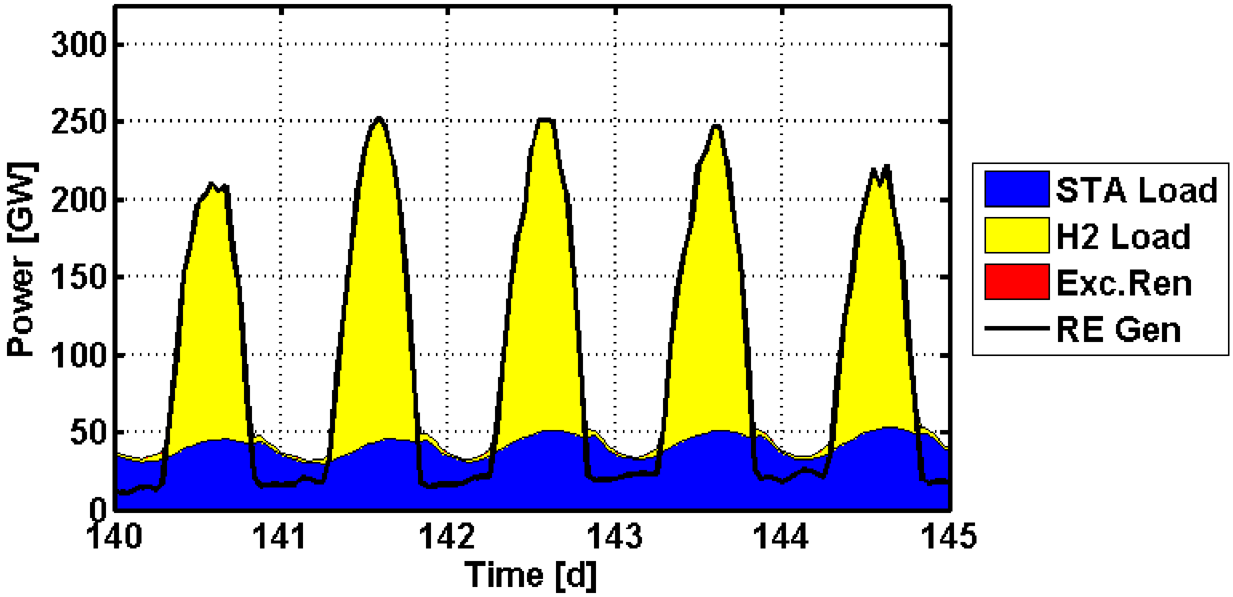


Figure 2 - Sample Timeseries of FCEVs with a GHG Minimal Infrastructure at 325 GW Installed Renewables

<u>**Plug-in Hybrid Gasoline Electric Vehicles – Immediate Charging**</u>

With a 40 mile range, PHEVs are able to meet approximately 86% of the vehicle miles traveled among California drivers on electricity. This causes the gasoline emissions component to be larger than the scenarios for the other vehicle types.

Using immediate charging, where vehicles are charged at a constant rate as soon as they are plugged in wherever charging infrastructure is available (home, workplace) until they are full only provides limited greenhouse gas emissions benefits. This occurs due to the mismatch between consumer charging patterns and renewable generation. At this high of a renewable capacity, much of the available renewable generation is sourced from solar power, since other renewable types have reached their maximum potential contribution. Consumers, however, tend to take their vehicle to the workplace in the morning when solar power is low, and also return to residences in the late afternoon / early evening when solar power is ramping down and the stationary load is increasing. While wind power is typically available during the nighttime hours, the size of the stationary load due to population growth is such that the entire wind generation is already utilized and does not provide excess renewable generation available for vehicle use. This causes the vehicle charging load to be placed at times when there is limited excess renewable generation available, causing this load to be met with natural gas-fired power plant generation and producing emissions. An example of this behavior is presented in the following timeseries of PHEVs with immediate charging at home only:

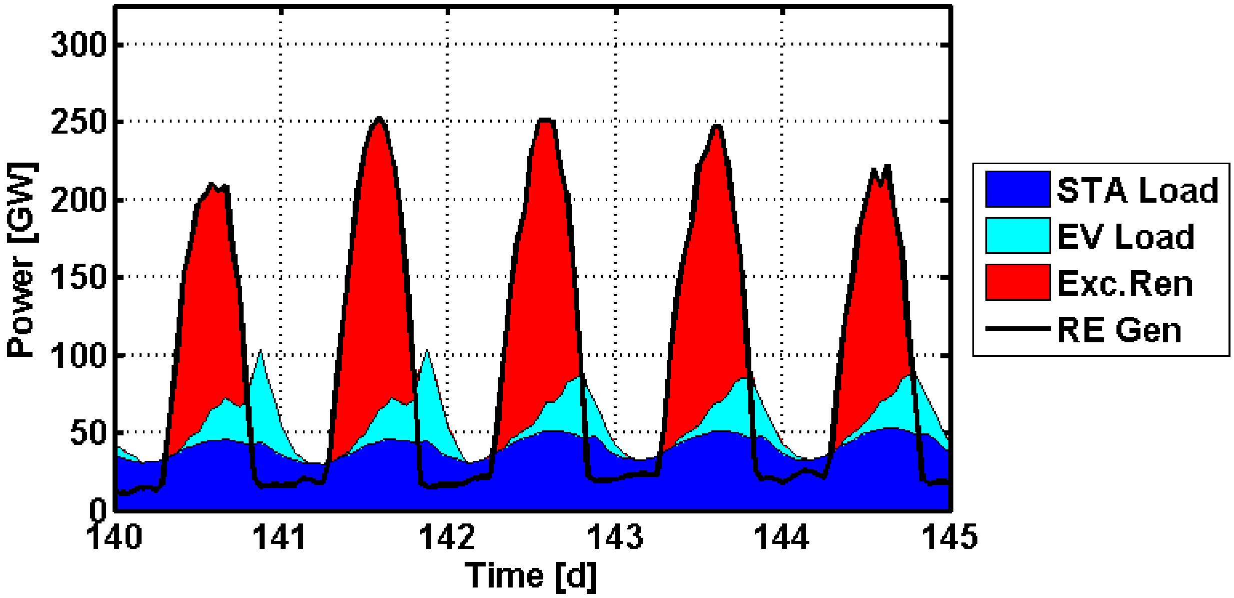


Figure 3 - Sample Timeseries of PHEVs with Immediate Charging at Home Only at 325 GW Installed Renewables

STA Load refers to the stationary (non-transportation fueling related) electric load demand, EV Load refers to the electric vehicle charging load, and "Exc. Ren" refers to unutilized renewable generation. The black line represents the total renewable generation profile.

Allowing charging infrastructure to be available at the workplace in addition to residences does not significantly alleviate this issue. This occurs since only slightly more than half of the vehicle population actually travels to workplaces during the daytime [10]. The other half of the vehicle population remains at home (as is the case with multi-car households) or travels to destinations other than workplaces, but still returns to residences in the late afternoon/early evening hours. Additionally, the dwelling time, which is the amount of time that a vehicle remains at a given location, is on average 6 hours for workplaces compared to 11 hours at residences, allowing more time for uninterrupted charging to full capacity at residences.

With immediate charging, significant emissions reductions are only possible by installing energy storage. The energy storage acts to capture unutilized excess renewable generation during the daytime and allows it to be used when consumers plug in their vehicles in the late evening and nighttime hours, and additionally to offset natural gas generation on the electric grid. The larger the energy storage system, the higher the reduction in greenhouse gas emissions. This behavior is exemplified in Figure 4:

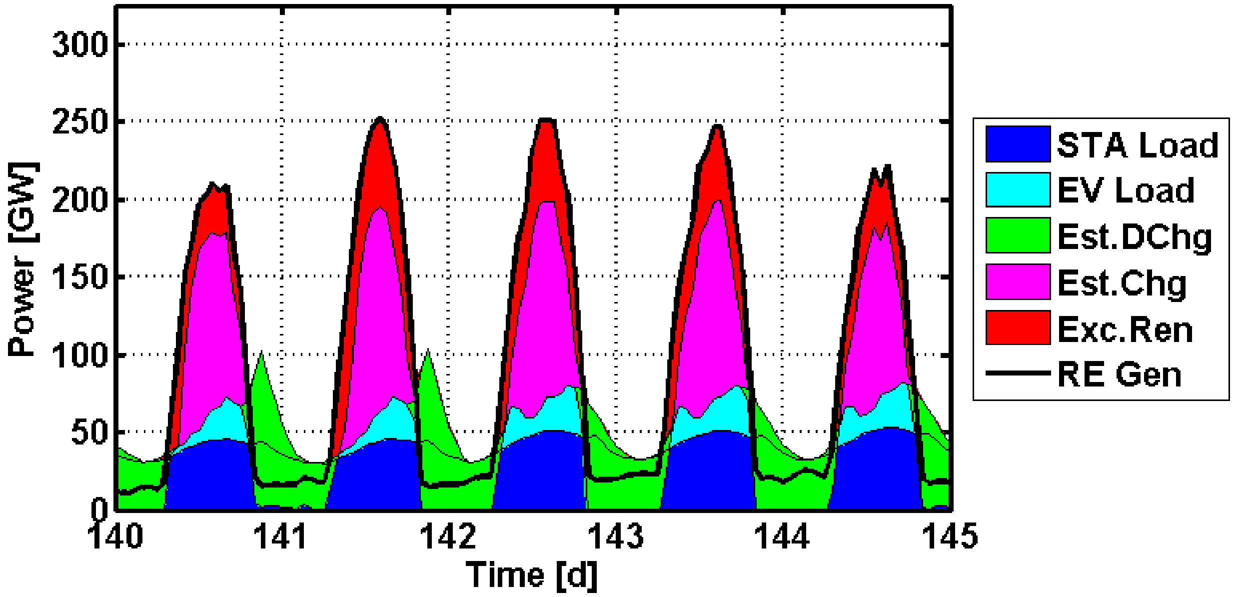


Figure 4 - Sample Timeseries of PHEVs with Immediate Charging at Home Only at 325 GW Installed Renewables and 70% Storage

In addition to the legend in the previous figure, Est. DChg refers to the discharge of the energy storage system, and Est.Chg refers to the charging load of the energy storage system.

Plug-in Hybrid Gasoline Electric Vehicles – Smart Charging

Using smart charging, emissions reductions due to the use of PHEVs are heightened. With consumers allowing grid-responsive control of their charging profile and allowing the grid operators to have knowledge of vehicle fleet travel patterns, the electric vehicle charging load is able to be better shaped to utilize renewable generation. For example, while a vehicle is plugged in, charging power is increased when excess renewable generation is high and decreased or shut off when it is low. These interactions allow a larger fraction of the electric vehicle charging load to utilize excess renewable generation. An example is presented in Figure 5:

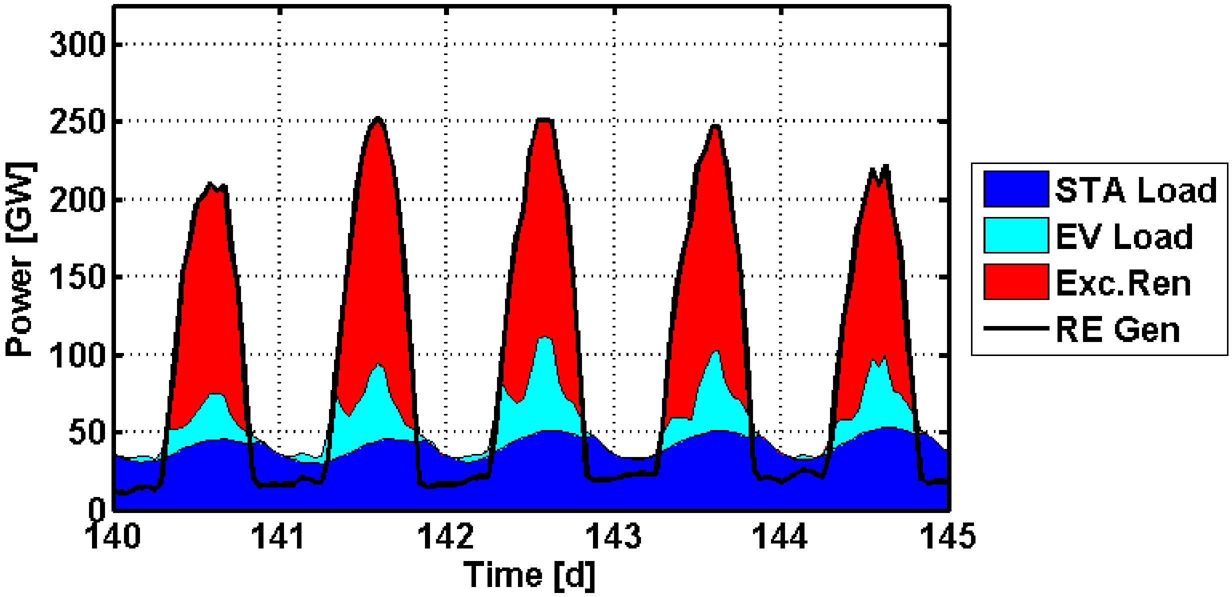


Figure 5 - Sample Timeseries of PHEVs with Smart Charging at Home Only at 325 GW Installed Renewables

Allowing charging infrastructure to be available at the workplace, however, still does not significantly increase the emissions benefit of using PHEVs, however. Utilizing energy storage further decreases greenhouse gas emissions due to the same behavior as explained for immediate charging.

Battery Electric Vehicles – Immediate Charging

Immediate charging, BEVs behave similarly to PHEVs, with the exception of the electric loads being larger. BEVs have higher electricity consumption per mile compared to an equivalent PHEV due to the weight of increased battery capacities – this is especially true for larger vehicles. Additionally, these vehicles are able to meet a larger fraction of the vehicle miles traveled demand on electric drive due to their longer electric range, causing their total electric loads to be larger. A 100 mile BEV and a 200 mile BEV meet 93.3% and 98.5% of all vehicle trips for a California consumer. Note that since these factors are not 100%, additional use of gasoline is required to meet the remainder. Therefore, the trends are similar to that for PHEVs, but exacerbated when the load magnitude is an important factor on combined greenhouse gas emissions. A snapshot of the load profile for immediate charging BEVs is presented in Figure 6:

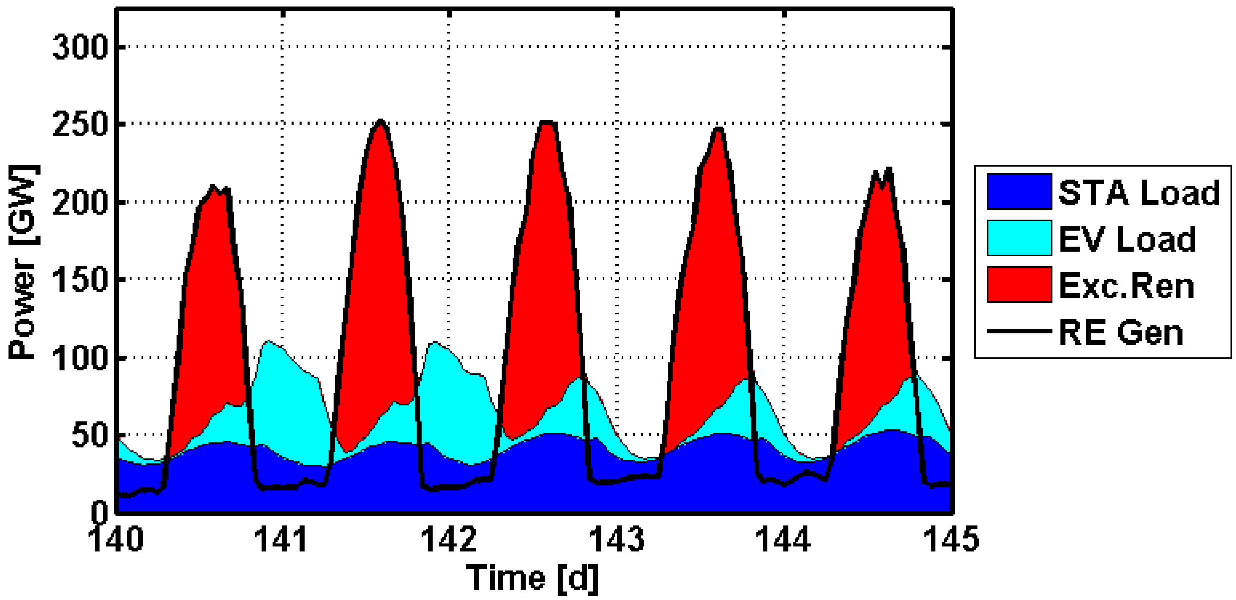


Figure 6 - Sample Timeseries of BEV200s with Immediate Charging at Home Only at 325 GW Installed Renewables

Immediate charging BEVs without energy storage actually produce more greenhouse gases compared to the same cases for PHEVs. Recall that with immediate charging, the vehicle charging load tends to be placed during times when renewable generation is low, causing this load to be met with natural gas-fired power plants. For BEVs, the magnitude of this load is larger, requiring more natural gas generation compared to the equivalent PHEV case. Additionally, this added load is met exclusively with natural gas power plants since it is added when all of the other power plant types (nuclear, hydropower, renewables) are already at capacity meeting the load demand during those hours. When the BEV load is met with natural gas load-following and peaking power plants as the marginal generator, the life cycle greenhouse gas emissions per mile of BEV travel is similar to, and occasionally worse than, that per mile of travel by an advanced gasoline hybrid vehicle when accounting for upstream processes such as fuel mining (except vehicle manufacturing).

For example, a gasoline vehicle fleet with a fleet-wide average fuel economy of 41.8 mpg produces 276.1 gCO2e per mile. For a 200 mile BEV, this figure is 218.647 gCO2e/mile if the load is met by an advanced combined cycle power plant operating at its design efficiency, and 325.282 gCO2e/mile if that load is met by an advanced fast-response cycle gas turbine operating at its design efficiency. However, combined cycle and gas turbine power plants do not operate at their design efficiency at all times, as these units must vary their power output to follow the profile of the load demand in time and their efficiency changes with power output. Therefore, when considering the operation of the grid, the life cycle greenhouse gas emissions for a mile of travel by a 200 mile BEV changes to 253.120 and 341.272 gCO2e/mile for combined cycle and simple cycle power plants, respectively. Note that this is different than the results of the previous APEP well-to-wheels GHG emissions study since this result takes into account grid operation and uses the emissions of the marginal generator, not the average generator as in the previous study. The details of these calculations are presented in the Appendix B. This shows that if the BEV load cannot be met renewably, it may not necessarily provide greenhouse gas benefits compared to advanced gasoline vehicles. The end result is that the total greenhouse gas emissions of the BEV cases is higher than that for PHEV cases when using immediate charging without energy storage, despite the fact that the PHEV cases have more gasoline powered miles.

Similar to the case for PHEVs, significant emissions reductions can be obtained by installing energy storage. This prevents the BEV load from being met by natural gas generation by shifting unutilized renewable generation to be available during the times when the BEV load occurs. A sample timeseries of this behavior is presented in Figure 7:

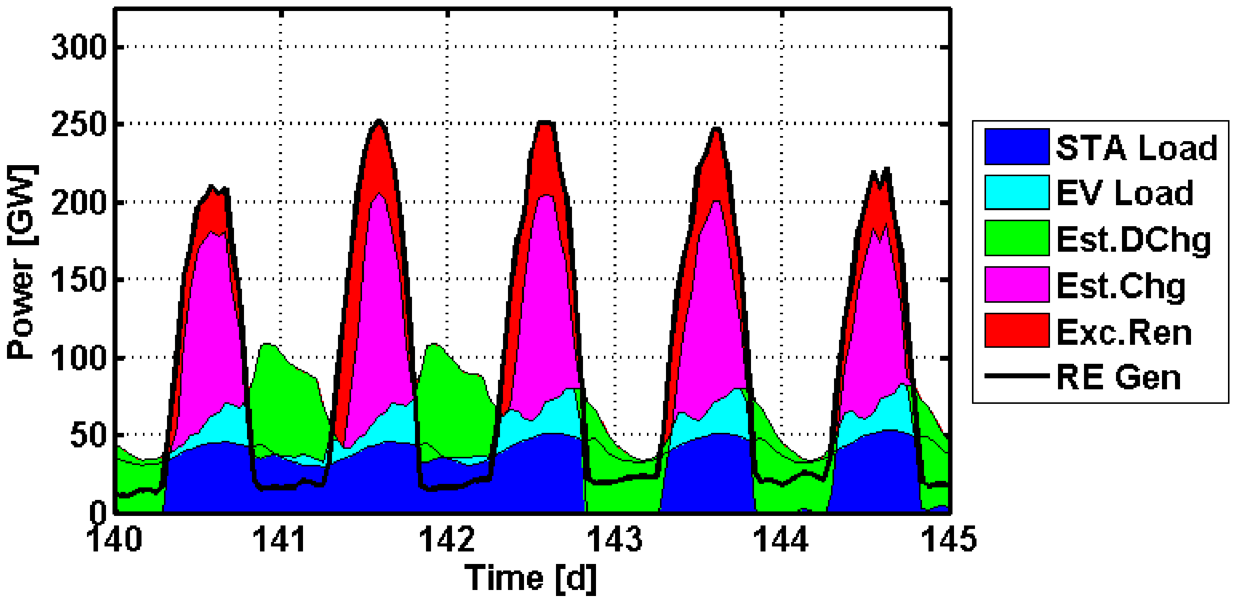


Figure 7 - Sample Timeseries of BEV200s with Immediate Charging at Home Only at 325 GW Installed Renewables and 70% Storage

Battery Electric Vehicles – Smart Charging

Using smart charging provides a significant improvement in greenhouse gas emissions reductions for BEVs, larger than that seen for PHEVs. Similar to smart charging for PHEVs, the electric load is shaped to best take advantage of renewable generation by increasing or decreasing the charging power at every hour depending on the availability of renewable generation. For BEVs, however, smart charging also entails an additional element that is not present for PHEVs. Unlike PHEVs, BEVs do not have an additional powertrain to fall back on when embarking on a long series of trips. Additionally, depending on vehicle usage, a BEV may not have a full charge when starting a series of trips. Therefore, BEV owners must manage their range and charging patterns more precisely compared to PHEV owners to ensure that all of their travel demand can be satisfied. Taking this aspect into account, smart charging with BEVs entails the added element of optimizing the BEV charging profile across multiple dwelling periods.

For example, consider a BEV owner who knows that they will be at two different destinations with available charging infrastructure. During the time they are at their first destination, excess renewable generation is forecasted to be low, but during the time that they are at their second destination, excess renewable generation is forecasted to be high. By scheduling their travel pattern with the grid operator, BEV charging can be reduced or withheld when the driver is at their first destination, and accelerated when they are at their second destination, provided that they have enough charge to travel between those destinations. In practice, this requires that a BEV owner be willing to schedule their travel pattern into the electric grid ahead of time for the benefits shown here to be realized in the real-world system.

With smart charging, allowing charging infrastructure to be available at home and workplace makes a larger difference compared to that for PHEVs. This occurs since BEV-specific smart charging allows vehicle charging to be accelerated during the work hours when excess solar generation is available, and withheld during the nighttime hours when renewable generation is relatively low. This allows more of the BEV charging load to be met with renewable generation. The result of this behavior is presented in Figure 8:

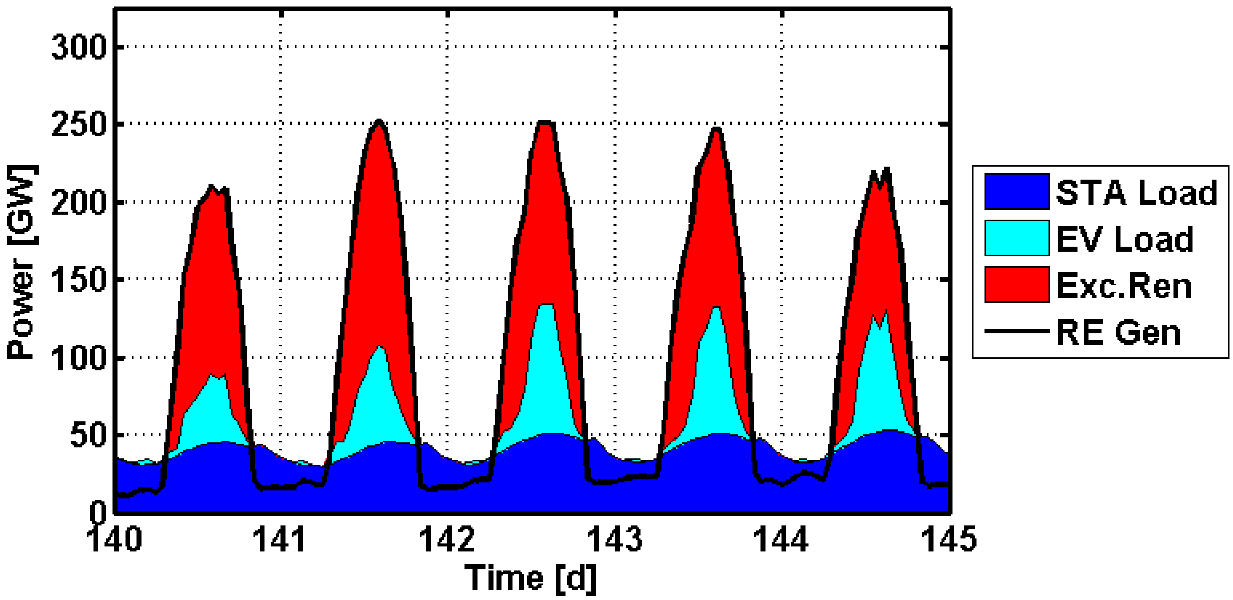


Figure 8 - Sample Timeseries of BEV200s with Smart Charging at Home and Work at 325 GW Installed Renewables

Similar to the case for immediate charging, implementing energy storage with smart charging also significantly improves greenhouse gas emissions reductions. Since smart charging works to shift vehicle loads to absorb renewable generation, this reduces the extent to which energy storage would be required to do so. The energy storage system in this case therefore has more capacity to capture additional excess renewable generation and use it to reduce natural gas power plant generation on the electric grid.

Plug-in Fuel Cell Electric Vehicles – Immediate Charging

The plug-in fuel cell vehicles provide the lowest combined greenhouse gas emissions of all of the plug-in vehicle types, and in general the PHFCV cases behave relative to each other in the same manner as that for the PHEV cases. These vehicles benefit from the lower weight of having a smaller battery compared to BEVs, and have small weight increases compared to regular PHEVs since using the fuel cell as a range extender does not require it to provide the total system power output for a vehicle, allowing the fuel cell system to be only slightly heavier than an internal combustion powertrain. This allows the electric charging load of PHFCVs to remain smaller than that for BEVs on a per-mile basis. Additionally, it allows miles that would have been met with gasoline power to be met by renewably-produced hydrogen. Since the 40-mile all electric range of the PHFCV allows 86% of the vehicle miles traveled by this vehicle to be met by the high-efficiency electric fuel pathway, only the remaining 14% is met with the lower-efficiency hydrogen pathway. This allows the hydrogen demand and total energy consumption for hydrogen production to be 1/7th of that for a pure-FCEV case and preventing it from using up all of the excess renewable generation.

With immediate charging, the smaller electric load compared to BEVs entails a smaller requirement for natural gas generation, indicating lower grid emissions. Offsetting gasoline powered miles with renewably produced hydrogen also reduces vehicle emissions. The combined effect is to produce lower greenhouse gas emissions compared to FCEVs, PHEVs, and BEVs. A snapshot of this result is presented in Figure 9:

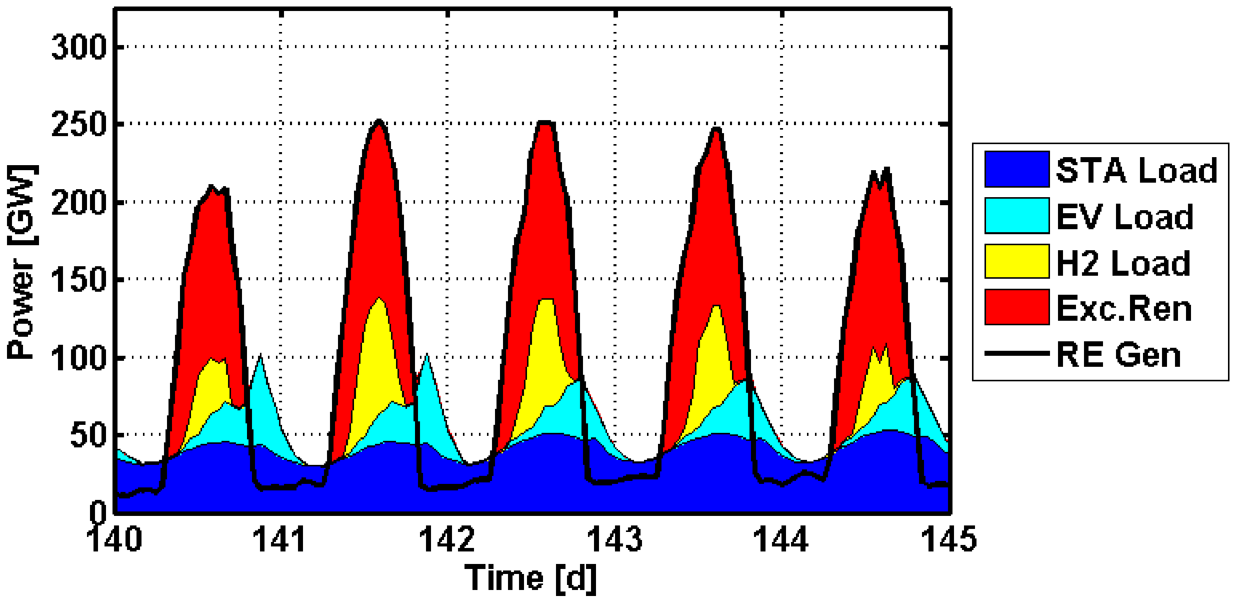


Figure 9 - Sample Timeseries of PHFCV40s with Immediate Charging at Home Only at 325 GW Installed Renewables and 100% Electrolysis

Similar to PHEVs, however, allowing workplace immediate charging does not significantly reduce greenhouse gas emissions. Implementing energy storage allows improved emissions reductions by capturing excess renewable generation and using it to meet the vehicle load and the stationary load when possible. A snapshot of this behavior is presented in Figure 10:

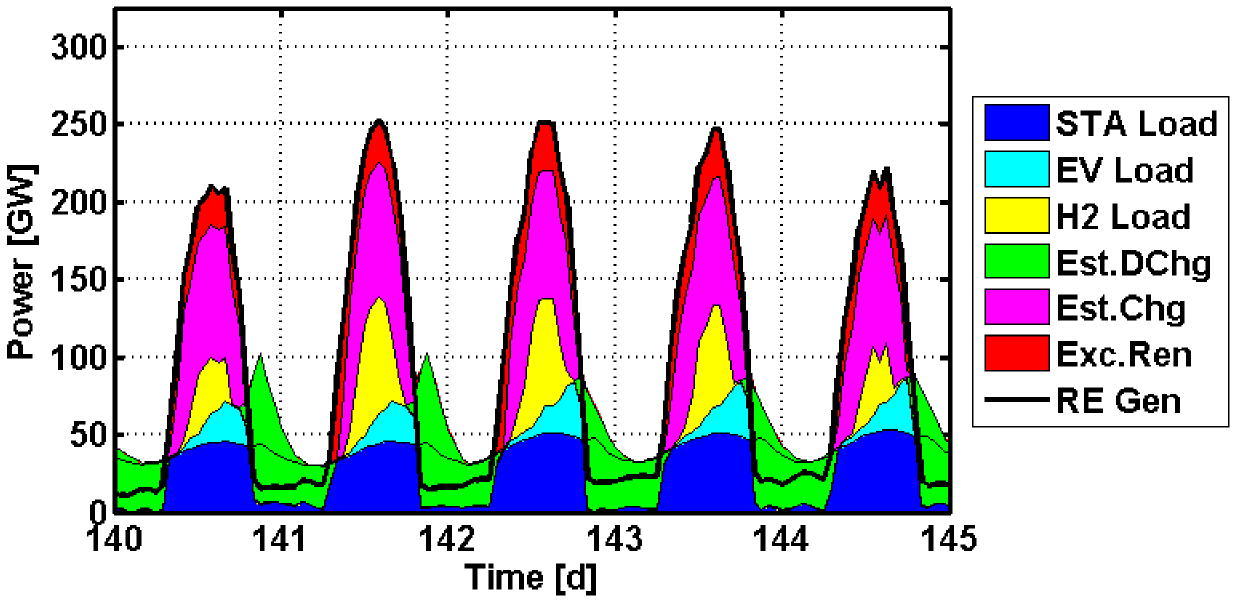


Figure 10 - Sample Timeseries of PHFCV40s with Immediate Charging at Home Only, 100% Electrolysis, and 70% Storage at 325 GW Installed Renewables

Plug-in Fuel Cell Electric Vehicles – Smart Charging

Smart charging is carried out for PHFCVs in the same manner as that for PHEVs, and contributes to additional emissions reductions by shaping the vehicle charging profile to better absorb excess renewable generation in a similar manner to that previously described for PHEVs. Lower electric loads also reduce emissions when the charging load cannot be met by renewables as well. This behavior is exemplified in Figure 11:

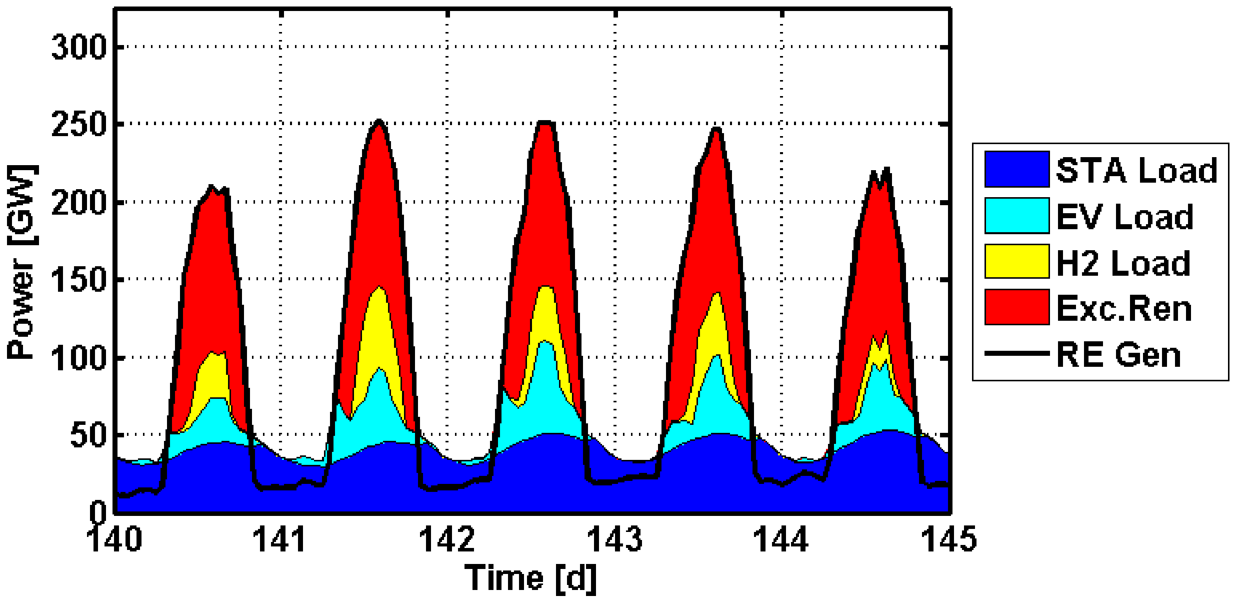


Figure 11 - Sample Timeseries of PHFCV40s with Smart Charging at Home and Work and 100% Electrolysis at 325 GW Installed Renewables

Introducing energy storage allows vehicle loads to be shifted to absorb renewable generation, and in addition allows excess renewable generation to be used to meet the stationary load demand as well, as presented in Figure 12:

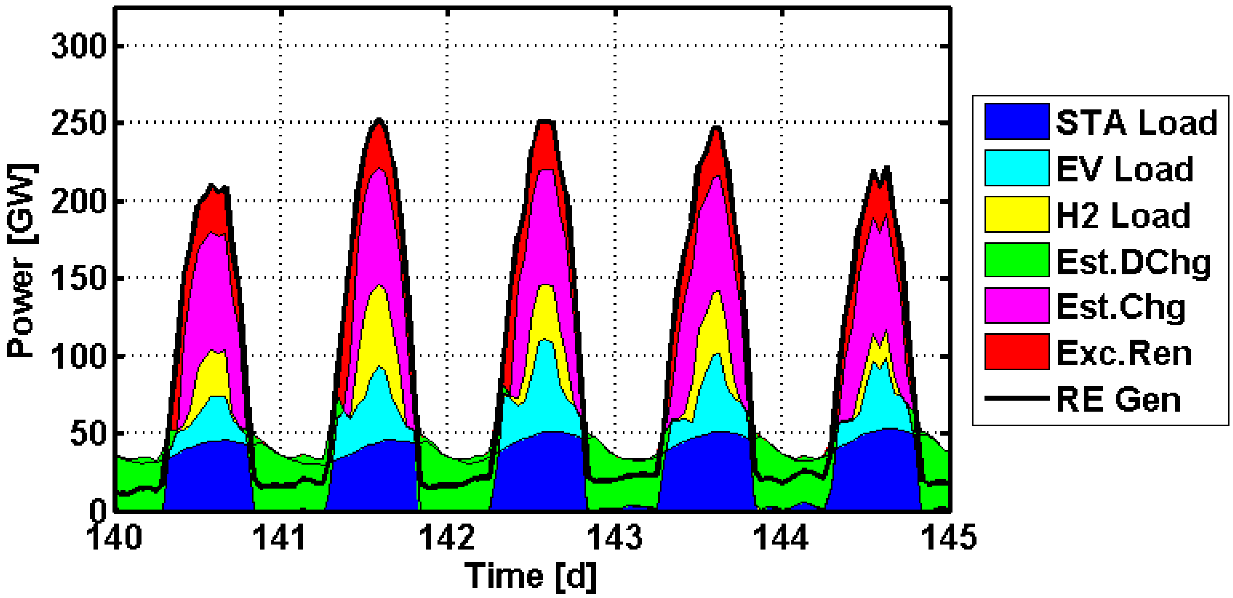


Figure 12 - Sample Timeseries of PHFCV40s with Smart Charging at Home and Work, 100% Electrolysis, and 70% Storage at 325 GW Installed Renewables

Specific Observations – 325 GW Installed Renewable Capacity

This section describes the performance of vehicle pathways relative to the AB32 goal and specific to the scenario of 325 GW of installed renewable capacity. A table which lists which cases for each vehicle type were successful at meeting the AB32 goal at 325 GW of installed renewable capacity is presented in Table 1. Additionally, cases which come within 5% of the goal are presented as near-successful cases. Recall that the EO S-21-09 goal for this study is calculated to be 50.7 MMT/yr.

Table 1 - Cases Which Satisfy EO S-21-09 Goal with 325 GW Installed Renewable Capacity

Vehicle Type	Successful and Near-Successful Cases
FCEV	**Successful** • GHG Minimal w/44.7 kWh/kg Electrolyzers + 70% Storage **Near Successful** • GHG Minimal w/44.7 kWh/kg Electrolyzers + 10% Storage
PHEV w/ 40 mile electric range	**Successful** • Immediate Charging at Home + 70% Storage • Immediate Charging at Home/Work + 70% Storage • Smart Charging at Home/Work + 70% Storage **Near Successful** • Smart Charging at Home/Work + 10% Storage
BEV w/ 200 mile electric range	**Successful** • Immediate Charging at Home + 70% Storage • Immediate Charging at Home/Work + 70% Storage • Smart Charging at Home/Work + 10% Storage • Smart Charging at Home/Work + 70% Storage **Near Successful** • None
BEV with 100 mile electric range	**Successful** • Immediate Charging at Home + 70% Storage • Immediate Charging at Home/Work + 70% Storage • Smart Charging at Home/Work + 10% Storage • Smart Charging at Home/Work + 70% Storage **Near Successful** • None
PHFCV w/ 40 mile electric range	**Successful** • Immediate Charging at Home + 70% Storage • Immediate Charging at Home/Work + 70% Storage • Smart Charging at Home/Work + 10% Storage • Smart Charging at Home/Work + 70% Storage **Near Successful** • None

Fuel Cell Electric Vehicles

At 325 GW of installed renewable capacity, only one of the FCEV cases is successful. This case requires a hydrogen production and delivery infrastructure optimized for low greenhouse gas emissions, which in this particular case entails 100% electrolysis. These electrolyzers must have efficiency improvements over current established technology, and energy storage must be installed. This occurs since while the hydrogen electrolysis load is almost freely dispatchable, the pathway efficiency uses up almost all of the available excess renewable generation at this capacity, leaving little left over for the energy storage system to capture and use to reduce natural gas powered generation. The case with a 70% energy storage size is successful, while using a 10% energy storage size is nearly successful.

Plug-in Hybrid Gasoline Electric Vehicles

For PHEVs, large amounts of storage were required to satisfy the EO S-21-09 goal. For immediate charging cases, a 70% storage size is required, whereas for the smart charging case, a 10% storage size can be nearly sufficient. The other cases did not satisfy the EO S-21-09 goal since these configurations were not able to take advantage of excess renewable generation, or still had a significant amount of emissions from the use of gasoline fuel to meet the trips that could not be satisfied by the 40 mile all electric range. As technologies are implemented to additionally capture renewable generation, the gasoline-powered emissions remain constant and comprise a larger fraction of the overall emissions.

Battery Electric Vehicles

For BEVs, the outlook is similar to that for PHEVs. Storage is required to satisfy the EO S-21-09 goal. This indicates that merely satisfying the vehicle load with renewables is not enough to meet the greenhouse gas emissions reduction goal – additional excess renewable must be captured and used to meet the stationary load during periods when renewable generation would otherwise be low as well. In contrast to PHEVs, the BEV cases allow the Smart Charging at Home/Work + 10% storage to move from near-successful to successful. This occurs due to the increased benefit that smart charging has for BEVs compared to PHEVs as described in the general observations.

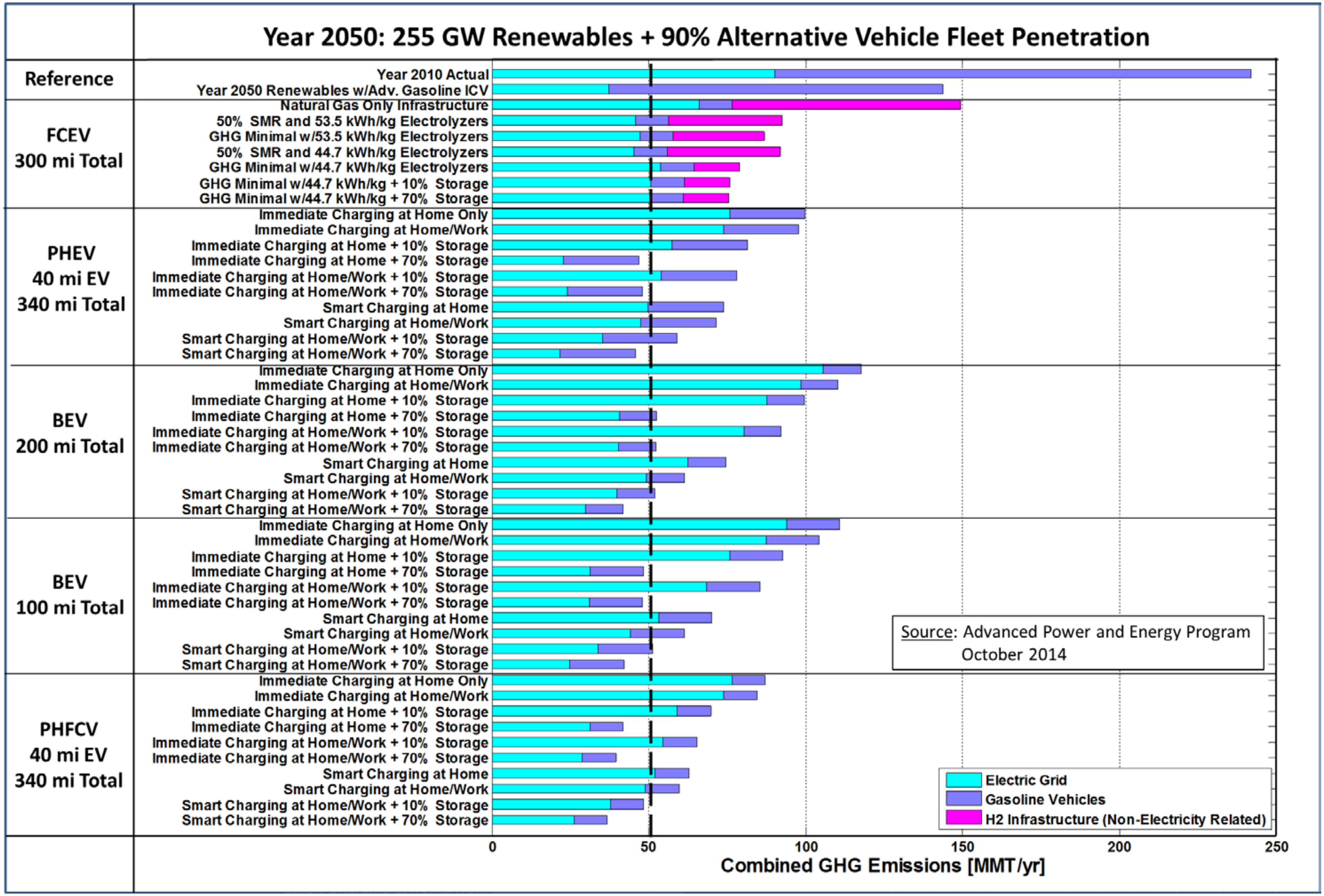
Plug-in Fuel Cell Electric Vehicles

For PHFCVs, the outlook is also similar to that for PHEVs and BEVs, and the behavior of the PHFCV cases relative to the EO S-21-09 goal is governed by the same factors. Energy storage is required to meet the EO S-21-09 goal. Similar to BEVs, the Smart Charging at Home/Work + 10% storage case is successful instead of near-successful, although this occurs due to the reduction in gasoline emissions by powering longer trips with renewable hydrogen instead of gasoline.

Updated April 1, 2016

Sensitivity Results: Lower Renewable Capacities

255 GW Installed Renewable Capacity



Source: Advanced Power and Energy Program
October 2014

Specific Observations – 255 GW Installed Renewable Capacity

This section describes the performance of vehicle pathways relative to the AB32 goal and specific to the scenario of 255 GW of installed renewable capacity. A table which lists which cases for each vehicle type were successful at meeting the AB32 goal at 325 GW of installed renewable capacity is presented in Table 2. Additionally, cases which come within 5% of the goal are presented as near-successful cases. Recall that the EO S-21-09 goal for this study is calculated to be 50.7 MMT/yr.

Table 2 - Cases Which Satisfy EO S-21-09 Goal with 255 GW Installed Renewable Capacity

Vehicle Type	Successful and Near-Successful Cases
FCEV	**Successful** • None **Near Successful** • None
PHEV w/ 40 mile electric range	**Successful** • Immediate Charging at Home + 70% Storage • Immediate Charging at Home/Work + 70% Storage • Smart Charging at Home/Work + 70% Storage **Near Successful** • None
BEV w/ 200 mile electric range	**Successful** • Smart Charging at Home/Work + 70% Storage **Near Successful** • Immediate Charging at Home + 70% Storage • Immediate Charging at Home/Work + 70% Storage • Smart Charging at Home/Work + 10% Storage
BEV with 100 mile electric range	**Successful** • Immediate Charging at Home + 70% Storage • Immediate Charging at Home/Work + 70% Storage • Smart Charging at Home/Work + 70% Storage **Near Successful** • Smart Charging at Home/Work + 10% Storage
PHFCV w/ 40 mile electric range	**Successful** • Immediate Charging at Home + 70% Storage • Immediate Charging at Home/Work + 70% Storage • Smart Charging at Home/Work + 10% Storage • Smart Charging at Home/Work + 70% Storage **Near Successful** • None

Fuel Cell Electric Vehicles

At the lower renewable capacity of 255 GW, none of the FCEV cases are successful or near successful at meeting the EO S-21-09 goal. The case which comes closest to meeting the goal is the GHG minimal w/44.7 kWh/kg Electrolyzers + 70% storage case which produces 75.5 MMT CO2e/yr of greenhouse gas emissions, being about 24.8 MMT/yr short of meeting the EO S-21-09 goal.

This occurs since at this renewable capacity, the amount of excess renewable generation is not large enough to allow all of the hydrogen demand to be met through renewable hydrogen electrolysis. Since the pathway efficiency of using steam methane reformation (SMR) is higher than that compared to non-renewable electrolysis, the GHG minimal cases shift towards relying on SMR to meet the hydrogen demand, which produces direct GHG emissions. With 53.5 kWh/kg electrolyzers, the GHG minimal case still procures 40% of its hydrogen production from SMR. With 44.7 kWh/kg electrolyzers, this drops to 20% from SMR, since more efficient electrolyzers produce more hydrogen for the same amount of excess renewable energy.

Additionally, the use of energy storage makes almost no impact on the greenhouse gas emissions of the FCEV cases. This occurs since hydrogen electrolysis uses all of the available excess renewable generation, leaving none left for the energy storage system to capture and use to meet the stationary load demand.

Overall, at lower renewable capacities, the low pathway efficiency of renewable hydrogen from electrolysis and the direct emissions from the relatively higher efficiency steam methane reformation process limits the ability of FCEV cases to meet the EO S-21-09 greenhouse gas goal.

Plug-in Hybrid Gasoline Electric Vehicles

For PHEVs, only the cases with large amount of energy storage (70% of renewable capacity) were able to meet the EO S-21-09 goal. Implementing a small amount of energy storage (10%) even with smart charging was not in the near-successful category as it was at 325 GW of installed renewable capacity. With lower excess renewable energy available and a smaller energy storage size compared to the 325 GW case, the ability to garner emissions reductions from capturing excess renewable energy and using it to offset natural gas generation is diminished.

The smart charging with 70% storage case performs slightly better than the equivalent cases for immediate charging, since smart charging frees up capacity in the energy storage system by better aligning the vehicle load with renewable generation, allowing the energy storage system to be focused on reducing natural gas-powered generation on the electric grid.

Battery Electric Vehicles

BEVs are impacted by the reduction in renewable capacity in the same manner as PHEVs, with the primary difference being the vehicle efficiencies. For 200 mile BEVs, only one of the cases (Smart Charging at Home/Work + 70% Storage) actually satisfies the EO S-21-09 goal, but three other cases are nearly successful at doing so. All of these cases require energy storage, with the immediate charging cases require large energy storage systems and the smart charging cases being almost adequate with a small energy storage system. The increased impact of smart charging on BEVs allows the best 200 mile BEV case to provide lower emissions than the equivalent PHEV case.

For 100 mile BEVs, all of the cases with large energy storage sizes satisfy the EO S-21-09 goal. The increased vehicle efficiency compared to the 200 mile BEVs allows certain cases to improve from “near successful” to “successful”. The case with the small energy storage size which was nearly successful for 200 mile BEVs, however, does not improve since the vehicle efficiency improvements are offset by emissions due to the increased use of gasoline to satisfy long distance trips in the 100 mile BEV cases.

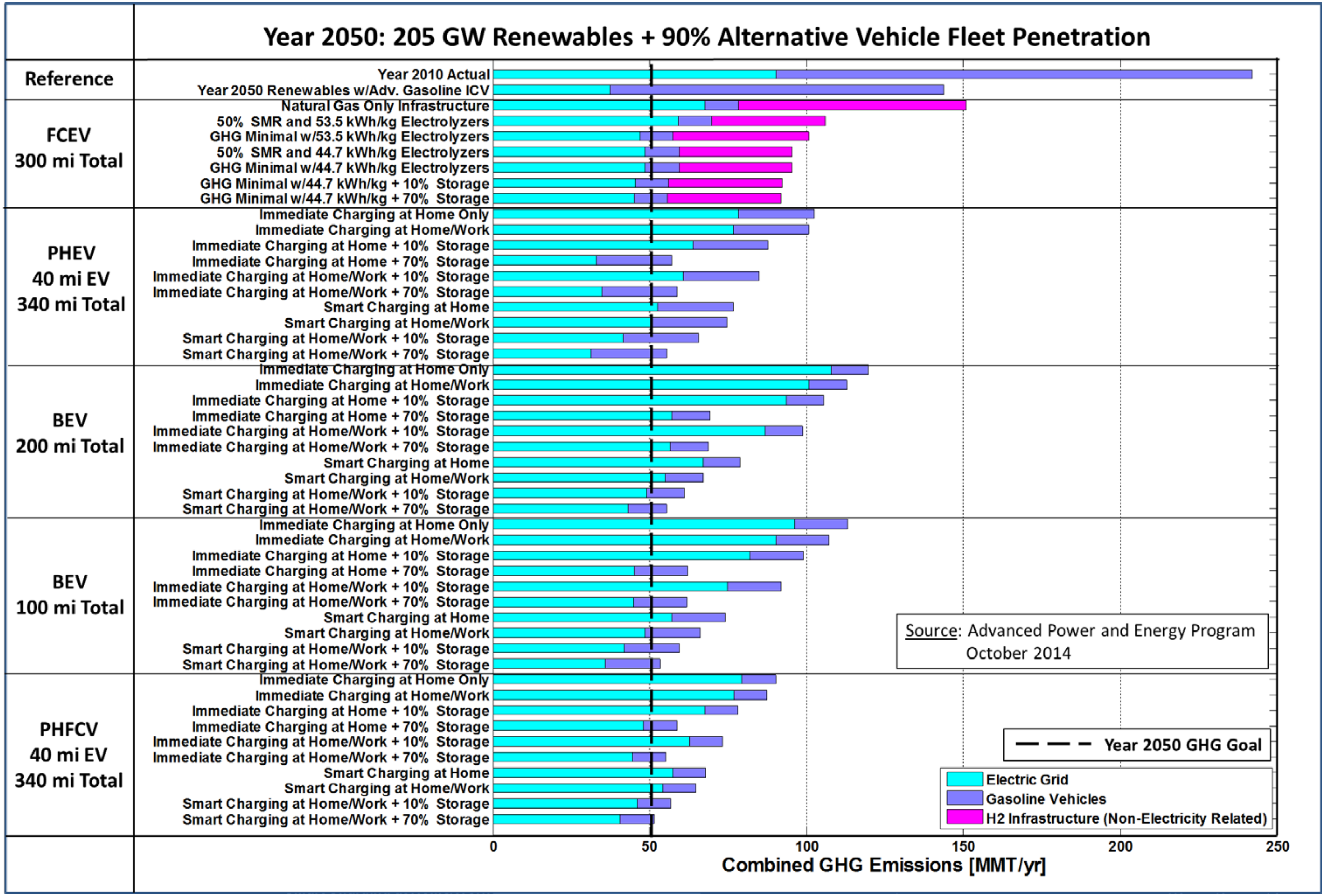
Plug-in Hybrid Fuel Cell Vehicles

PHFCVs have four cases which satisfy the EO S-21-09 goal, all of them requiring energy storage. The cases with large energy storage systems (70% of renewable capacity) are able to capture enough excess renewable energy and use it to meet both vehicle and stationary loads. The case which was only “near successful” for BEVs which used smart charging but a small energy storage system is improved to the “successful” category due to further improvements in the electric consumption efficiency of the vehicle and the ability to replace gasoline with renewably produced hydrogen. Since the hydrogen demand is small for this vehicle type, there is still enough excess renewable generation to satisfy it.

Overall, PHFCVs combine the reduction of gasoline travel requirement with improved vehicle efficiencies to produce the most cases which satisfy the EO S-21-09 goal at this renewable capacity.

Updated April 1, 2016

205 GW Installed Renewable Capacity



Source: Advanced Power and Energy Program
October 2014

Specific Observations – 205 GW Installed Renewable Capacity

This section describes the performance of vehicle pathways relative to the AB32 goal and specific to the scenario of 205 GW of installed renewable capacity. A table which lists which cases for each vehicle type were successful at meeting the AB32 goal at 325 GW of installed renewable capacity is presented in Table 3. Additionally, cases which come within 5% of the goal are presented as near-successful cases. Recall that the EO S-21-09 goal for this study is calculated to be 50.7 MMT/yr.

Table 3 - Cases Which Satisfy EO S-21-09 Goal with 205 GW Installed Renewable Capacity

Vehicle Type	**Successful and Near-Successful Cases**
FCEV	**Successful** • None **Near Successful** • None
PHEV w/ 40 mile electric range	**Successful** • None **Near Successful** • None
BEV w/ 200 mile electric range	**Successful** • None **Near Successful** • None
BEV with 100 mile electric range	**Successful** • None **Near Successful** • Smart Charging at Home/Work + 70% Storage
PHFCV w/ 40 mile electric range	**Successful** • None **Near Successful** • Smart Charging at Home/Work + 70% Storage

Fuel Cell Electric Vehicles

Since none of the FCEV cases were able to satisfy the EO S-21-09 goal with 255 GW of installed renewable capacity, it is unsurprising that the same is true at the lower renewable capacity of 205 GW of installed renewable capacity. With an even lower amount of excess renewable generation available due to a larger fraction being used to meet the stationary load, the GHG minimal FCEV cases rely even more on steam methane reformation to meet the hydrogen demand with the lowest potential greenhouse gas emissions. The effects described for the 255 GW renewable capacity case are simply exacerbated at 205 GW, and the best case for FCEVs is the "GHG Minimal w/44.7 kWh/kg Electrolyzers + 70% Storage" case, which produces 91.9 MMT CO2e/yr of greenhouse gas emissions, 81% more than the desired emissions level of 50.7 MMT CO2e/yr.

Plug-in Hybrid Gasoline Electric Vehicles

None of the PHEV cases satisfy the EO S-21-09 goal with 205 GW of installed renewable capacity. Even with the increased pathway efficiency of PHEVs compared to FCEVs, there is simply not enough excess renewable energy available to satisfy the stationary and vehicle load demand in a carbon-free manner. The use of energy storage helps in reducing emissions by enabling the system to use what excess renewable generation is available, but these cases still fall short of meeting the goal. Additionally, the larger fraction of gasoline-powered miles contributes to difficulties in reducing emissions.

Battery Electric Vehicles

None of the BEV cases are able to satisfy the EO S-21-09 goal at this renewable capacity, for the same primary reason as that for PHEVs. There is not enough excess renewable energy available for use in both the vehicle and stationary loads. Similarly, the use of large energy storage systems reduces the emissions by the largest extent, but still falls short of the goal.

One case is able to come within 5% of the goal for the 100 mile BEVs due to its lower electric energy consumption per mile of travel, producing 53.5 MMT CO2e/yr of greenhouse gas emissions. This case requires smart charging, home and workplace charging availability, and a large energy storage system.

Plug-in Hybrid Fuel Cell Vehicles

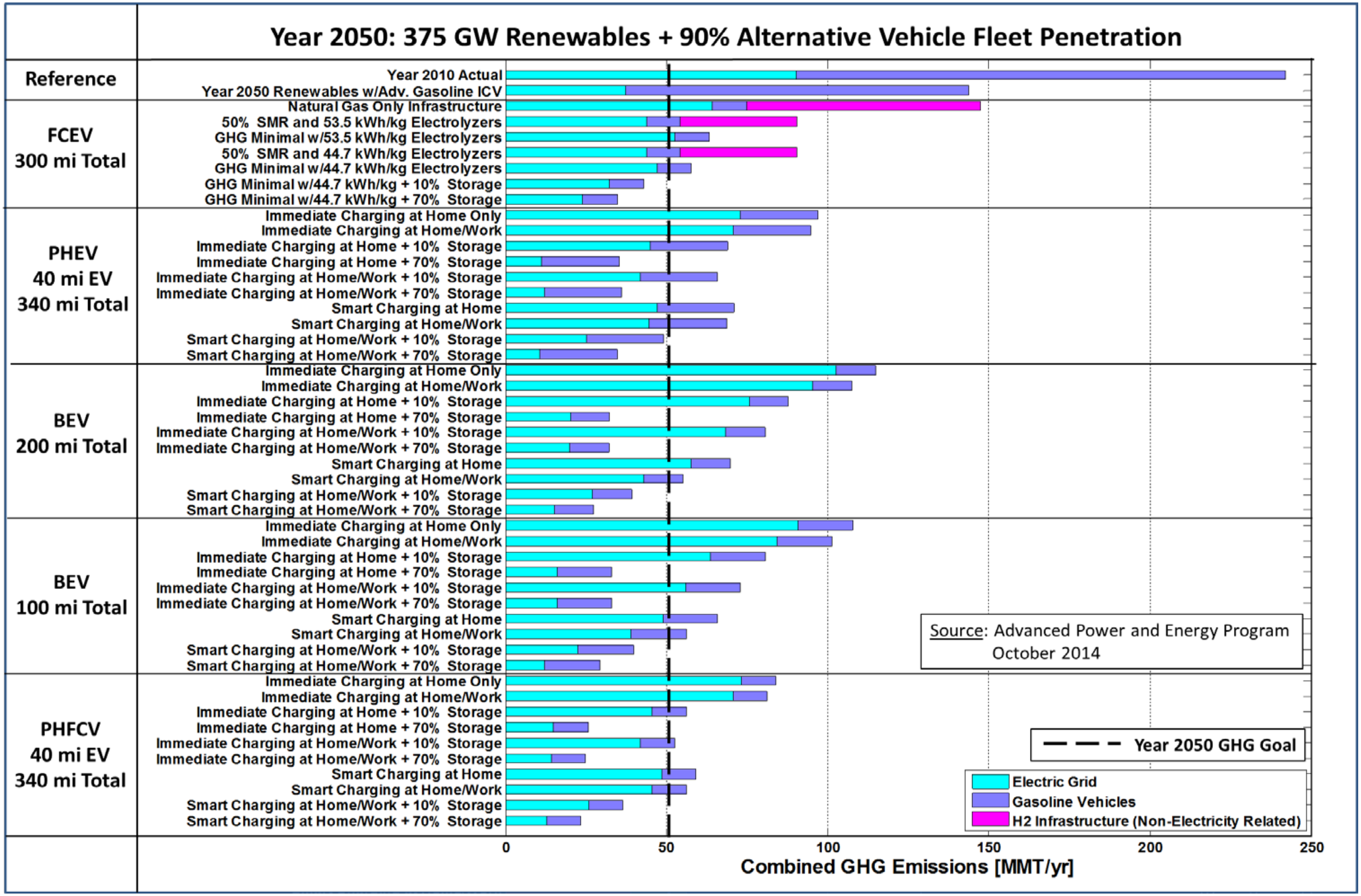
PHFCVs are still not able to satisfy the EO S-21-09 goal with 205 GW of renewable capacity installed on the electric grid for the same primary reasons as for BEVs and PHEVs. One case – Smart Charging at Home/Work + 70% storage – is able to come very close to meeting the 50.7 MMT/CO2e/yr goal by producing 51.4 MMT CO2e/yr in greenhouse gas emissions. Even at this renewable capacity, however, there is still enough excess renewable energy to allow the small hydrogen demand to be met by renewable electrolysis.

At low renewable capacity levels, the PHFCV with smart charging, home and workplace charging availability, a large energy storage system, and GHG minimal hydrogen production and delivery infrastructure technically provides the largest greenhouse gas emissions reductions. The economics of such a vehicle and that for the development of dual infrastructures to different scales will determine whether this is the best practical solution, however.

Updated April 1, 2016

Sensitivity Results: Higher Renewable Capacities

375 GW Installed Renewable Capacity



Source: Advanced Power and Energy Program October 2014

Specific Observations – 375 GW Installed Renewable Capacity

This section describes the performance of vehicle pathways relative to the AB32 goal and specific to the scenario of 375 GW of installed renewable capacity. A table which lists which cases for each vehicle type were successful at meeting the AB32 goal at 375 GW of installed renewable capacity is presented in Table 4. Additionally, cases which come within 5% of the goal are presented as near-successful cases. Recall that the EO S-21-09 goal for this study is calculated to be 50.7 MMT/yr.

Table 4 - Cases Which Satisfy EO S-21-09 Goal with 375 GW Installed Renewable Capacity

Vehicle Type	Successful and Near-Successful Cases
FCEV	**Successful** • GHG Minimal w/44.7 kWh/kg Electrolyzers + 70% Storage • GHG Minimal w/44.7 kWh/kg Electrolyzers + 10% Storage **Near Successful** • None
PHEV w/ 40 mile electric range	**Successful** • Immediate Charging at Home + 70% Storage • Immediate Charging at Home/Work + 70% Storage • Smart Charging at Home/Work + 70% Storage • Smart Charging at Home/Work + 10% Storage **Near Successful** • None
BEV w/ 200 mile electric range	**Successful** • Immediate Charging at Home + 70% Storage • Immediate Charging at Home/Work + 70% Storage • Smart Charging at Home/Work + 10% Storage • Smart Charging at Home/Work + 70% Storage **Near Successful** • None
BEV with 100 mile electric range	**Successful** • Immediate Charging at Home + 70% Storage • Immediate Charging at Home/Work + 70% Storage • Smart Charging at Home/Work + 10% Storage • Smart Charging at Home/Work + 70% Storage **Near Successful** • None
PHFCV w/ 40 mile electric range	**Successful** • Immediate Charging at Home + 70% Storage • Immediate Charging at Home/Work + 70% Storage • Smart Charging at Home/Work + 10% Storage • Smart Charging at Home/Work + 70% Storage **Near Successful** • Immediate Charging at Home/Work + 10% Storage

Fuel Cell Electric Vehicles

With 375 GW of renewable capacity installed on the grid, two of the FCEV cases are able to meet the EO S-21-09 goal. These cases require a hydrogen production and delivery infrastructure which is optimized for lowest greenhouse gas emissions, improvements in electrolyzer efficiency according to the U.S. DOE target, and an energy storage system. Since there is a larger amount of excess renewable generation available, the hydrogen demand can be met renewably while still leaving enough left over for the energy storage system to use towards reducing natural gas-fired generation. The larger energy storage system provides the lowest greenhouse gas emissions, but a small energy storage system will still enable satisfaction of the EO S-21-09 goal.

Plug-in Hybrid Gasoline Electric Vehicles

The results for PHEVs at 375 GW of installed renewable capacity are essentially extensions of that at the 325 GW installed renewable capacity level. Increased renewable capacity increases the amount of excess renewable generation available for use. This reduces emissions for all cases except the immediate charging cases without energy storage, where the PHEV load is not primarily using renewable generation. The reduction in emissions due to use of this extra renewable generation allows the case with smart charging at home/work and a small energy storage system to now satisfy the goal, improved from 'near successful' at 325 GW. Again, however, all of the cases which satisfy the goal require some level of energy storage. Lack of smart charging requires large energy storage systems; whereas smart charging allows the system to only require a small energy storage system.

Battery Electric Vehicles

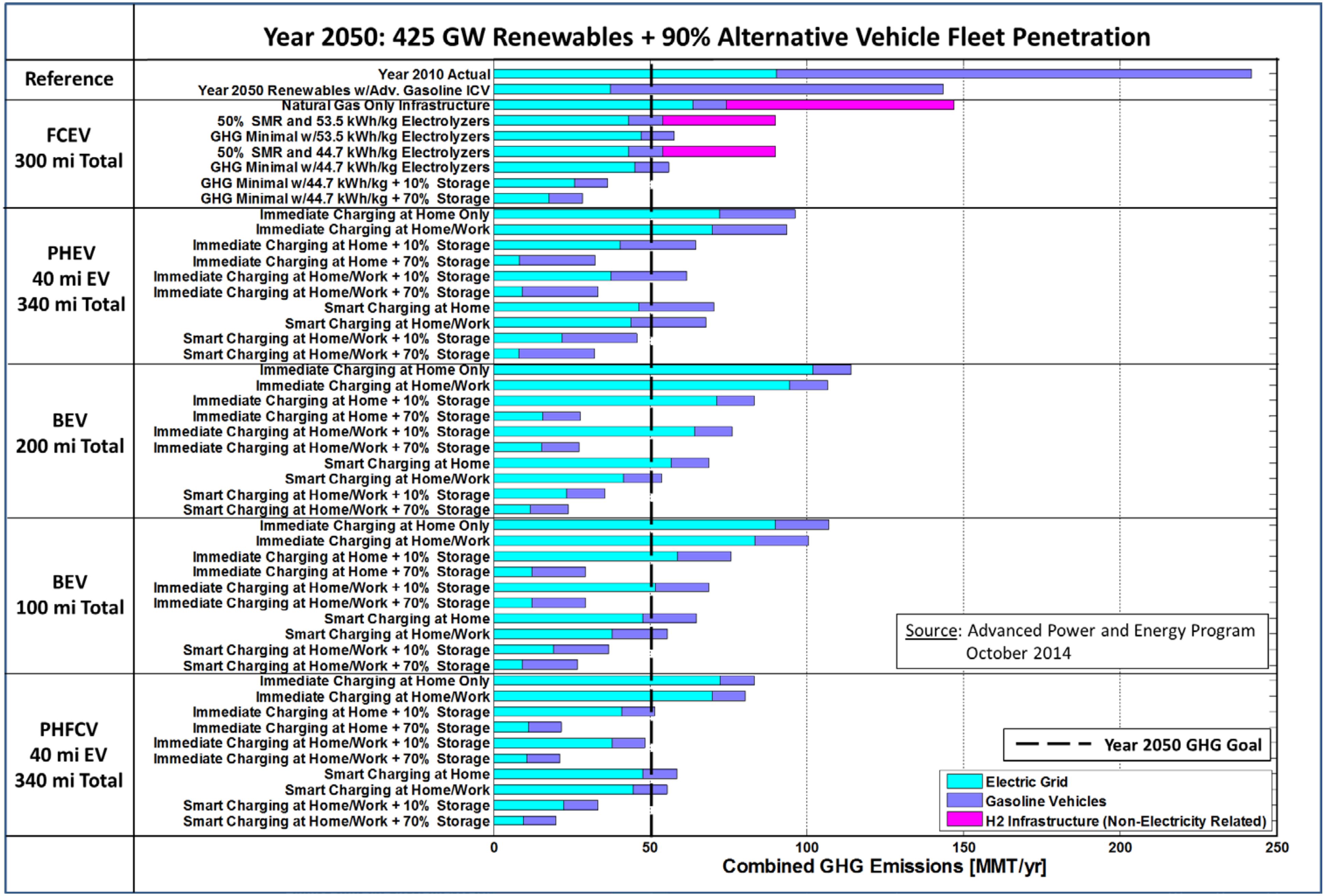
The results for BEVs at 375 GW of installed renewable capacity are similar to that for PHEVs in being essentially extensions of the results at the 325 GW installed renewable capacity level. Use of extra excess renewable generation through storage allows larger emissions reductions. Taking advantage of this extra generation requires storage of some capacity, however, as aligning the vehicle load with renewable generation is somewhat constrained by travel patterns and is not sufficient to reduce emissions below the goal level.

Plug-in Hybrid Fuel Cell Vehicles

PHFCVs provide the largest emissions reductions out of all of the vehicle types at the 375 GW level, similar to the results at the lower renewable capacities, due to the combination of minimized gasoline usage, low electric energy consumption per mile, and a significantly smaller hydrogen demand which allows completely renewable hydrogen production. At this capacity, the same four cases which satisfied the EO S-21-09 goal for PHEVs and BEVs also do so for PHFCVs. In contrast to PHEVs and BEVs, however, the use of immediate charging with a small energy storage system is "near successful" in satisfying the EO S-21-09 goal, under the condition that charging infrastructure is available at residences and workplaces.

Updated April 1, 2016

425 GW Installed Renewable Capacity



Source: Advanced Power and Energy Program
October 2014

Specific Observations – 425 GW Installed Renewable Capacity

This section describes the performance of vehicle pathways relative to the AB32 goal and specific to the scenario of 425 GW of installed renewable capacity. A table which lists which cases for each vehicle type were successful at meeting the AB32 goal at 425 GW of installed renewable capacity is presented in Table 5. Additionally, cases which come within 5% of the goal are presented as near-successful cases. Recall that the EO S-21-09 goal for this study is calculated to be 50.7 MMT/yr.

Table 5 - Cases Which Satisfy EO S-21-09 Goal with 425 GW Installed Renewable Capacity

Vehicle Type	Successful and Near-Successful Cases
FCEV	**Successful** • GHG Minimal w/44.7 kWh/kg Electrolyzers + 70% Storage • GHG Minimal w/44.7 kWh/kg Electrolyzers + 10% Storage **Near Successful** • None
PHEV w/ 40 mile electric range	**Successful** • Immediate Charging at Home + 70% Storage • Immediate Charging at Home/Work + 70% Storage • Smart Charging at Home/Work + 70% Storage • Smart Charging at Home/Work + 10% Storage **Near Successful** • None
BEV w/ 200 mile electric range	**Successful** • Immediate Charging at Home + 70% Storage • Immediate Charging at Home/Work + 70% Storage • Smart Charging at Home/Work + 10% Storage • Smart Charging at Home/Work + 70% Storage **Near Successful** • Smart Charging at Home/Work
BEV with 100 mile electric range	**Successful** • Immediate Charging at Home + 70% Storage • Immediate Charging at Home/Work + 70% Storage • Smart Charging at Home/Work + 10% Storage • Smart Charging at Home/Work + 70% Storage **Near Successful** • Smart Charging at Home/Work
PHFCV w/ 40 mile electric range	**Successful** • Immediate Charging at Home + 70% Storage • Immediate Charging at Home/Work + 10% Storage • Immediate Charging at Home/Work + 70% Storage • Smart Charging at Home/Work + 10% Storage • Smart Charging at Home/Work + 70% Storage **Near Successful** • Immediate Charging at Home + 10% Storage

Fuel Cell Electric Vehicles

With 425 GW of renewable capacity installed on the electric grid, the FCEV cases which incorporate energy storage are successful at satisfying the EO S-21-09 goal. The case with a GHG minimal infrastructure configuration and improved electrolyzers without storage are not able to satisfy the goal even though the electric loads of the hydrogen infrastructure are met with renewable generation, but this case comes close towards satisfying the goal. This further suggests that energy storage is needed to capture additional excess renewable generation and use it to offset natural gas generation on the electric grid is required to meet the EO S-21-09 goal. Merely satisfying the vehicle load renewably and the stationary load only when renewable generation occurs is not sufficient. Overall, these results are similar to that for 375 GW but with further emissions reductions for the cases which incorporate energy storage.

Plug-in Hybrid Gasoline Electric Vehicles

The results for PHEVs at 425 GW of installed renewable capacity are a further extension of the results at 375 GW. The same four cases satisfy the EO S-21-09 goal, with immediate charging requiring large energy storage systems and smart charging only requiring small energy storage systems. These storage-based cases do not perform better than the equivalent BEV cases at this renewable capacity, since there is so much excess renewable generation that the grid emissions are similar, and the emissions due to increased reliance on gasoline-powered travel do not decrease with renewable capacity.

Battery Electric Vehicles

The results for BEVs at 425 GW expand the trends displayed for 375 GW, with the same storage-based cases satisfying the EO S-21-09 goal. The primary change is that a small amount of the additional excess renewable generation is taken advantage of by the smart charging algorithm for BEVs, allowing the smart charging case with home and workplace availability case to be 'near successful' in meeting the goal. However, the fact that this case is unable to meet the goal also highlights the point of energy storage being requited to meet the long term greenhouse gas reduction goal.

Plug-in Hybrid Fuel Cell Vehicles

PHFCVs provide the largest emissions reductions out of all of the vehicle types at this renewable capacity. Due to a reduction in reliance on gasoline powered travel relative to BEVs - since the range of these vehicles is long and the hydrogen used for long trips is created renewably – there are five PHEV cases which satisfy the EO S-21-09 goal and one which is near successful. All of these cases require energy storage at some capacity. The immediate charging case with a small energy storage system is nearly successful, while all other cases require energy storage. This further demonstrates the point of requiring energy storage to meet the EO S-21-09 goal.

Key Takeaways and Conclusions

This study examined the impact of different transportation fueling infrastructure configurations and grid interface management strategies on the ability for alternative vehicle deployment pathways to provide reductions in greenhouse gas emissions in conjunction with grid renewable resources. This study considered the constraints of consumer travel patterns, vehicle use and efficiency characteristics, and the operating constraints of the electric grid, providing insight into how these factors affect real-world greenhouse gas emissions reduction potential as opposed to theoretical reductions based on bulk supply chain analyses.

First, a summary of the key points regarding the performance of different vehicle pathways are presented. Next, two sets of conclusions are presented. The first is based on the general observations of the performance and behavior of vehicle pathways in the context of greenhouse gas emissions, and the second is based on the ability of these vehicle pathways to satisfy a specific greenhouse gas reduction goal – 80% below year 1990 levels by the year 2050 – as stipulated by California’s Assembly Bill 32 (EO S-21-09).

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Summary of GHG Pathway Performance by Vehicle Type

The following table summarizes key points related to the greenhouse gas emissions reduction potential of each vehicle type.

Vehicle Type	Key Highlights	Potential Disruptive Factors
Advanced ICV	• Even with efficiency improvements, there is a limit on GHG emissions reductions with vehicles that are 100% dependent on gasoline	N/A
FCEV 300 mi H2	• Significant GHG emissions reduction possible, but requires higher renewable capacities compared to other alternative vehicle types. • Sufficient range to satisfy 100% of consumer vehicle mileage in one vehicle • Electric load is freely flexible to absorb renewable generation. • Production mix must be optimized for the amount of excess renewable generation. • Worst case does not reduce GHG emissions more than advanced ICV. • Fuel cell becomes heavy in larger vehicles with higher power requirements. • High efficiency pathway (NG SMR) has direct emissions, cannot use renewable elec. • Pathway which uses renewable electricity (Electrolysis) has a low overall efficiency.	• Use of biogas can allow the SMR to be carbon neutral, but biogas potential in CA is currently limited but advanced biogas production technologies can potentially support a large FCEV penetration. • Low natural gas prices producing cheap hydrogen make the worst case to be the most economical at the moment.
PHEV 40 mi EV 340 mi Tot.	• Meets 86% of consumer vehicle mileage on electric drive. • Still requires gasoline usage for longer trips (14% of vehicle mileage). • Smaller batteries keep vehicle weights down and electric drive efficiencies high. • Smaller IC engines used as range extenders are light and also keep weight down. • Smart charging and/or energy storage is required for significant GHG reductions	• Lack of smart charging (consumer behavior cooperation) or energy storage severely limits GHG reduction potential.
Pure BEV 200 mi EV	• Meets 98.5% of consumer vehicle mileage on electric drive. • Low energy density requires high battery weights for 200 mile range • Large battery weights reduce electric drive efficiencies, especially in larger vehicles. • Smart charging and/or energy storage is required for significant GHG reductions • Worse than PHEVs and best FCEV cases if immediate charging is used w/o storage	• Breakthroughs in battery energy density can reduce battery weights and keep efficiencies high • Lack of smart charging or energy storage severely limits GHG reduction potential.
Pure BEV 100 mi EV	• Meets 93% of consumer vehicle mileage on electric drive. • Still requires non-trivial gasoline usage and therefore ownership of a gasoline vehicle • Smart charging and/or energy storage is required for significant GHG reductions • Smaller batteries relative to BEV200 keep weights down allow electric drive efficiencies to remain high, especially in larger vehicles. • Worse than the best FCEV cases if immediate charging is used w/o storage.	• Breakthroughs in battery energy density can significantly increase electric drive efficiencies. • Lack of smart charging (consumer behavior cooperation) or energy storage severely limits GHG reduction potential.
PHFCV 40 mi EV 340 mi Tot.	• Meets 100% of consumer vehicle trips in one vehicle, 86% on pure electric drive. • Hydrogen meets 14% of consumer trips, significantly reducing the hydrogen demand and allowing it to be met in a carbon-free manner with lower renewable capacities. • Fuel cell acting as a range extender does not have to provide total system power output, allowing a low-weight fuel cell. • Smaller batteries reduce weight and keeps electric drive efficiencies high. • Smart charging and/or energy storage is required for significant GHG reductions	• Requires development of both H2 fueling and EV charging infrastructure (albeit to smaller scale than pure pathways) • Dual novel powertrain potentially costly. • Lack of smart charging (consumer behavior cooperation) or energy storage severely limits GHG reduction potential.

Conclusions: General Observations

- **Minimizing greenhouse gas emissions for FCEVs requires optimization of the production mix based on available excess renewable generation.**
    - The two primary pathways for producing hydrogen are through steam methane reformation and hydrogen electrolysis. The former is higher efficiency but emits direct emissions, while the latter is low efficiency but can use renewable generation. The share of each method in the hydrogen production mix must be selected to minimize GHG emissions.
    - While not evaluated here, the availability of sufficient biogas resources could contribute a carbon neutral source of hydrogen through a high efficiency pathway. Determining the amount of available biogas resources and its impact on emissions is a topic of future work.

- **Relying purely on natural gas for hydrogen production in fueling FCEVs does not provide greenhouse gas emissions benefits compared to state of the art gasoline hybrid vehicles.**
    - Hybrid gasoline vehicles have reached a point where their efficiencies are very high. Combined with upstream emissions for gasoline production being low compared to that for natural gas mining, a strong reliance on natural gas for FCEVs can produce as much life cycle GHG emissions compared to that for state of the art gasoline hybrids.

- **Lack of load dispatchability for plug-in vehicles (BEVs, PHEVs, and PHFCVs) can limit their potential greenhouse gas benefits.**
    - All of the cases using immediate charging without energy storage for plug-in vehicles did not reduce greenhouse gas emissions below a certain level even with increasing renewable capacities while the FCEV cases using electrolysis could achieve lower GHG emissions as a result of the large dispatchable electrolysis load.
    - Consumer travel behavior places the electric vehicle charging load during times when renewable generation is relatively low, causing it to be met with natural gas generation and limiting the use of renewable generation without grid-responsive charging management.

- **Smart charging and/or energy storage are required for significant greenhouse gas emissions reductions from plug-in vehicles (BEVs, PHEVs, and PHFCVs).**
    - When consumers are unwilling to schedule their travel patterns into the grid and allow grid operator control of vehicle charging (immediate charging), a large amount of energy storage must be installed to compensate and shift renewable generation to occur at the time of the vehicle charging load.
    - Alternatively, allowing grid operator control and providing knowledge of one's travel patterns allows the electric vehicle charging load to better use renewable generation.

- **Fuel cells as a range extender for plug-in electric vehicles (e.g., PHFCV) provided the lowest emissions of all vehicle types considered with currently available, state-of-the-art technologies.**
    - The characteristics of FCEVs pose challenges for the use of fuel cells as the sole vehicle powertrain due to low carbon-free pathway efficiency and high weight for vehicles with high power outputs. High availability of biogas resources can alleviate the first issue and improvements in fuel cell power density can alleviate the second, but it remains to be seen whether these will occur.
    - The characteristics of BEVs pose challenges regarding the weight of batteries impacting vehicle efficiency when scaled to provide sufficient range with current energy densities, especially in larger vehicle types. A breakthrough in battery energy density could alleviate this issue, but it remains to be seen whether this will occur.
    - With current state-of-the-art technologies, PHFCVs have the following benefits relative to other alternative vehicle types:
        - Using a relatively small battery compared to BEVs, which keeps weight down and increases efficiency especially for larger vehicle classes, keeping efficiencies higher.
        - Using the fuel cell as a range extender allows it to remain light since it does not need to meet total system power output alone, keeping vehicle efficiencies higher.
        - Using renewable hydrogen instead of gasoline to meet longer vehicle trips. By having hydrogen fuel only meet 14% of the miles traveled per vehicle (vs. 100% for FCEVs), the hydrogen demand is significantly smaller, reducing the requirement for excess renewable generation.

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Conclusions: Meeting the 2050 EO S-21-09 GHG Emissions Reduction Target

- **Energy storage is required to meet the long-term greenhouse gas emissions goal regardless of vehicle type.**
  - For most of the renewable capacity levels considered, only the cases which utilized energy storage were able to meet the EO S-21-09 goal **regardless of vehicle type.**
  - Meeting the transportation load with renewable generation but only allowing the stationary load to use renewable generation at the time of occurrence does not enable enough offset of carbon-based power to meet the EO S-21-09 goal, even with increasingly high installed renewable capacities.
  - Excess renewable generation from high generation periods must be captured and used to meet the stationary load during times when renewable generation is low to provide enough emissions reductions.

- **FCEVs can meet the long-term greenhouse gas emissions goal, but require larger renewable capacities to do so compared to the other vehicle types.**
  - Due to the lower efficiency of the renewable hydrogen supply chain, FCEVs require more excess renewable generation to produce hydrogen in a carbon-free manner.
  - The best FCEV case was able to meet the EO S-21-09 goal within a small margin at a renewable capacity of 325 GW, compared to 255 GW for the best PHEV 40 / BEV 200 cases, and 205 GW for the best BEV 100 / PHFCV 40 case.

- **A minimum of 205 GW of installed nameplate renewable capacity is required to meet the long-term greenhouse gas emissions goal.**
  - Only the BEV 100 and PHFCV 40 were close to meeting the goal at 205 GW.

  - All other cases resulted in insufficient emission reduction due to either a lack of dispatchability and/or lack of sufficient excess renewable generation.

- **Smart charging for plug-in vehicles allows the use of smaller energy storage systems in meeting the long-term greenhouse gas emissions goal.**
  - With immediate charging, much of the capacity of the energy storage system is used to compensate for the mismatch between renewable generation profiles and vehicle charging profiles.
  - With smart charging, some cases were able to meet the EO S-21-09 goal with an energy storage system sized to 10% of the renewable capacity and average daily renewable generation.
  - With smart charging, the vehicle charging profile is more closely aligned with renewable generation profiles, the energy storage system can be operated to focus on capturing excess renewable generation to meet the stationary load and offset natural-gas power plant generation.

Appendices

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Appendix A: Vehicle Types, Cases, and Major Parameters

Vehicle Types

- **Fuel Cell Electric Vehicle (FCEV):** This refers to a vehicle that uses a hydrogen fuel cell to convert pressurized hydrogen gas stored onboard into electricity to drive an electric motor.

- **Plug-in Hybrid Gasoline Electric Vehicle (PHEV):** This refers to a vehicle that uses an electric motor to power the wheels. The battery which drives the electric motor can be charged by plugging the vehicle into the electric grid or by use of an on-board gasoline engine to maintain battery charge on long trips.

- **Battery Electric Vehicle (BEV):** This refers to a vehicle that exclusively uses a large battery to power an electric motor to drive the wheels. The battery is recharged by plugging the vehicle into the electric grid.

- **Plug-in Hybrid Fuel Cell Vehicle (PHFCV):** This refers to a vehicle which is similar to a PHEV, but relies on a hydrogen fuel cell instead of a gasoline engine when necessary. The battery which drives the electric motor can be charged by plugging the vehicle into the electric grid or by the hydrogen fuel cell to maintain battery charge on longer trips.

Vehicle Cases

- **Reference Cases**
  - **Year 2010 Actual:** The actual combined electricity and light-duty transportation GHG emissions in the year 2010.

  - **Year 2050 Renewables w/Advanced Gasoline ICV**: The vehicle population is scaled to year 2050 levels and renewables are installed, but the light duty transportation fleet remains entirely composed of advanced gasoline hybrid vehicles.

- **Fuel Cell Electric Vehicles (FCEV)**
  - **Natural Gas Only:** Hydrogen production is sourced completely from natural gas steam methane reformation and truck delivery to hydrogen fueling stations.

  - **50% SMR:** 50% of the hydrogen production is sourced from natural gas steam methane reformation, and 50% from water electrolysis. This is carried out for two different electrolyzer efficiencies:
    - 53.5 kWh/kg H2 – represents current established electrolyzer efficiencies
    - 44.7 kWh/kg H2 – represents the U.S. Department of Energy year 2015 efficiency target.

  - **GHG Minimal:** The hydrogen production and delivery mix is selected to produce the lowest combined greenhouse gas emissions for the given installed renewable capacity. For example, if a large amount of excess renewable generation is present, a larger fraction of the hydrogen demand will be met by renewable-based electrolysis.
    - This is also carried out for two different electrolyzer efficiencies.

  - **GHG Minimal + Storage:** This takes the GHG Minimal case and installs battery energy storage systems on the grid. Two different sizes of energy storage are used:
    - **10% Storage**: An aggregate power capacity of 10% of the installed renewable capacity and an aggregate energy capacity of 10% of the daily average renewable generation is used.
    - **70% Storage**: An aggregate power capacity of 10% of the installed renewable capacity and an aggregate energy capacity of 10% of the daily average renewable generation is used.

- **Plug-in Vehicles (PHEV, BEV, PHFCV) – Immediate Charging**

  Immediate charging refers to BEVs charging immediately at their maximum rate upon consumers plugging these vehicles into the grid when they arrive at locations with charging infrastructure.
  - **Home Only**: Charging infrastructure is only available at residences.

  - **Home and Work**: Charging infrastructure is available at residences and workplaces.

  - **Home + 10% Storage**: Charging infrastructure is only available at residences, but battery energy storage systems are installed on the grid with an aggregate power capacity of 10% of the installed renewable capacity and an aggregate energy capacity of 10% of the daily average renewable generation.

  - **Home + 70% Storage**: Charging infrastructure is only available at residences, but battery energy storage systems are installed on the grid with an aggregate power capacity of 70% of the installed renewable capacity and an aggregate energy capacity of 70% of the daily average renewable generation.

  - **Home/Work + 10% Storage**: Charging infrastructure is available at residences and workplaces, but battery energy storage systems are installed on the grid with an aggregate power capacity of 10% of the installed renewable capacity and an aggregate energy capacity of 10% of the daily average renewable generation.

  - **Home/Work + 70% Storage**: Charging infrastructure is available at residences and workplaces, but battery energy storage systems are installed on the grid with an aggregate power capacity of 70% of the installed renewable capacity and an aggregate energy capacity of 70% of the daily average renewable generation.

- **Plug-in Vehicles (PHEV, BEV, PHFCV) – Smart Charging**
  Smart charging refers to two simultaneous components:
  1. The BEV charging profile is shaped to respond to electric grid behavior to maximize absorption of renewable generation
  2. Consumer travel patterns are known for the year by electric grid operators. This allows them to plan how to shape the BEV charging profile based on knowledge of when vehicles are plugged in and how much these vehicles need to be charged.

  - **Home Only:** Smart charging infrastructure is only available at residences.

  - **Home and Work:** Smart charging infrastructure is available at residences and workplaces.

  - **Home/Work + 10% Storage:** Smart charging infrastructure is available at residences and workplaces, but battery energy storage systems are installed on the grid with an aggregate power capacity of 10% of the installed renewable capacity and an aggregate energy capacity of 10% of the daily average renewable generation.

  - **Home/Work + 70% Storage:** Smart charging infrastructure is available at residences and workplaces, but battery energy storage systems are installed on the grid with an aggregate power capacity of 70% of the installed renewable capacity and an aggregate energy capacity of 70% of the daily average renewable generation.

  - Note: For the PHFCV cases, the fuel cell infrastructure configuration is set according to the GHG Minimal w/ 44.7 kWh/kg case.

Major Parameters

Vehicle Efficiency

Vehicle efficiency characteristics were determined for representative vehicle classes for each powertrain type: automobiles, small trucks/SUVs, and large trucks/SUVs using the NREL FastSim and NREL ADVISOR vehicle modeling tools and available data for currently released models. Fleetwide average vehicle efficiency factors for each vehicle type were determined from knowledge of the vehicle-miles-traveled by each vehicle class from the CARB EMFAC data.

- **FCEV**
  - Passenger Car: 58.0 mi/kg H2
  - Small SUV/Truck: 49.6 mi/kg H2
  - Large SUV/Truck: 29.4 mi/kg H2
- **PHEV w/ 40 mile electric range**
  - Passenger Car: 0.319 kWh/mi Electric, 45.8 mpg Gasoline
  - Small SUV/Truck: 0.370 kWh/mi, Electric, 36.9 mpg Gasoline
  - Large SUV/Truck: 0.434 kWh/mi Electric, 21.9 mpg Gasoline
- **BEV w/ 100 mile electric range**
  - Passenger Car: 0.309 kWh/mi Electric

  - Small SUV/Truck: 0.430 kWh/mi Electric
  - Large SUV/Truck: 0.575 kWh/mi Electric
- **BEV w/ 200 mile electric range**
  - Passenger Car: 0.344 kWh/mi Electric
  - Small SUV/Truck: 0.462 kWh/mi Electric
  - Large SUV/Truck: 0.626 kWh/mi Electric
- **PHFCV w/ 40 mile electric range**
  - Passenger Car: 0.325 kWh/mi Electric, 56.7 mi/kg H2
  - Small SUV/Truck: 0.372 kWh/mi, Electric, 48.7 mi/kg H2
  - Large SUV/Truck: 0.435 kWh/mi Electric, 29.3 mi/kg H2
- **Gasoline Vehicles**
  - Gasoline Vehicles based on current state-of-the-art hybrid vehicle efficiencies
  - Passenger Car: 50 mpg Gasoline
  - Small SUV/Truck: 28 mpg Gasoline
  - Large SUV/Truck: 24 mpg Gasoline

Vehicle Parameters

The major parameters for vehicle types are as follows:

- Peak Power Output:
  - Passenger Car Average: 172 hp
  - Light SUV/Truck Average: 179 hp
  - Heavy SUV/Truck Average: 254 hp
- Battery Specific Mass: 7.1 kg/kWh – equivalent to Tesla Model S 85 kWh model
- Electric Motor Peak Efficiency: 93%
- Fuel Cell Model: ANL50H2 with 60% Peak Efficiency
- Driving Cycles for simulation: EPA UDDS, EPA HWYFET. Each repeated 4 times continuously.
- Transmission: 1-speed for BEV, FCEV, and PHFCV, CVT for PHEV
- Battery Maximum Power: Equivalent to electric motor power
- AC/DC Conversion Efficiency: 85%
- Maximum Plug-in Vehicle Charging Power: 10 kW
- Ratio of Range-Extender Power to Total System Power: 55.8% (equivalent to 2014 Chevrolet Volt)

Grid Model Parameters

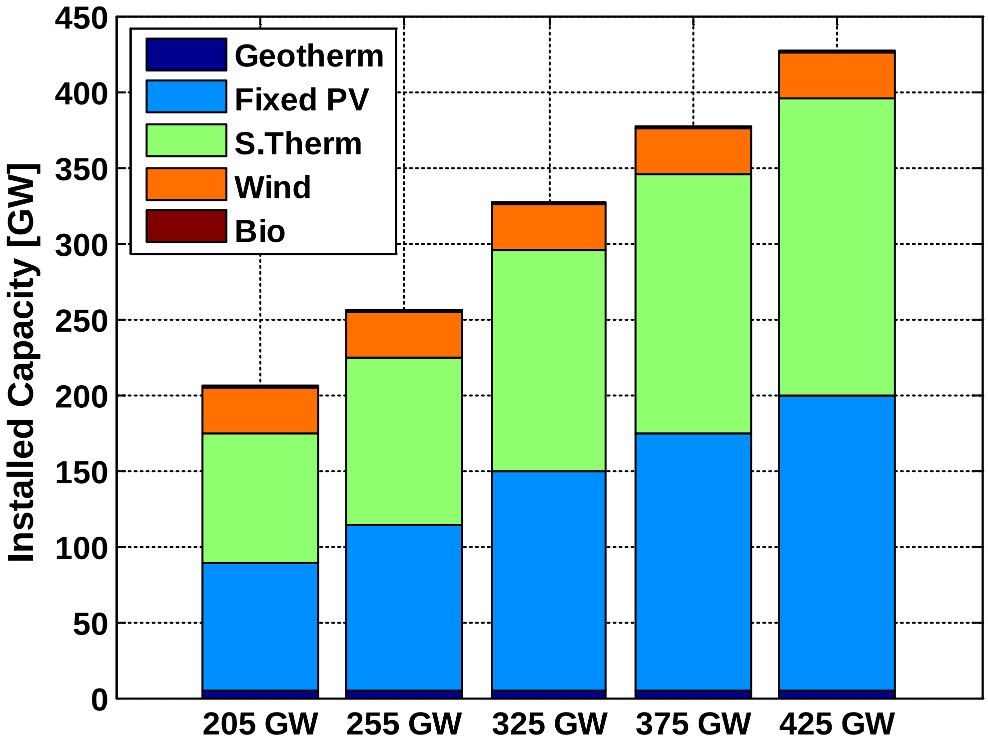
This study uses a detailed model of electric grid operations to simulate electric grid behavior [6]. The following are some of the major parameters used in the model.

- **Peaking (Fast-Response) Power Plant Parameters**
  - Base Model: GE LM6000 Aeroderivative Gas Turbine [11]
  - Fuel: Natural Gas
  - Individual Unit Capacity: 50 MW
  - Design Point Efficiency: 41%
  - Minimum Part-Load Condition for an Individual Unit: 30% of Rated Power

- **Load-Following (Moderate-Response) Power Plant Parameters**
  - Base Model: GE FlexEfficiency 60 Advanced Combined Cycle [12]
  - Fuel: Natural Gas
  - Individual Unit Capacity: 405 MW
  - Design Point Efficiency: 61%
  - Minimum Part-Load Condition for an Individual Unit: 40% of Rated Power

- **Renewable Capacity Breakdown by Type**

  The renewable resource portfolio for each of the renewable capacity increments used in this study is presented as follows:



For all cases, fixed solar PV and solar thermal resources make up the bulk of the renewable resource mix. Wind has an installed capacity of approximately 31 GW, but does not increase in these cases since the potential of high-quality wind resources in California is limited. Geothermal and biopower make up small fractions of the mix as well due to potential limits. At this scale of renewables for the state, solar resources are the only types that can be continually increased. For these cases, solar PV and solar thermal capacities each make up 50% of the total solar resource capacity.

Calculation of EO S-21-09 Goal for Relevant Sectors

To calculate a target to represent the EO S-21-09 goal that is consistent with the sectors included, the year 1990 level GHG emissions for those sectors was obtained from the CARB greenhouse gas inventory [13], and are presented as follows:

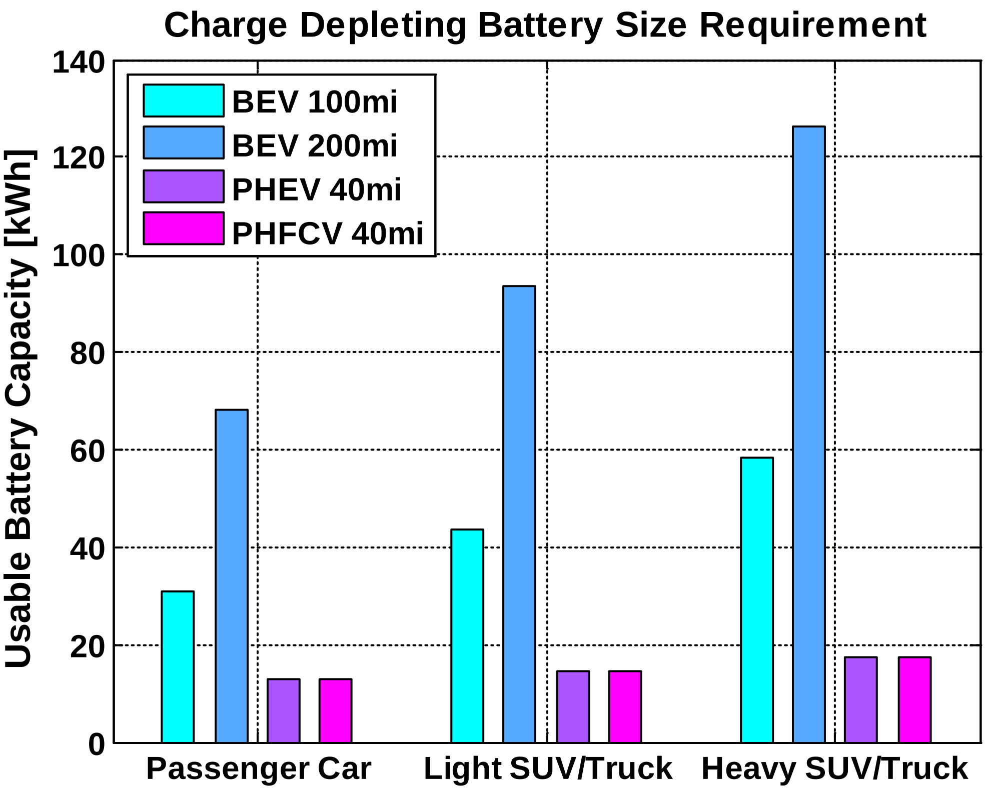
Component	Year 1990 GHG Emissions [MMT CO2e/yr]
Electricity Generation	115.843
Petroleum Refining	27.633
Road Transportation – Cars	63.746
Road Transportation – Light Duty Trucks	44.754
Fugitive Natural Gas Emissions	1.505
Fugitive Oil Emissions	0.139
Total 1990 Emissions	**253.62**
Total 2050 Target	**50.7240**

Appendix B: Supplemental Results

This section presents supplementary results that are referred to in the description of the main results, which help to further explain the behavior and factors which gave rise to those results.

Usable Battery Capacity Requirements for Plug-in Vehicles

This section presents the required battery capacity sizes required for plug-in vehicles. Especially for BEVs, the weight of the batteries required to provide sufficient vehicle range can affect the electric energy consumption per mile. These capacities were determined using the NREL FastSim and NREL ADVISOR tools. Note that this refers to the **minimum** required battery capacity for vehicles of different plug-in vehicle classes to provide a given all electric range. Constraints on minimum and maximum charge levels due to preferred operating modes will increase the actual battery size requirement for a given vehicle class.

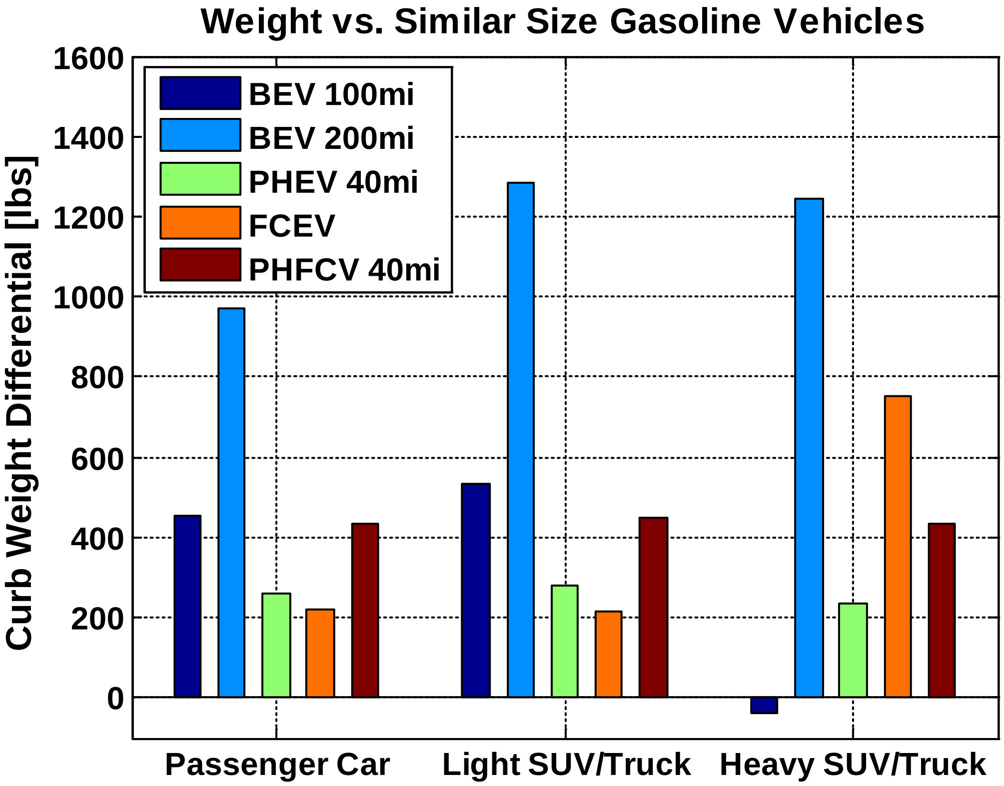


With current technologies and vehicle efficiencies, large battery sizes may be required to provide high all-electric ranges for different vehicle classes. PHEVs which provide shorter all electric ranges require relatively small battery capacities between 10 and 20 kWh depending on vehicle class. BEVs with a 100 mile range require larger batteries which increase weight, on the order 30 to 58 kWh. For BEVs with a 200 mile range, the large battery sizes required increase vehicle weight and decrease electric drive efficiency compared to the other vehicle types.

PHFCVs have similar battery size requirements to PHEVs, since the weight differential of removing the internal engine combustion system and adding a fuel cell system is relatively small.

Curb Weight Differential of Alternative Vehicles

This section presents the differential between the curb weights of alternative vehicle powertrains and equivalent size gasoline vehicles for different vehicle classes. These results also provide a rationale for the vehicle efficiency factors simulated and used in the study. These weights were determined using the NREL FastSim and NREL ADVISOR tools.



For 200 mile BEVs, even with current state of the art energy densities (Tesla Model S), the weight of batteries acts to increase the weight of a vehicle by a significant amount compared to equivalent size and power gasoline vehicles. Light SUVs and trucks tend to have similar power outputs compared to automobiles, but have higher weights, lower aerodynamic efficiencies, and higher rolling resistances. This contributes to higher curb weight differentials for BEVs compared to passenger cars since enough energy must be required to overcome these losses to provide the required range. A similar principle holds for heavy SUVs and trucks, but the base vehicle is heavier than that for light SUVs and trucks.

BEVs with a 100 mile range do not have as significant of a weight increase as 200 mile BEVs, since batteries are a lower fraction of the overall weight. For heavy SUVs and trucks, the weight differential is actually negative. In these vehicles, the chassis is a large contributor to weight. Additionally, heavier vehicles tend to have heavier internal combustion powertrains to meet power requirements. Removal of the internal combustion powertrain reduces weight, which creates a larger margin for a portion of the batteries to be added without increasing weight relative to gasoline vehicles. This effect also explains why PHEVs have a larger increase in weight for heavy SUVs/trucks relative to 100 mile BEVs, since these vehicles retain the internal combustion engine powertrain components albeit at smaller scale. BEVs can also scale to meet power output requirements without significant increases in weight, since increasing the size of the electric motor does not add much additional mass.

PHEVs only increase vehicle weights by a small amount, due to allowing the use of smaller batteries and a smaller internal combustion engine relative to the gasoline only versions, since it does not need to meet the total system power output alone.

FCEVs do not significantly increase weight for passenger cars, since passenger cars have low power outputs and the fuel cells can be kept relatively small and light. This is also the case for light SUVs and trucks. For heavy SUVs/trucks, higher power levels require larger fuel cells. Fuel cell weight scales with power output, and the larger power levels required to carry payloads and move larger vehicles require relatively heavy fuel cells.

PHFCVs have lower weight increases than FCEVs, especially for larger vehicles, since smaller fuel cells can be used. The fuel cell acts primarily as a generator, and may not need to provide the full system power output at all times. These vehicles are still heavier than PHEVs, since fuel cells are still slightly heavier than internal combustion engines of the same power output.

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Calculation of Life Cycle Greenhouse Gas Emissions for Immediate Charging BEVs

This section presents the calculation of the life cycle greenhouse gas emissions per mile results presented in the primary results, when explaining how **BEVs with immediate charging and no energy storage** produce life cycle emissions that are comparable to that for advanced hybrid gasoline vehicles since they would be fueled by non-renewable power generation from natural gas power plants at the scale of 90% vehicle penetration. It is important to note that these calculations are for the fuel supply chain only, and do not include vehicle manufacturing.

For BEVs that are fueled by electricity generated from natural gas, greenhouse gas emissions are solely associated with natural gas combustion and mining. We must first calculate the amount of natural gas required to fuel a mile of travel, taking into account losses on the electric grid, and then calculate the life-cycle greenhouse gas emissions.

$$E_{NG}\left[\frac{MJ}{mi}\right] = E_{vehicle} \cdot \frac{1}{\eta_{charge}} \cdot \frac{1}{\eta_{T/D}} \cdot \frac{1}{\eta_{PP}(PL)} \cdot \frac{3.6\ MJ}{kWh}$$

$$EM_{GHG,NG}\left[\frac{g\ CO_2e}{mi}\right] = E_{NG}\,[MJ] \cdot \left[\sum EF_{i,NG}\right]$$

For gasoline vehicles, emissions are calculated according to the following:

$$EM_{GHG,Gas}\left[\frac{g\ CO_2e}{mi}\right] = mpg_{vehicle} \cdot \left(EF_{comb} + EF_{upstream}\right)$$

Where:

Parameter	**Description**	**Units**
$E_{vehicle}$	Plug-in Vehicle Energy Consumption	kWh/mi
η_{charge}	AC/DC EV charging efficiency	%
$\eta_{T/D}$	Transmission and Distribution grid losses	%
$\eta_{PP}(PL)$	Power Plant Efficiency as a function of part-load condition	%
E_{NG}	Natural gas energy requirement	MJ/mi
$EF_{i,NG}$	Emissions factor for ith component of natural gas supply chain	gCO2e/MJ NG
$EM_{GHG,NG}$	Greenhouse Gas Emissions from Natural Gas pathway	gCO2e/mi
$mpg_{vehicle}$	Gasoline vehicle fuel economy	mi/gal
EF_{comb}	Emissions factor for gasoline combustion	gCO2e/gal
$EF_{upstream}$	Emissions factor for gasoline upstream processes	gCO2e/gal
$EM_{GHG,Gas}$	Greenhouse Gas Emissions from Gasoline pathway	gCO2e/mi

For this calculation, we use an aggregate emissions factor from [14], which takes into account natural gas combustion in power plants, mining emissions from methane and carbon dioxide leakage/venting, and upstream combustion. Gasoline process emissions factors have been obtained from [15], with the upstream factor calculated according to EPA standards [16]. This parameter along with others utilized are presented as follows:

Parameter	**Value**
$E_{vehicle}$	BEV 100 mile: 0.384 (fleet-wide average) BEV 200 mile: 0.423 (fleet-wide average)
η_{charge}	85 %
$\eta_{T/D}$	90 %
$\eta_{PP}(PL)$	Load Following Power Plant: 61% at design power 53% in operation (from grid model) Peaking Power Plant: 41% at design power 38% in operation (from grid model)
$\sum EF_{i,NG}$	67 g CO2e/MJ Natural Gas
$mpg_{vehicle}$	41.8 (fleet-wide average)
EF_{comb}	8.78
$EF_{upstream}$	2.195

Using these parameters, the results for the marginal life cycle greenhouse gas emissions of immediate charging BEVs and advanced gasoline hybrid vehicles are as follows:

Pathway	**Life-Cycle Greenhouse Gas Emissions [g CO2e/mi]**
Advanced Gasoline Hybrid	276.100
BEV 200 mile – Load Following Power Plant (design)	218.647
BEV 200 mile – Peaking Power Plant (design)	325.282
BEV 200 mile – Load Following Power Plant (actual operation)	253.120
BEV 200 mile – Peaking Power Plant (actual operation)	341.273
BEV 100 mile – Load Following Power Plant (design)	198.488
BEV 100 mile – Peaking Power Plant (design)	295.292
BEV 100 mile – Load Following Power Plant (actual operation)	229.784
BEV 100 mile – Peaking Power Plant (actual operation)	309.808

Appendix C: Model Description

Overall Modeling Methodology

This study combines an array of modeling tools for vehicle powertrain simulations, vehicle infrastructure, vehicle electric load dispatch, and electric grid dispatch models to assess the importance of grid integration for achievable greenhouse gas reductions. The overall layout of the interaction between these models is presented in Figure 13:

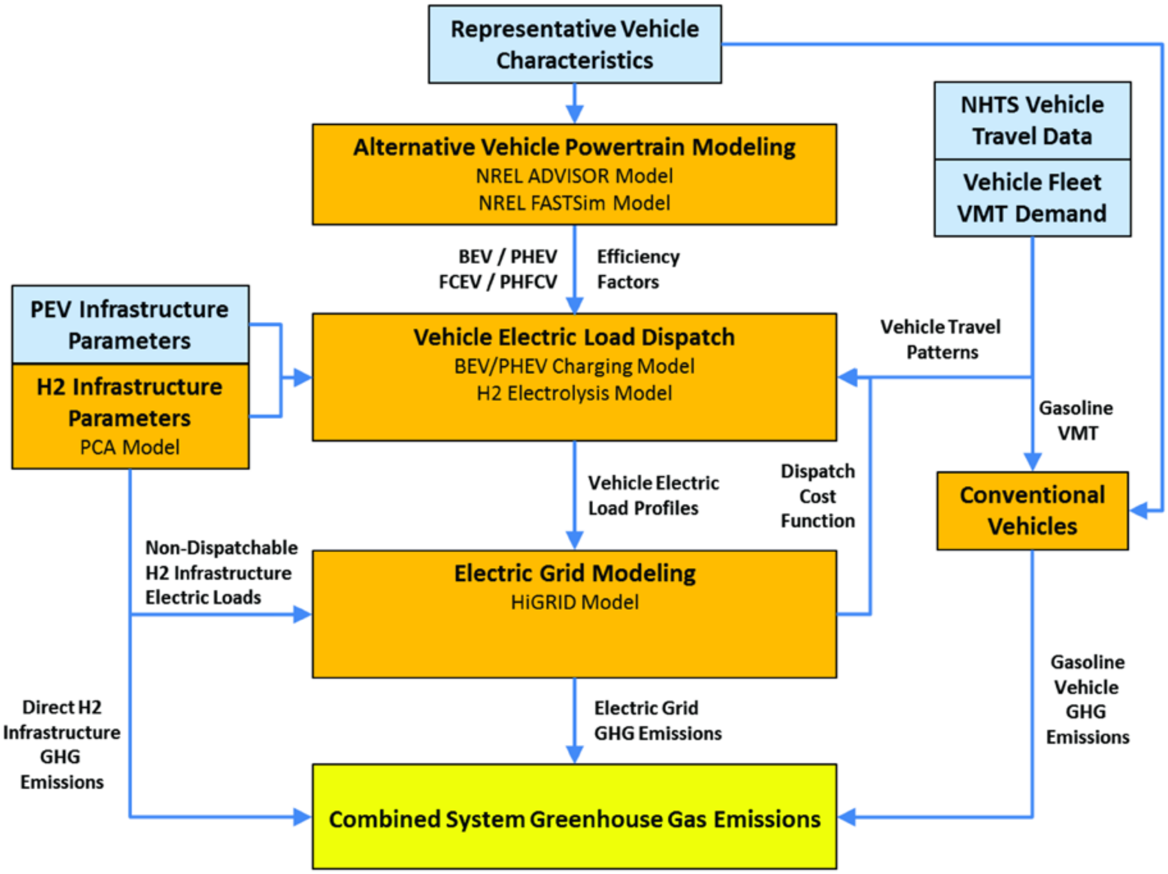

Figure 13 - Integration of Modeling Tools

First, representative vehicle types for different vehicle classes in the light-duty vehicle fleet are chosen and their characteristics (aerodynamics, chassis weight, etc…) are determined. Each of these vehicle types are then simulated with different powertrains (BEV, PHEV, FCEV, PHFCV) using the ADVISOR and FASTSim alternative vehicle powertrain modeling tools to determine vehicle efficiency factors and fuel economy. The efficiency factors are combined with vehicle travel data from the National Household Travel Survey, vehicle-miles-traveled demand data, PEV charging infrastructure settings, and hydrogen infrastructure parameters to inform the vehicle electric load dispatch models. These models determine the profile of the dispatchable electric loads associated with PEV charging or hydrogen production based on vehicle constraints, and alternative vehicle travel demand. The vehicle-related electric load profiles are developed in response to a cost function from the electric grid model, which is taken to be the net load profile (native load minus renewable generation) in this study. Once vehicle-related electric load profiles are determined, these load profiles are input into the electric grid model. This step resolves the temporal behavior of electric grid resources including generators and energy storage in response to the added vehicle loads, taking into account generator constraints, renewable variability, and grid reliability constraints, and determines the greenhouse gas emissions associated with the electric grid.

Note that vehicle infrastructure electric loads which are non-dispatchable, such as hydrogen pipeline loads, are not included in the vehicle electric load dispatch model and are directly input into the electric grid model as fixed profile loads. Additionally, the portion of the vehicle miles traveled demand which is unable to be satisfied by alternative vehicles is met by gasoline hybrid vehicles, which produce direct emissions.

Modeling of the Electric Grid

Modeling of the electric grid was conducted through use of the Holistic Grid Resource Integration and Deployment (HiGRID) model [6].

Since many of the phenomena that contribute to variability in renewable generation such as wind speed, temperature, cloud cover, and humidity also affect the operation of other generators as well, each resource data signal is temporally coincident. Figure 14 presents the flow diagram for the HiGRID model. The systems modeled in HiGRID are composed of generation resources, both renewable and conventional, and additional complementary resources such as energy storage and demand side-management strategies that all act to balance the system by not only providing sufficient energy to meet the demand, but also providing sufficient generation reserves to maintain reliability.

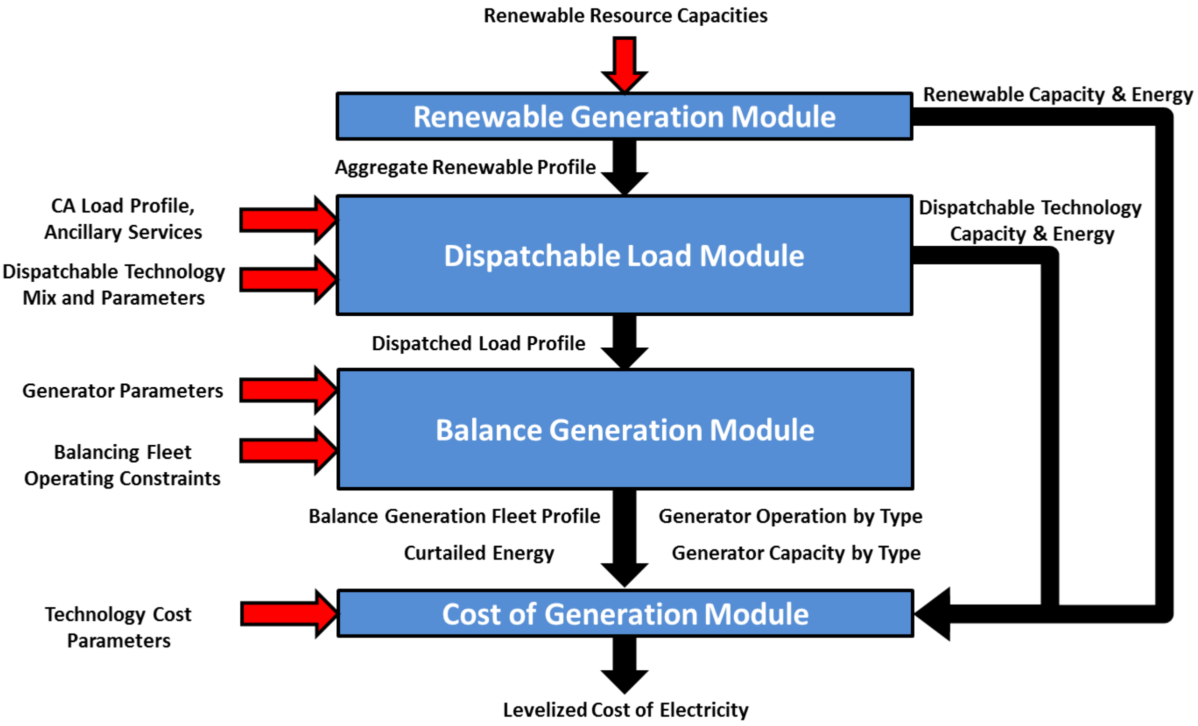

Figure 14 - HiGRID Model Flowchart

The HiGRID tool makes use of 4 distinct modules, 3 of which are used in this study. Within each, the fuel use and GHG emissions produced from the relevant technologies are accounted for and are summed at the end of each total model run.

Renewable Generation Module: This module takes the capacity of different renewable resources as an input, and uses models of each type to determine the time-resolved profile of power generation and power delivered to load for each resource type. The generation profile of the combined renewable resource mix is composed and fed into the dispatchable load module.

Dispatchable Load Module: The dispatchable load module takes the time resolved electric demand profile and aggregate renewable generation profile as inputs to compose the net load profile. This module dispatches complementary technologies and loads in response to the behavior of the net load profile or balance generators through an iterative process, within the operating constraints of each technology. Included are models for hydroelectric generation, energy storage, demand response, electric vehicle charging, and hydrogen production/storage. The option for some technologies to meet ancillary service requirements for the grid such as spinning reserve and regulation capacity is also available. After all selected technologies are dispatched, the adjusted net load profile and the remaining portion of ancillary services required to be met by balance generators are calculated.

Balance Generation Module: The balance generation module determines the sizing and dispatch of base-load, load-following, and peaking generation that is required to meet the adjusted net load profile and remaining ancillary services, within the performance capabilities of different generator classes. Base-load generators such as nuclear and coal power plants are dispatched on an installed capacity and monthly capacity factor basis that includes planned outages. Load-following and peaking generators are dispatched to meet the remainder of the adjusted net load profile.

Each of these classes of generators has performance limitations including minimum operation time, ramping limitations, part-load operation range, and generator size.

Modeling of Plug-in Electric Vehicle Charging

Consumer Travel Patterns

The vehicle travel behavior data is sourced from the 2009 National Household Travel Survey (NHTS) [8]. Data for California were selected, trips occurring without a personally owned vehicle were deleted, person-chain data were converted to vehicle-chain data, daily trips data with unlinked destinations or significant over-speed were deleted, and tours were organized into home based daily tours (first trip from home, last trip to home). From the data set, 20,295 vehicles were selected covering 83,005 unique individual vehicle trips.

Vehicle and Infrastructure Configuration Parameters

The plug-in electric vehicle infrastructure model allows for consideration of a number of different configurations for the charging infrastructure and vehicle capabilities. These different configurations alter the charging profile and the effect that vehicle charging has on the electric grid as travel patterns are adjusted to meet consumer needs. Included are the following:

Charging Location: The locations with electric vehicle chargers installed. This includes residences (home), workplaces, or both.

Charging Power: The maximum charging power of installed electric vehicle chargers per unit.

Electric Range: The maximum electric range in miles. For BEVs, this is the entire vehicle range, otherwise it is the range after which supplementary propulsion would need to be activated.

Vehicle Efficiency: The “fuel economy” of a PEV in kWh per mile.

The penetration of plug-in electric vehicles is then input to represent the fraction of electric vehicles in the fleet, scaling the charging profile of the vehicle fleet accordingly.

Electric Vehicle Charging Management for PHEVs and PHFCVs

PHEV energy usage is modeled using a tool constructed by Zhang, Brown, and Samuelsen [7, 10], and is also repurposed for PHFCVs. Inputs include: vehicle type, miles per gallon (or kilogram of hydrogen), electric energy consumption per mile, battery depth of discharge, vehicle range, charging power, charging location and charging strategy, and consumer travel patterns.

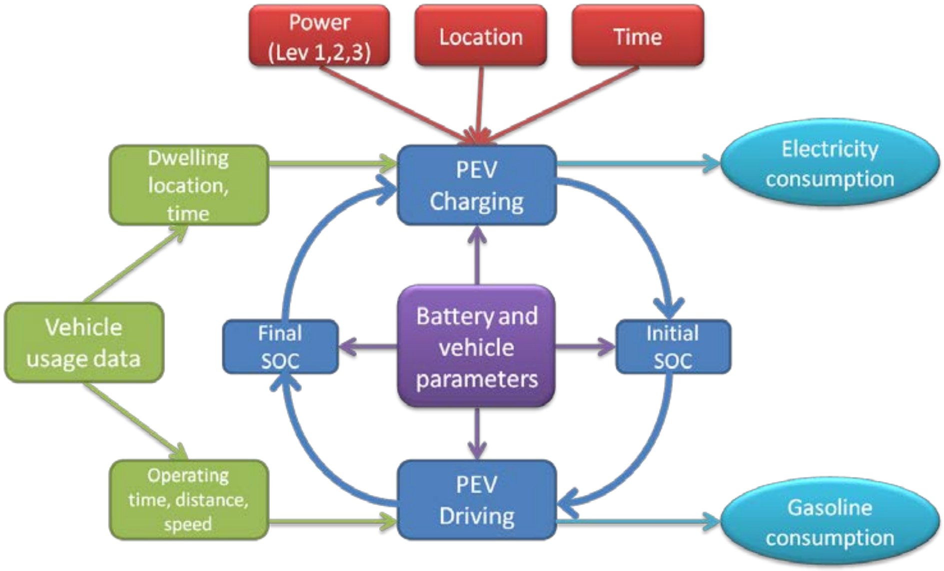

Figure 15 - PHEV Operating and Charging Model [17]

The model ensures that all trips can be made either on electricity or gasoline/hydrogen with a goal to maximize the portion of miles driven using electricity. Two charging strategies are used here:

Immediate charging: Vehicle owners plug their car in immediately when they arrive to their destination and begin charging at maximum power until the vehicle is completely charged.

Smart charging: Vehicle owners rely on a control signal to determine when the vehicle will charge and what the charging power will be.

3.2.3. Electric Vehicle Charging Management for BEVs

BEV charging is different than that for a PHEV or PHFCV. For the latter, travel beyond the electric range can be met by gasoline or hydrogen, which allows a consumer to continue using the vehicle in the same manner as a standard gasoline vehicle. The use of electric drive is preferred but it does not alter consumer travel patterns. For a BEV, however, consumer travel patterns may need to be changed to ensure that travel needs are met to the extent possible.

The BEV smart charging strategy considers an entire day's travel pattern and determines the optimal charging behavior based on a specific charging rate schedule that follows the net load demand of the electric grid. This differs from the PHEV smart charging methodology because it assumes complete knowledge of travel patterns and the control signal at least a day ahead of time and optimizes charging across multiple dwelling periods. A dwelling period refers to a segment of time where a vehicle is parked at a given location.

The fundamental hypothesis is that drivers will adjust their charging behavior such that some objective can be achieved, in this case minimal GHG emissions. Although optimal charging has been implemented in previous studies [18-23], it has not been utilized to determine the impact on GHG emissions.

Figure 16 shows a schematic diagram of the model. Optimization requires knowledge of the whole day's vehicle travel pattern and the control signal during each dwelling activity, which can be provided by the NHTS data and the forecast for the net load demand, respectively. Given particular charging power limits, charging station locations, battery capacity constraints, and energy conservation, the cost function can be minimized. The model outputs the location and duration of daily charging activity for each individual vehicle captured in the NHTS data. With the large and representative data set of NHTS, the summation of individual results is used to provide fleet-wide characteristics.

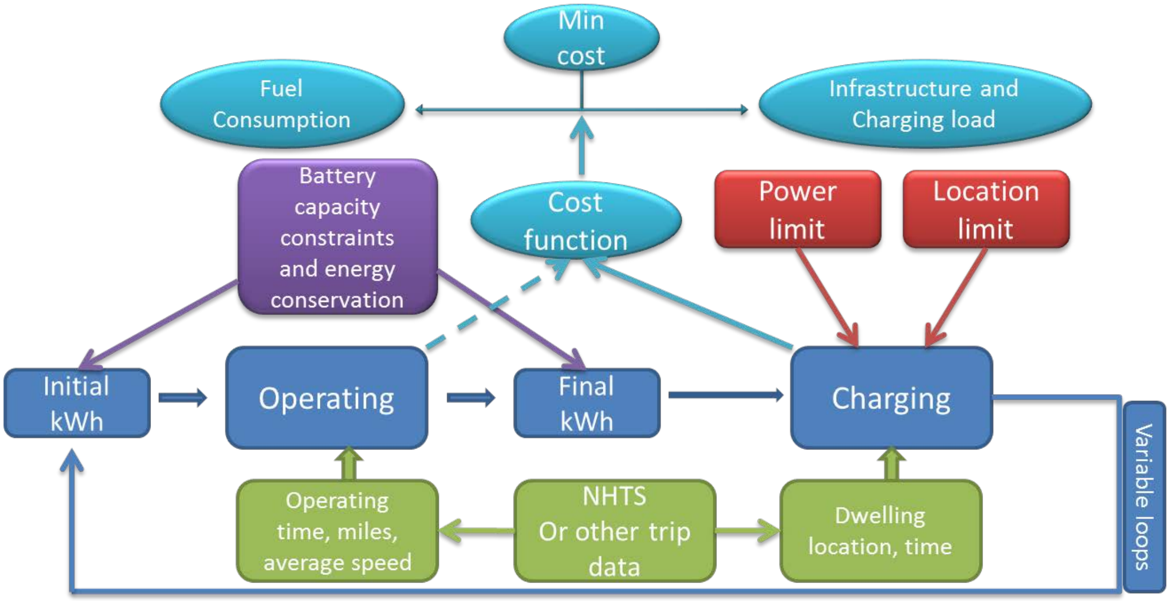

Figure 16 - PEV optimal operating and charging model [7].

Figure 17 shows an example of BEV battery charging and discharging energy throughout the course of one day. Solid red circles represent trip starting points while checkered black circles signify ending locations. For example, a vehicle may make m trips during the course of 24 hours (3 trips in the figure). The periods of battery state-of-charge (SOC) decrease (i.e., electricity consumption) are shown as $y_1, y_2, \dots \dots\ y_m$. Following each trip, a dwelling activity takes up a set of dwelling hours, indicated by $x_{m1}, x_{m2}, \dots \dots, x_{m\ seg(m)}$. The optimization problem solves for the accumulated stored battery energy in each hour during each dwelling activity, represented by x_{ij} , required to fulfill a day's driving at the lowest cost.

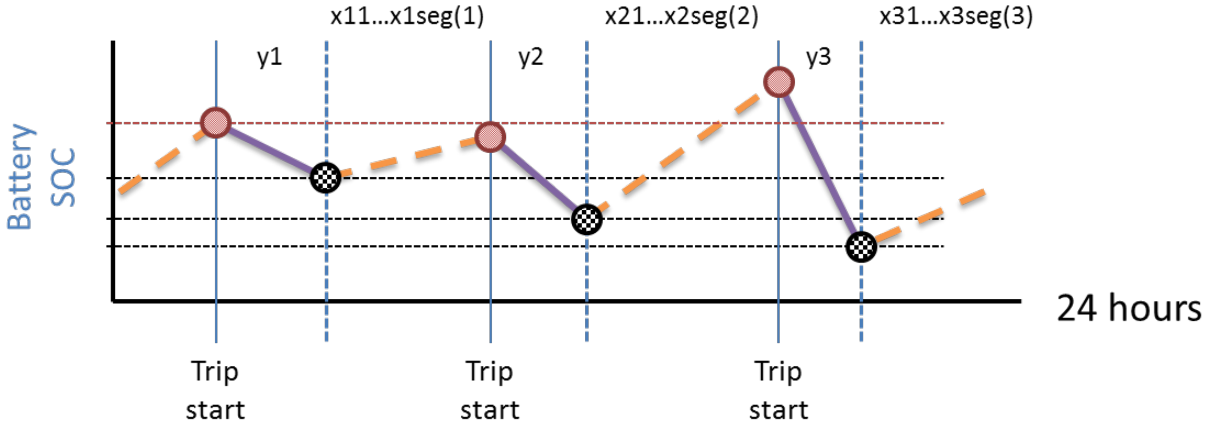

Figure 17 - Example of BEV optimal charging model [7].

Hydrogen Fuel Cell Vehicle Infrastructure Modeling

The processes associated with hydrogen production, delivery, and dispensing all require energy in different forms, and produce emissions both in isolation and due to additional load placed on the electric grid. Some of these processes can also be treated as dispatchable loads which can provide a benefit to the electric grid in terms of its ability to mitigate the effects of renewable variability.

The Preferred Combination Assessment (PCA) modeling approach developed by the University of California, Irvine [9] is utilized to capture these effects. This enables detailed calculation of criteria pollutant and GHG emissions, as well as total resource consumption as a function of the supply chain configuration. The hydrogen demand and the distances over which it must be delivered are two of the required inputs. Outputs include criteria pollutant /GHG emissions, and energy consumption. Figure 18 represents a simplified description of the model.

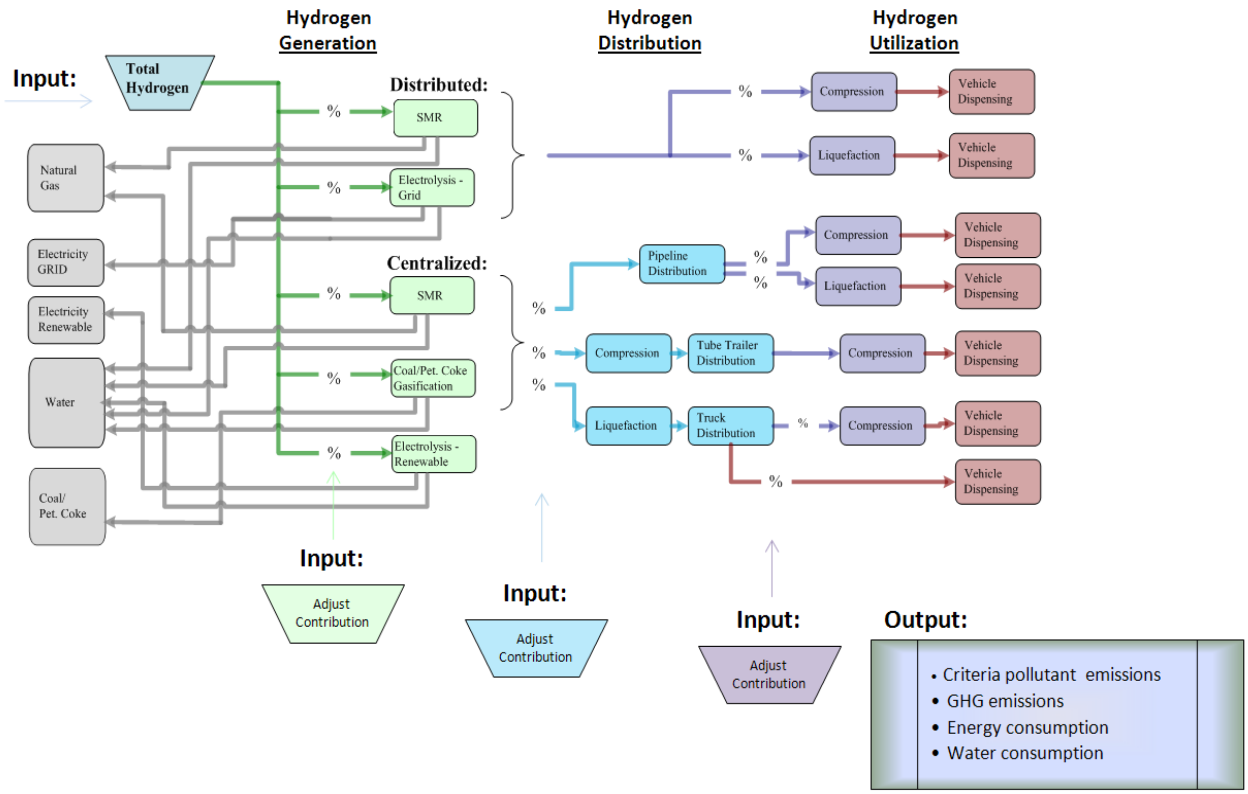

Figure 18 – PCA Model [9]

The temporal profile of the different electric loads is linked to the behavior of different parts of the system. The loads associated with the chemical methods of producing hydrogen and that associated with injection into the delivery system (truck, pipeline, etc…) are assumed to be flat in time, since these plants commonly operate at steady state. By contrast, the loads associated with the dispensing of hydrogen at filling stations are tied to the profile of the hydrogen demand. The shape of hydrogen demand profile has been determined by paralleling the shape of the average gasoline dispensing profile as provided by [24], and scaled to match the aggregate hydrogen demand appropriately.

Electrolysis for hydrogen production is treated as a highly dispatchable load, and the load profile produced by the electrolyzers is constructed in response to a cost function from the electric grid, as explained in the next section.

3.3.1. Dispatchable Electrolysis Model

The dispatch of the electrolyzer fleet is carried out by using a variable moving window, exhaustive 1-D optimization approach, subject to the constraints of hydrogen storage size and in response to a cost function. For this application, an exhaustive 1-D optimization was found to converge to the same result faster than a formal optimization algorithm subject to the same constraints, although this may change in the future as additional constraints are added.

The algorithm proceeds as follows:

- Set initial fill level of bulk hydrogen storage
- Subtract yearly hydrogen demand profile from storage fill
- Record the hour immediately before the storage fill level becomes negative: t_{empty}
- Search backwards in time from t_{empty} to find the last hour when the storage fill level was at maximum capacity: t_{full}
  - If the storage fill level was never at maximum capacity, t_{full} is set to the first hour of the year.

  - Optimization window is from t_{full} to t_{empty}. Within optimization window, examine the cost function and find the time point with the lowest function value.
- If adding electrolyzer increment will overfill storage at selected point, exclude point
- An electrolyzer must be activated in this time window to prevent violating fill constraints.
- Add a given amount of electrolysis load at optimal point
- Update hydrogen storage fill profile and cost function profile
- Repeat until end of year is reached.

An example of a single step of the optimization approach is presented in Figure 19.

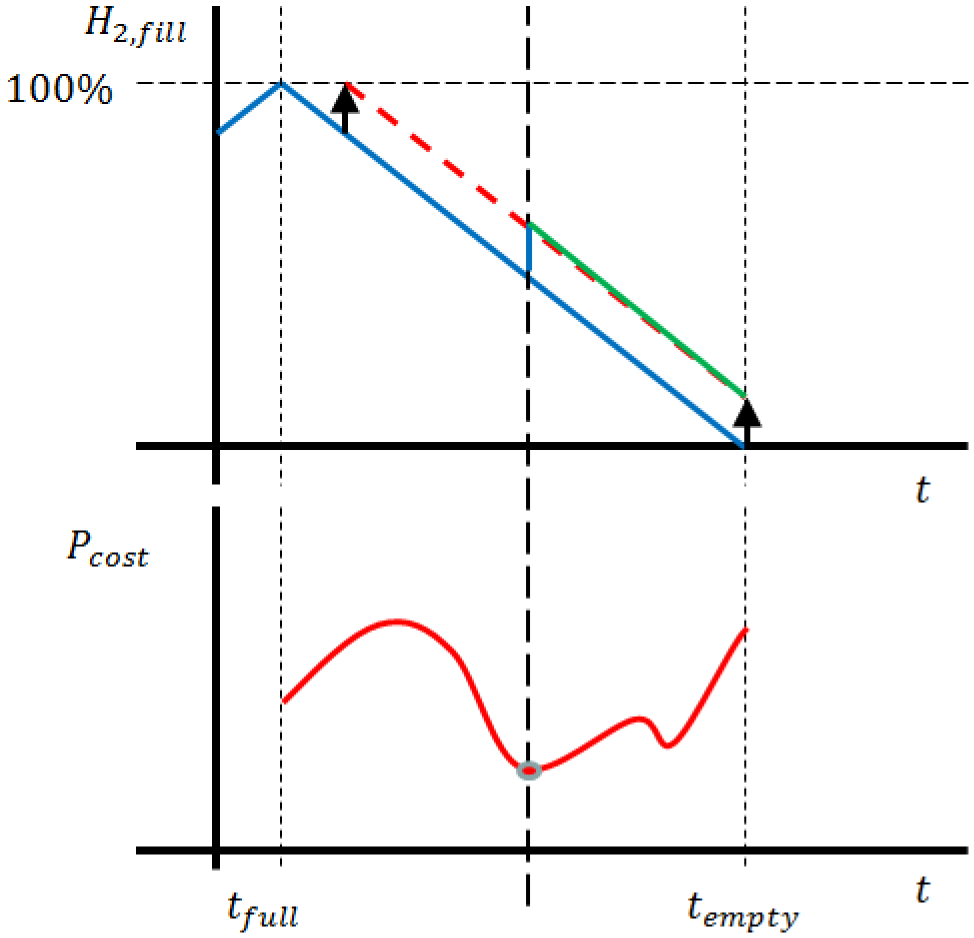

Figure 19 - One Step of the Optimization Algorithm

This simple algorithm produces an electrolysis load profile that responds to the value of the input cost function within constraints. The cost function used in this model is based on the net electric load on the electric grid after less flexible complementary technologies have been applied and is updated in-situ as electrolyzer increments are added:

$$P_{Cost} = P_{load} - P_{Ren} - P_{\mathrm{hydro}} + P_{PEV} + P_{H2,nondis} + P_{H2inc}$$

Where:

- P_{cost} = Cost function value: net load profile entering electrolysis module
- P_{hydro} = Profile of load subtracted due to non-renewable hydropower generation
- P_{ren} = Profile of load subtracted due to aggregate renewable generation profile
- P_{PEV} = Profile of load added due to EV charging
- $P_{H2,nondis}$ = Profile of load added due to non-dispatchable hydrogen loads
- P_{H2inc} = Profile of hydrogen electrolysis load. Updated in-situ until optimization ends

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