Appendix A
Range Limitations of Battery Electric Vehicles

One of the key factors limiting the widespread adoption of battery electric vehicles (BEVs) is their limited range. While in principle the range of any electric vehicle could be extended by adding more batteries, in reality there are real-world limits to the range of a BEV.

The practical range of a BEV is limited by a process called “mass compounding”: For every kg of battery mass added to increase range, the size and weight of other BEV components must also be increased to maintain the performance and safety of the vehicle; adding more batteries requires at a minimum:

- The mechanical system holding the battery bank must be enlarged to properly support those extra batteries.
- The electric motor and controller size must be increased to provide adequate acceleration for the BEV to safely enter a high-speed roadway or to safely pass another vehicle.
- The brakes must be enlarged to safely stop the BEV under all conditions.
- The entire vehicle structure should be strengthened to adequately protect passengers in a crash.
- The suspension system should be enlarged to provide a comfortable ride with the extra mass.
- Finally, still more batteries must be added as a result of these extra mass components listed above to achieve the desired range, and the process steps outlined above must be repeated which lead to still larger components in a nonlinear feedback process.
Battery Specifications

We consider two types of batteries: High-energy batteries required for BEVs to maximize range, and high-power batteries required for peak power augmentation on fuel cell electric vehicles (FCEVs)

High-Energy Batteries for BEVs

The best-selling BEV in the USA, the Nissan Leaf, uses advanced lithium-ion batteries. The main characteristics of the Leaf Li-ion battery are summarized in Table A.1. The calculated useful specific energy for this battery is 54.4 Wh/kg. Nissan claims a much higher specific energy of 140 Wh/kg, but the 54.4 Wh/kg is calculated directly from the Nissan battery data [A.1], which lists a useful energy of 16 kWh and a total battery pack mass of 293.9 kg.\(^1\)

The Nissan spec sheet also claims a specific power of 2.5 kW/kg, compared to the calculated specific power of 306 W/kg or 0.306 kW/kg. Thus, the Nissan claim is high by a factor of 8.2. Put it another way, if the specific power was really 2.5 kW/kg, then the 293.9-kg battery would have a power capacity of 734.8 kW, far above the stated power level of “above 90 kW.”\(^2\)

High-Power Batteries for FCEVs

FCEVs typically include a battery to provide peak power acceleration and also to improve efficiency by storing the energy generated with regenerative braking. However, the peak power battery for a FCEV does not need to be as heavy as a BEV battery, since its main function is to provide power, not energy.\(^3\) As shown in Fig. A.1, most batteries can be tailored to provide high power at the sacrifice of less energy storage. By reducing the battery cell plate thickness, the battery can respond more quickly and provide more power, moving to the right in Fig. A.1, but

\(^1\)The battery does store 24 kWh of energy, but not all energy can be used from any battery without seriously shortening its lifetime or destroying the battery and creating the havoc of running out of energy in some remote location. The useful energy assuming 67% depth of discharge (DOD) is 16 kWh. But even if you did completely discharge the battery, the specific energy would still be only 24 kWh/293.9 kg = 0.08166 or 81.66 Wh/kg, still well short of the claimed specific energy of 140 Wh/kg.

\(^2\)The most likely explanation for these wide differences in claimed and calculated parameters may be that Nissan is listing the attributes of individual battery cells or modules, and not the full battery pack; for example, the individual cells have a calculated specific energy of 157 Wh/kg and each module (4 cells) has a specific energy of 132 Wh/kg, and the average of these two values is 145 Wh/kg, close to the claimed 140 Wh/kg.

\(^3\)The hydrogen stored onboard a FCEV provides the energy required for long driving range, eliminating the need for a heavy energy storage battery bank.
Table A.1 Key parameters of the Nissan Leaf Li-ion battery pack

<table>
<thead>
<tr>
<th></th>
<th>Specific power (W/kg)</th>
<th>Nominal specific energy (Wh/kg)</th>
<th>Useful specific energy (Wh/kg)</th>
<th>Nominal energy density (Wh/l)</th>
<th>Usefull energy density (Wh/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery power (kW)</td>
<td>90</td>
<td>306.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nominal energy (kWh)</td>
<td>24</td>
<td>81.7</td>
<td></td>
<td>485.6</td>
<td></td>
</tr>
<tr>
<td>Useful energy (kWh)</td>
<td>16</td>
<td>54.4</td>
<td></td>
<td>323.7</td>
<td></td>
</tr>
<tr>
<td>Battery mass (kg)</td>
<td>293.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Battery volume (l)</td>
<td>49.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*a24 kWh stored; 16 kWh useful at 67 % DOD
*b1.57 m × 0.1188 m × 0.265 m

at the expense of reduced energy storage capacity. The Leaf Li-ion battery (54.4 WH/kg useful specific energy and 306 W/kg useful specific power) is shown on this chart along with the FCEV battery with higher specific power (400 W/kg) at the expense of lower specific energy (≈22 Wh/kg). Thus, the FCEV battery is closer to the battery used in a hybrid electric vehicle (HEV) than to a BEV (“EV goal” in Fig. A.1).

Mass Compounding

Malen and Reddy measured the mass compounding effects of 32 late model (2002–2007) vehicles [A.2]. They found that adding a load such as 100 kg of batteries will require an additional 59.8 kg for 12 vehicle subsystems such as

![Ragone chart for various batteries, showing the relation between the Nissan Leaf high-energy battery and the high-power battery for a FCEV](Foto.png)
structure, brakes, and suspension systems. This added mass will require still more batteries to provide the desired range.

The mass for any electric vehicle is limited by the useful specific energy (in Wh kg$^{-1}$) of the complete storage system. As shown in Fig. A.2, the specific energy of battery systems has improved over the last few decades, from 35 Wh kg$^{-1}$ for the lead-acid (Pb-A) batteries used to start ICVs for a century to 75 Wh kg$^{-1}$ for nickel-metal hydride (NiMH) batteries used in the original Prius HEVs, to the advanced lithium ion (Li-ion) batteries used in laptop computers, cell phones, and now BEVs such as the Nissan Leaf BEV; the USABC goal for BEV batteries is 150 Wh kg$^{-1}$. As shown in Fig. A.2, the specific energy for a fuel cell energy storage system (hydrogen tanks, plus the fuel cell system plus a peak power battery system) is better (larger) than even advanced Li-ion batteries that meet the minimum goals for the US Advanced Battery Consortium long-term commercialization goals [A.3]. Most car companies are now storing hydrogen at 70 MPa (700 bar) on their FCEVs. The specific energy of these hydrogen storage systems is 1.3 times the specific energy of the USABC goal for batteries.

The breakdown of FCEV energy storage mass is shown in Fig. A.3 for a 70-MPa (700-bar) system storing 5.1 kg of hydrogen. The hydrogen tank storage system mass is 133 kg, accounting for 48% of the FC system mass.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure.png}
\caption{Useful specific energies for battery and fuel cell systems}
\end{figure}

\begin{itemize}
\item This amount of hydrogen (5.1 kg) is sufficient to provide a range of approximately 350 miles for this FCEV. The hydrogen plus tank mass would be much less for the shorter ranges associated with BEVs.
\end{itemize}
Mass Compounding for BEVs

According to Malen and Reddy [A.2], the final mass of a vehicle after mass compounding is given by

\[ M_f = M_i + \Delta + \Delta G \]  \hspace{1cm} (A.1)

where
- \( M_i \) is the initial vehicle mass,
- \( M_f \) is the final vehicle mass,
- \( \Delta \) is the change in mass (e.g., due to increased battery or motor/controller mass), and
- \( G \) is the secondary vehicle mass coefficient

\[ G = \gamma / (1 - \gamma) \]  \hspace{1cm} (A.2)

where \( \gamma = \) the sum of the influence coefficients for all vehicle components which Malen and Reddy measured as 0.39 for the average of late model vehicles. In this case,

\[ G = \frac{0.39}{(1 - 0.39)} = 0.6393 \]  \hspace{1cm} (A.3)

For the initial vehicle mass, we use an aluminum-intensive vehicle (AIV Sable) developed by the Ford Motor Company in the mid-1990s as part of the partnership for a new generation of vehicles (PNGVs) between the auto companies and the Clinton administration to improve fuel economy by lowering the mass of vehicles.\(^5\) The estimated mass of this vehicle without the drivetrain (the “glider”) is estimated at 825 kg as summarized in Table A.2.

To determine the mass of a BEV based on this lightweight glider, we need to add a battery bank and a motor/controller system and associated electrical

\(^5\)Ford developed their first FCEVs under this same, PNGV program.
equipment. The size of the battery is determined by the total mass of the vehicle and the design range target for the vehicle. We have previously developed a vehicle drive simulation model for electric vehicles both battery- and fuel cell-powered under contract to the Ford Motor Company. The total amount of energy required per kilometer traveled for the motor/controller is shown in Fig. A.4 as a function of the vehicle test mass. The upper dashed line is the energy per mile required with a 1-kW AC load plus a 500-W accessory load, and the lower solid line assumes no AC but with a 500-W accessory load. For comparison, the triangle shows the measured energy per km for the Nissan Leaf BEV based on a curb mass of 1521 kg plus 80 kg for the driver or a total of 1601 kg test mass, and the square shows the data for a 2012 Tesla Model S with their large 85-kWh battery and a test mass of 2163 kg as tested by Edmunds, showing an excellent match between experimental data and our simulation model. Edmunds, an independent testing company, measured an energy requirement of 0.213 kWh/km (0.343 kWh/mile) for the Leaf

<table>
<thead>
<tr>
<th>AIV Sable design basis</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test weight</td>
<td>1291</td>
</tr>
<tr>
<td>ICE</td>
<td>195</td>
</tr>
<tr>
<td>Fuel system</td>
<td>64.9</td>
</tr>
<tr>
<td>Exhaust, cat converter, and muffler</td>
<td>30.8</td>
</tr>
<tr>
<td>Transmission and Differential</td>
<td>95.7</td>
</tr>
<tr>
<td>Driver</td>
<td>80</td>
</tr>
<tr>
<td>Estimated glider mass</td>
<td>824.6</td>
</tr>
</tbody>
</table>

Fig. A.4 Energy per km required to the motor/controller of an electric vehicle as a function of vehicle test mass
BEV [A.4]. The required motor/controller input energy per mile is given by a linear fit to the upper line in Fig. A.4:

\[ E_b = m_1 \times M_f + b_1 \] 

(A.4)

where

- \( E_b \) is the energy per km required from the battery pack (kWh/km)
- \( M_f \) is the final test mass of the vehicle
- \( m_1 \) is the slope of the energy/kg versus \( M_f \) line = \( 6.959 \times 10^{-5} \) kWh/kg-km, and
- \( b_1 \) is the intercept of the linear curve fit. = 0.111667 kWh/km

The mass of the battery pack will increase for longer ranges; for the initial mass, we assume a range of 117.5 km (73 miles— the EPA-rated range of the Leaf BEV).

The resulting initial mass of the battery for a range of 117.5 km is then

\[ M_b = E_b \times R/SE \] 

(A.5)

where SE is the specific energy of the battery pack = 0.0544 kWh/kg from Table A.1. The initial mass of the BEV at 117.5 km design range is given by

\[ M_i = M_b + M_{mc} + M_g + M_L \] 

(A.6)

where

- \( M_{mc} \) is the mass of the motor/controller,
- \( M_g \) is the glider mass = 824.6 kg from Table A.2, and
- \( M_L \) is the vehicle load (passengers and cargo)

The vehicle load term is needed to account for the mass of passengers and cargo. At the very least, there will always be one “passenger”: the driver! The size of the battery bank and motor system will need to be increased to accommodate this extra mass. The power required from the vehicle motor is set by the power

![Motor power required for 10-s acceleration from zero to 96.5 km/h (60 mph) as a function of vehicle test mass](Fig. A.5)
required to accelerate from zero to 96.5 km/h (60 mph) in 10 s,\(^6\) as shown in Fig. A.5. The required motor power is given by a linear fit to those data:

\[
P_m = m_2 \times M_f + b_2
\]  

(A.7)

where

- \(P_m\) is the required peak power (kW)
- \(m_2\) is the slope of the motor power curve = 0.06459 kW/kg
- \(b_2\) the \(y\)-intercept = 3.12 kW

Given the required motor power, we can estimate the mass of the motor and controller from various motor manufacturers as summarized in Fig. A.6. In this case, there is much scatter in the data, so we take the upper bound shown in Fig. A.6 for motors with greater than 40 kW of power (which covers all BEVs considered here).

The mass of the motor/controller is then given approximately by:

\[
M_{mc} \approx m_3 \times P_m + b_3
\]  

(A.8)

where

- \(m_3\) is the slope of the topline = 0.04357 kg/kW
- \(b_3\) is the intercept of that line = 92 kg

Substituting the above equations in Eq. A.6, we can solve the initial BEV test mass:

\[
M_i = (m_1 M_i + b_1) \times R/SE + m_3 (m_2 M_i + b_2) + b_3 + M_g + M_L
\]  

(A.9)

or

\[
M_i = [M_g + M_L + b_1 R/SE + m_3 b_2 + b_3 + M_g]/[1 - m_1 R/SE - m_2 m_3]
\]  

(A.10)

The parameters for calculating the initial BEV mass via Eq. A.10 are summarized in Table A.3 where we assume only one passenger—the driver with a mass of 80 kg. For a range of 117.5 km,\(^7\) the initial battery would have a mass of 460.7 kg with the Nissan Leaf specific energy of 54.4 Wh/kg, and the total BEV test mass would be 1462 kg.

Now that we have calculated the initial test mass of the BEV based on the Nissan Leaf, we can resume using Eq. A.1 to calculate how the BEV mass increases with increasing range above the 117.5 km assumed design range.

The “\(\Delta\)” in Eq. A.1 refers to the increased mass due to larger batteries and larger motors. The battery mass (Eq. A.5) increases linearly with vehicle mass, and the motor/controller mass increases linearly with motor power (Eq. A.8), which in turn increases linearly with range (A.7).

---

\(^6\)The vehicle motor must also have enough power for actions such as hill-climbing and accelerating at lower speeds, etc., but the zero to 37 km/s acceleration in 10 s requires the highest power.

\(^7\)The EPA lists the range of the Nissan Leaf at 73 miles or 117.5 km.
Therefore, the BEV change in mass is given by the difference between the component masses at a range \( R \) and the initial value for that component at \( R = 117.5 \text{ km} \):

\[
\Delta = M_b \ - \ 460.7 + M_{mc} \ - \ 96.3 \text{ kg.} \tag{A.11}
\]

Substituting these equations into Eq. A.1 yields the final BEV mass as a function of range including the effects of mass compounding:

\[
M_f = M_i + \Delta C = M_i + (M_b + M_{mc})C - (460.8 + 96.7)C = (M_b + M_{mc})C - 556.9C \tag{A.12}
\]

\[
= M_i + [m_1M_f + b_1]RC/SE + m_3(m_2M_f + b_2) + b_3]C - 556.9C \tag{A.13}
\]

Or

\[
M_f = M_i + M_L + [b_1R/SE + m_3b_2 + b_3 - 556.9]C/[1 - m_1RC/SE - m_2m_3C] \quad \text{for BEVs} \tag{A.14}
\]

where \( C = 1 + G = 1.6393 \).
Mass Compounding for FCEVs

FCEVs are also subject to mass compounding, although the effects are quite small compared to BEVs, since adding extra range for a FCEV means enlarging the hydrogen tanks, which weigh much less than batteries per kWh of stored energy. Almost all car companies now store hydrogen at high pressure in carbon fiber-wrapped tanks, the same technology that has been used to store natural gas in natural gas vehicles for more than 50 years. Hydrogen is typically stored at approximately 70 MPa (≈10,150 psi) compared to 24.8 MPa (3600 psi) for NGVs.

The weight percent of hydrogen in carbon fiber-wrapped tanks is shown in Fig. A.7 for two vendors of 700-bar tanks. The weight percent of hydrogen is in the range of 4 % or higher for tanks that store 1–5 kg of hydrogen. Five kg of hydrogen is enough to travel up to 212 km (342 miles) given the measured fuel economy of 42.4 km/kg (68.3 miles/kg) measured by the DOE National Laboratories for the Toyota Highlander SUV FCEV [A.6]. Hydrogen content will be less for shorter range vehicles in the calculations below, and FCEV fuel economy should rise with smaller vehicles and more recent fuel cells that should have higher efficiency and higher fuel economy.

The weight percents shown in Fig. A.7 do not take into account the hydrogen remaining in the tank. A vacuum pump would have to be installed to pull all the hydrogen out of the tank, which would not be cost-effective. Therefore some hydrogen will necessarily remain in the tank when the driver pulls into the station to fill up more hydrogen (this is analogous to not totally depleting the battery bank on a BEV.) Figure A.8 shows the impact of leaving some hydrogen in the tank. The solid line shows the useful hydrogen from a tank with a water volume of 29.2 l as a function of the minimum tank pressure left in the tank. In this particular case, the vendor lists a hydrogen capacity of 1.2 kg (upper dashed line), but this water volume would only hold 1.15 kg even if all hydrogen were removed. With a minimum residual pressure of 2 bar (29 psig), this particular tank could deliver only 1.14 kg of useful hydrogen to the fuel cell.

The net result is that a tank designed to hold 4 % hydrogen by weight will yield slightly less hydrogen taking into account the nonzero residual pressure for an “empty” tank as shown in Fig. A.9. We assume an “empty” tank pressure of 20 bar (29 psig) which yields a net useful hydrogen weight percent of 3.84 % for a tank with a nominal 4 % by weight hydrogen capacity.

The volume occupied by these tanks is limited by the compressibility of hydrogen. If hydrogen were an ideal gas, then the amount of hydrogen in a tank would double if the pressure was increased from 350 bar to 700 bar. However, hydrogen is not an ideal gas, as shown in Fig. A.10. Instead of doubling the internal mass of stored hydrogen by doubling the pressure from 350 to 700 bar, the internal mass of stored hydrogen increases by only 67 %.

---

8With the major exception that a depleted battery either significantly shortens the battery life, or even destroys the battery, a depleted hydrogen tank suffers no degradation.
Fig. A.7  Weight percent of hydrogen versus kg of 700-bar hydrogen stored ("Old LC" refers to the Lincoln Composites which is now Hexagon Lincoln; Luxfer is the composite tank fabricator that acquired Dynatek, a former leading Canadian composite tank manufacturer)

Fig. A.8  Useful stored hydrogen for a 700-bar compressed hydrogen tank with a water volume of 29.2 l as a function of the residual pressure in the tank when it is refilled

Fig. A.9  Net useful hydrogen weight % as a function of residual empty tank pressure
With the assumed 4 % hydrogen weight percent for an empty 700-bar tank and a 3.84 % useful weight percent assuming a 20-bar (29 psig) residual pressure in an “empty” tank, then the mass of the tank plus the hydrogen is given by:

\[ M_t = \frac{(1 - 3.84 \%) \times M_h}{3.84 \%} = 25.022 \times M_h \]  

\[ (A.15) \]

where

- \( M_t \) is the mass of the hydrogen plus the tank and
- \( M_h \) is the mass of the hydrogen

The amount of hydrogen required for a given range and vehicle test mass is derived from the vehicle simulation model by calculating the kg of hydrogen required per km traveled in the FCEV, as shown in Fig. A.11. The hydrogen required per km is given by:

\[ M_h = (m_4 M_f + b_4) \times R(\text{km}) \]  

\[ (A.16) \]

where

- \( m_4 \) slope of line = \( 3.79 \times 10^{-6} \) in Fig. A.7
- \( M_f \) the final vehicle test mass (kg), and \( b_4 = 0.00539 \) kg of H2/km

Combining Eqs. A.15 and A.16 yields the combined mass of the tank plus hydrogen as a function of the vehicle test mass and range:

\[ M_t = (m_5 M_f + b_5) \times R(\text{km}) \]  

\[ (A.17) \]

where

- \( m_5 = 9.48 \times 10^{-5}\text{kg}^{-1}\text{km}^{-1} \)
- \( B_5 = 0.13487 \) kg/km

---

Fig. A.10  Nonlinear compressibility of hydrogen compared to an ideal gas
The power required from the fuel cell system and the peak power battery can also be represented by linear fits to the vehicle drive cycle simulations given by Eq. A.7; this peak power for acceleration can be provided by both the fuel cell system and the peak power battery. We assume here that 90% of the power for normal driving is provided by the fuel cell and 10% by the peak power battery. The total power from the fuel cell from Eq. A.7 is then given by:

\[
P_{fc} = 0.9 \times (m_2 M_f + b_2) = \text{power required from the fuel cell system}
\]  
(A.18)

\(m_2\) is the slope of the motor power curve = 0.06459 kW/kg,

and

\(b_2\) the \(y\)-intercept = 3.12 kW,

and

\[
P_b = 0.1 \times (m_2 M_f + b_2) = \text{power required from the peak power battery}
\]  
(A.19)

The mass of the peak power battery becomes:

\[
M_b = \frac{P_b}{SP_b}
\]  
(A.20)

where \(SP_b\) = the specific power of the peak power battery (0.4 kW/kg).

The mass of the fuel cell system is determined by the fuel cell specific power in kW/kg. The specific power of fuel cell systems has been increasing over time as companies improve their technology. In the late 1990s, fuel cell specific power was in the one kW/kg range, but Nissan announced a new fuel cell system in October 2011 that delivered 85 kW with a mass of only 43 kg or a specific power of 1.98 kW/kg [A.6] and a volume of only 34 l or a power density of 2.5 kW/l, which we use here, with the expectation that improvements will reduce the weight and volume of future fuel cell systems. The resulting mass of the fuel cell system becomes:

Fig. A.11 Kilogram of hydrogen required per km of range versus vehicle test mass

Appendix A: Range Limitations of Battery Electric Vehicles
\[ M_{fc} = \frac{P_{fc}}{SP_{fc}} \] (A.21)

where \( SP_{fc} \) = the specific mass of the fuel cell system (1.98 kW/kg)

To calculate the initial mass of the FCEV, we use an equation similar to Eq. (A.6) that we used to calculate the initial BEV mass above. We assume that the FCEV uses the same glider as the BEV. The initial FCEV mass becomes:

\[ M_i = M_g + M_{fc} + M_b + M_t + M_{mc} + M_L \] (A.22)

where \( M_L \) = the vehicle load (at least 80 kg for the driver.)

Or

\[
M_i = M_g + M_L + 0.9/SP_{fc} \times (m_2M_i + b_2) + (1 - 0.9)/SP_b \times (m_2M_i + b_2) \\
+ (m_5M_i + b_5) \times R + m_3(m_2M_i + b_2) + b_3 \\
\] (A.23)

To simplify these equations, define a new constant, \( Q \):

\[ Q \equiv 0.9/SP_{fc} + 0.1/SP_b \] (A.24)

Which leads to the following equation for the initial FCEV mass at the same range as the BEV (117 km):

\[ M_i = [M_g + M_L + Qb_2 + b_5R + b_3 + m_3b_2]/(1 - Qm_2 - m_5R - m_3m_2) \] (A.25)

With the parameters listed above, the initial mass of the FCEV for 117 km range is 1079 kg, which is lighter than any of the other AFVs at that range as shown in Table A.4.

Next we need to solve for the change in mass, \( \Delta \), to solve Eq. A.12 for the final FCEV mass as a function of range. The four main FCEV components initially weigh 174.4 kg as summarized in Table A.5.

To solve Eq. A.12 for the final FCEV mass requires a formula for the change in mass, \( \Delta \):

**Table A.4** Test mass of the alternative vehicles at a range of 117 km

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCEV</td>
<td>1079</td>
</tr>
<tr>
<td>USABC goal BEV</td>
<td>1150</td>
</tr>
<tr>
<td>NiMH BEV</td>
<td>1320</td>
</tr>
<tr>
<td>Leaf Li-ion BEV</td>
<td>1462</td>
</tr>
<tr>
<td>Pb-A BEV</td>
<td>1796</td>
</tr>
</tbody>
</table>

**Table A.5** Initial mass (kg) of FCEV drivetrain components

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel cell system</td>
<td>33.2</td>
</tr>
<tr>
<td>Peak power battery</td>
<td>18.2</td>
</tr>
<tr>
<td>Motor controller</td>
<td>95.2</td>
</tr>
<tr>
<td>Hydrogen + tank</td>
<td>27.9</td>
</tr>
<tr>
<td>Total drivetrain mass</td>
<td>174.4</td>
</tr>
</tbody>
</table>
From Eq. A.12, we have:

\[
\Delta = M_{fc} + M_b + M_{mc} + M_t - 174.4
\]

\[
= QP_m + m_3P_m + b_3 + (m_5M_t + b_5)R(km) - 174.4
\]

\[
= (Q + m_3)P_m + b_3 + (m_5M_t + b_5)R - 174.4
\]

From Eq. A.12, we have:

\[
M_t = M_i + \Delta C
\]

\[
= M_i + C[(Q + m_3) \times (m_2M_t + b_2) + b_3 + (m_5M_t + b_5)R - 174.4]
\]

(A.27)

Or

\[
M_t = [M_i + [(Q + m_3)b_2 + b_3 + b_5R - 174.4] \times C]/[1 - (Q + m_3)m_2C - m_5RC]
\]

(A.28)

Equation A.14 for BEVs and Eq. A.27 for FCEVs are plotted in Fig. A.12. The FCEV mass changes very little with range, while the mass of the BEVs grows rapidly with range as the battery bank mass increases. Even if batteries are developed in the future that meet the USABC commercialization goals, the BEV will still have a much greater mass than a FCEV. Two datum points are shown in Fig. A.12 representing the curb mass of the Nissan Leaf plus driver (763 kg (1601 lbs) and the EPA estimated range of 117 km (73 miles). This point is above our estimated mass for a BEV with Leaf battery parameters, indicating that our equations are slightly conservative (projecting lower mass than this one example.)

The second BEV point is for the Tesla Model S (85-kWh battery version), which Edmunds tested with a curb weight of 2163 kg (4770 lbs) [A.7] to which we add 80 kg for the driver and which the EPA has certified a range of 426 km (265 miles). The Tesla point falls just above the USABC goal line for advanced Li-ion batteries. However, the EPA data on the Tesla Model S are not valid [A.8].
For example, they claim an energy consumption of 0.38 kWh/mile and a range of 265 miles. But this would require $0.38 \times 265 = 100.7$ kWh of battery energy, but the Tesla Model S battery reportedly holds only 85 kWh of energy. Even if the 85 kWh battery were completely discharged, the range would be only $85/0.38 = 224$ miles, which is still very good for a BEV. However, the Edmunds testing company did achieve a 267 mile range on one Model S test drive with a nominal 85-kWh battery pack [A.7], so either the Tesla battery holds more than 85 kWh or the fuel economy is better (lower) than 0.38 kWh/mile specified by the EPA.

The battery parameters used in Fig. A.12 are summarized in Table A.6.

### Table A.6  Battery parameters used in Fig. A.12

<table>
<thead>
<tr>
<th>Battery type</th>
<th>Specific energy (kWh/kg)</th>
<th>Energy density (kWh/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb-A BEV</td>
<td>0.035</td>
<td>0.095</td>
</tr>
<tr>
<td>NiMH BEV</td>
<td>0.075</td>
<td>0.135</td>
</tr>
<tr>
<td>Leaf Li-ion BEV</td>
<td>0.054</td>
<td>0.324</td>
</tr>
<tr>
<td>USABC goal BEV</td>
<td>0.15</td>
<td>0.324</td>
</tr>
</tbody>
</table>

Energy Storage Volume

Most readers know that batteries are heavy, but some may not realize that batteries also take up substantial space. We have also calculated the volume required for energy storage for BEVs and FCEVs as summarized in Fig. A.13. In the case of BEVs, the storage volume is just the space occupied by the battery bank. For FCEVs, the storage volume is taken as the sum of the volumes for the hydrogen storage tank, the peak power battery, and the fuel cell system itself: In other words, all the components that are required to deliver electricity to the motor/controller as a replacement for the battery bank.

The battery energy densities are taken from Table A.6. The FCEV component volumes are estimated as follows:

- **FC system:** based on Nissan FC with 85 kW and 34 l or 2.5 kW/l [A.5]
- **Peak power battery:** high-power battery (400 W/kg) but low energy (22 Wh/kg); we assume a Li-ion energy density of 324 Wh/l or 0.0679 l/kg of battery.
- **Hydrogen fuel tank:** The fuel tank volume is given by:
  \[
  V_t = 30.7M_h + 3.23 \tag{A.29}
  \]
  where $M_h$ = the quantity of hydrogen required (kg) (see Eq. A.16)

Note: the energy density goal for the USABC commercialization goal is only 0.230 kWh/l; since the Nissan Leaf battery has already demonstrated 0.324 kWh/l, we increased the energy density goal to that value.
As shown in Fig. A.13, the required volume for storing batteries on BEVs grows very rapidly as range increases. The horizontal dashed line at the top of the figure corresponds to the total cargo storage available on the Nissan Leaf BEV, listed as 679 l (24 ft³). Thus, if one tried to build a BEV with Pb-A batteries, then the entire cargo space on the Leaf would be occupied above a range of 180 km (112 miles), while a BEV with NiMH batteries would run out of cargo space at 300 km (186 mile) range, and the Leaf itself would fill all its cargo space to achieve a range of approximately 350 km (217 miles).

If a battery technology could achieve the USABC commercialization goals, then ranges above 500 km (311 miles) would be feasible, although, even then, the volume required for the entire hydrogen and fuel cell system would still occupy only 41% of the space required for an advanced battery system meeting USABC goals with a 500 km range.

References


Appendix A demonstrated that BEVs will be limited to small cars traveling short distances, since both the weight and volume of batteries for larger cars traveling longer distances are excessive. This appendix explores the consequences of this limitation in terms of the number of light-duty vehicles (LDVs) affected and their contribution to greenhouse gas (GHG) emissions and oil consumption in the USA.

The fraction of small cars and trucks sold in the USA has been decreasing as shown in Fig. B.1, dropping from $\approx 40\%$ of market share in the 1980s to only $28.8\%$ in 2012 as American drivers began buying larger cars, wagons, SUVs, vans, and pickup trucks. The fraction of GHG emissions generated by smaller cars and trucks has also been decreasing from approximately $40\%$ of all new car and truck emissions in the 1980s to $26.3\%$ in 2012 [B.1]. So to the degree that the distribution of new cars sold approximates the distribution of cars on the road (OTR), replacing small cars with BEVs would affect only $26\%$ of greenhouse gases.

![Fraction of new small cars and trucks sold each year and the fraction of GHG emissions from those small cars and trucks compared to all new cars sold each year](image)

**Fig. B.1** Fraction of new small cars and trucks sold each year and the fraction of GHG emissions from those small cars and trucks compared to all new cars sold each year.
The emissions listed in Fig. B.1 are the fraction of GHGs attributed to new cars compared to all new cars sold that year. It does not indicate the GHG emissions from all cars on the road (OTR). To estimate the fraction of GHGs attributable to small cars and trucks OTR, we need to determine the mixture of vehicles OTR over time.

The Oak Ridge National Laboratory has published lists of survival rates [B.2] for light-duty cars and trucks as shown in Fig. B.2. New cars and trucks survive for several years. On the average, only 4.5% of cars survive after 30 years, and only 5.5% of light-duty trucks are OTR after 30 years. By multiplying the annual new car and truck sales times the appropriate survival rates, we can estimate the number of LDVs OTR by vehicle class. As shown in Table B.1, the estimated percentage of all small cars and trucks OTR was only 37.9% in 2012, and the percentage of all small cars and trucks sold in 2012 was only 28.8%.

In addition, not all “small” cars are really suitable for becoming a battery EV. For example, the General Motors’ Cadillac GTS Wagon is classified as a “small wagon” by the EPA which is based solely on its passenger volume of 3160 l (111.6 ft³). But the Cadillac GTS is a very heavy car with a curb weight of 1826 kg (4025 lbs), which would not be a good candidate for a battery EV without a major reduction in curb weight. Assuming a test weight of 1904 kg, this vehicle would initially require a battery delivered energy of 0.226 kWh/km (0.364 kWh/mile) (see Appendix A). Assuming a range of 161 km (100 miles), the battery bank

---

10Light-duty cars include sedans, wagons, and car-based SUVs.
11Light-duty trucks include pickup trucks, vans, and truck-based SUVs.
12Small vehicles include all small pickup trucks, small vans, small wagons and small SUVs.
13The last row of Fig. B.2 is the average of just the small vehicles.
14EPA defines a small wagon as having less than 3681 l (130 cu. Ft.) of passenger and cargo space.
15Curb weight plus 80 kg for the driver.
would have to initially deliver 36.4 kWh of energy to travel 161 km on one charge. Assuming that battery manufacturers achieve the USABC specific energy goal of 150 Wh/kg, then the battery bank would have an initial mass of \( \frac{36.4}{0.15} = 243 \) kg. After mass compounding, the final Cadillac BEV vehicle test mass would become\(^\text{16}\):

\[
M_f = 1909 + 242 \times 1.6393 = 2306 \text{ kg.}
\]

This higher BEV test mass after mass compounding would then require a larger battery bank that could deliver 0.254 kWh/km (0.408 kWh/mile) or a final battery energy capacity of 40.8 kWh for a 161-km (100 mile) range. From Chap. 6, the battery alone would then cost between $6120 assuming that the battery industry meets the USABC battery cost goal of $150/kWh and as much as $20,400 for the battery alone by 2020 with other estimates of lithium-ion battery costs in the range between $200/kWh and $500/kWh by the 2020 time frame. These high battery costs could inhibit the purchase of heavy BEVs such as the Cadillac GTS Wagon and might also preclude affordable battery warranties that would also limit BEV sales.

\(^{16}\)See Eq. A.1 in Appendix A.
We conclude that not all “small wagons” could be affordably converted to run on batteries. 

Access to overnight parking spaces. In addition to high mass limitations, BEV sales will be hindered by the lack of a parking space to park the vehicle overnight. One main benefit of a BEV is the opportunity to “refuel” by plugging in the BEV overnight at the driver’s residence. Researchers at Carnegie Mellon University have estimated that only 56% of US motor vehicles have access to a dedicated parking space suitable for overnight charging and that only 22% of all vehicles have access to a charging outlet [B.3]. Therefore, even if they have a dedicated parking space, they would still have to install an appropriate electrical outlet near that parking space.

The total percentage of US vehicles that could be converted to BEVs is estimated in Table B.2 by multiplying the percentage of vehicles OTR and the percentage that could be affordably converted to BEVs and the percentage of those that have access to off-street parking for nighttime charging, with the final estimate that approximately 31% of all US motor vehicles (light-duty cars and trucks) could become BEVs in the future.

<table>
<thead>
<tr>
<th>Vehicles on the road (%)</th>
<th>2012 % sales</th>
<th>Average OTR and sales (%)</th>
<th>% that could be BEVs</th>
<th>% that have access to off-street parking</th>
<th>Net BEV percentages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small car</td>
<td>24.7</td>
<td>25.1</td>
<td>24.9</td>
<td>100</td>
<td>56</td>
</tr>
<tr>
<td>Midsize car</td>
<td>18.1</td>
<td>21.7</td>
<td>19.9</td>
<td>50</td>
<td>56</td>
</tr>
<tr>
<td>Large car</td>
<td>8.3</td>
<td>6.2</td>
<td>7.3</td>
<td>30</td>
<td>56</td>
</tr>
<tr>
<td>Small wagon</td>
<td>2.2</td>
<td>3.6</td>
<td>2.9</td>
<td>95</td>
<td>56</td>
</tr>
<tr>
<td>Midsize wagon</td>
<td>1.0</td>
<td>0.3</td>
<td>0.7</td>
<td>50</td>
<td>56</td>
</tr>
<tr>
<td>Large wagon</td>
<td>0.2</td>
<td>0.0</td>
<td>0.1</td>
<td>30</td>
<td>56</td>
</tr>
<tr>
<td>Small NT SUV</td>
<td>0.3</td>
<td>0.0</td>
<td>0.1</td>
<td>90</td>
<td>56</td>
</tr>
<tr>
<td>Midsize NT SUV</td>
<td>1.5</td>
<td>4.0</td>
<td>2.7</td>
<td>40</td>
<td>56</td>
</tr>
<tr>
<td>Large NT SUV</td>
<td>0.8</td>
<td>2.9</td>
<td>1.8</td>
<td>25</td>
<td>56</td>
</tr>
<tr>
<td>Small pickups</td>
<td>2.9</td>
<td>0.0</td>
<td>1.46</td>
<td>80</td>
<td>56</td>
</tr>
<tr>
<td>Midsize pickup</td>
<td>10.6</td>
<td>0.2</td>
<td>5.4</td>
<td>30</td>
<td>56</td>
</tr>
<tr>
<td>Large pickup</td>
<td>0.1</td>
<td>9.8</td>
<td>4.9</td>
<td>20</td>
<td>56</td>
</tr>
<tr>
<td>Small van</td>
<td>6.7</td>
<td>0.0</td>
<td>3.35</td>
<td>80</td>
<td>56</td>
</tr>
<tr>
<td>Midsize van</td>
<td>0.6</td>
<td>4.9</td>
<td>2.8</td>
<td>30</td>
<td>56</td>
</tr>
<tr>
<td>Large van</td>
<td>10.3</td>
<td>0.2</td>
<td>5.2</td>
<td>20</td>
<td>56</td>
</tr>
<tr>
<td>Small T SUV</td>
<td>1.1</td>
<td>0.0</td>
<td>0.5</td>
<td>80</td>
<td>56</td>
</tr>
<tr>
<td>Midsize T SUV</td>
<td>9.0</td>
<td>10.3</td>
<td>9.7</td>
<td>30</td>
<td>56</td>
</tr>
<tr>
<td>Large T SUV</td>
<td>7.4</td>
<td>10.6</td>
<td>9.0</td>
<td>20</td>
<td>56</td>
</tr>
<tr>
<td>All small vehicles</td>
<td>37.9</td>
<td>28.8</td>
<td>33.3</td>
<td>Total estimated BEV potential:</td>
<td>31.0</td>
</tr>
</tbody>
</table>
References


Appendix C
Estimated Future US Light-Duty Vehicle Sales, Vehicles on the Road, and Number of Miles Driven Annually

The impact of adding alternative vehicles on the environment and oil consumption will depend on the total number of vehicles on the road in the future and the efficiency and number of miles that those vehicles are driven. Each of these factors grew rapidly in the second half of the twentieth-century with growth rates that cannot be sustained. We have to select suitable growth rates over the twenty-first century to model the impact of alternative vehicles. These estimates are not meant to precisely predict the future, but rather to postulate a set of plausible vehicle use parameters over the century as a basis for judging the potential impact of adding different alternative vehicles. These estimated growth rates will not affect the relative merits of various alternative vehicles, but they will determine when we will meet various societal goals, such as reducing GHG emissions to 80% below 1990 levels or cutting oil consumption such that oil from friendly American nations could supply all US oil demands in some future oil crisis.

Total Number of Light-Duty Vehicles (LDVs) on the Road

The number of LDVs (passenger cars and light-duty trucks) OTR is projected to grow by the DOE’s Energy Information Administration from approximately 228 million in 2011 to approximately 291 million by 2040 (Fig. C.1). If we assume a linear extrapolation of the AEO-2014 data through the end of the century, then there would be approximately 429 million LDVs OTR by the end of the century as shown in Fig. C.1, while this linear extrapolation may be too optimistic since it implies some combination of very high population growth, more cars per person (which is already approaching one vehicle per adult in the USA) While this growth rate may not materialize, it should not change the relative merits of various alternative vehicles to reduce pollution and fossil fuel consumption.
Annual LDV Travel per Vehicle

To model the GHG emissions and oil consumption over the twenty-first century, we also need to estimate the miles traveled by each vehicle. Figure C.2 shows the historical growth in VMT, the linear extrapolation of those historical data, and two future projections: the EIA’s projection from 2011 to 2040, and the linear extrapolation of those AEO-2014 data through the end of the century, which we use...
in the model to estimate GHG emissions and oil consumption [C.1]. Thus, this model projects just over 12,000 miles per year per vehicle by 2100, far less than the 18,000 miles per vehicle predicted by a linear extrapolation of historical data. Thus, we assume that the rapid rise in VMT per vehicle in the twentieth century cannot be sustained in the twenty-first century.

**Alternative Vehicle Sales Fractions**

For each alternative vehicle, we estimate the fraction of new cars sold each year that will be that type of alternative vehicle. All other vehicles sold will either be conventional internal combustion vehicles (ICVs) or another type of AFV that would reduce GHGs or oil consumption.

**Gasoline-Powered Hybrid Electric Vehicle (HEV) Sales**

For the HEV sales, we already have a multiyear sales history on which to base our projections. As shown in Table C.1, over 3 million HEVs were sold in the USA between 1999 and 2013. More than 70% of these HEVs were sold by Toyota including 1.54 million of their iconic Prius HEVs17[C.2].

In this computer model, we start with the historic HEV sales record and project into the future using a logistics function fit to the historic data as shown in Fig. C.4 for the early years and Fig. C.5 over the twenty-first century. The logistics function is given by:

\[
F = \frac{A}{1 + \exp(G \times (Y - Y_o))}
\]  

(C.1)

where \(A = 0.985\), which means that 98.5% of all LDVs sold will be hybrids by the end of the century; \(G = 0.18\), a curve shape factor; and \(Y_o = 2032\), the year when half of all LDVs sold are HEVs.

The total number of LDVs sold each year is taken from the AEO-2014 projections as shown in Fig. C.3. We use the Department of Energy’s AEO-2014 projections through 2040 [C.1] and then reduce the linear extrapolation of the AEO-2014 data by 85% between 2040 and 2100 on the assumption that the number of LDVs sold will not maintain the AEO projection through 2100. By 2100, the model therefore projects annual sales of 18.6 million LDVs rather than the 21.9 million annual sales implied by a linear extrapolation of the AEO-2014 data.

Equation C.1 yields the estimated number of HEVs sold each year as shown in Fig. C.4 in the short term and in Fig. C.5 through the twenty-first century. By 2100 in this model, 98.5% of all LDVs sold are HEVs.

17Although the Prius is the most famous HEV, it was not the first HEV sold in the USA. Honda sold 17 of their small insight HEVs in 1999 in the USA before Toyota sold their first 5562 Prius HEVs in 2000.
We have fewer data on PHEV sales, and since sales of the first commercial PHEV, the Chevy Volt only began in 2010. Through the 3rd quarter of 2014, approximately 42,500 PHEVs have been sold in the USA [C.3].

Assuming that 4th

Table C.1  Number of hybrids sold in the USA between 1999 and 2013

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Number Sold (1999-2013)</th>
<th>Sales Share</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toyota/Lexus</td>
<td>2,185,696</td>
<td>70.79 %</td>
</tr>
<tr>
<td>Honda/Acura</td>
<td>361,559</td>
<td>11.71 %</td>
</tr>
<tr>
<td>Ford/Mercury/Lincoln</td>
<td>292,171</td>
<td>9.46 %</td>
</tr>
<tr>
<td>Chevy/GMC/Buick/Cadillac</td>
<td>92,039</td>
<td>2.98 %</td>
</tr>
<tr>
<td>Hyundai</td>
<td>62,188</td>
<td>2.01 %</td>
</tr>
<tr>
<td>Nissan/Infiniti</td>
<td>39,474</td>
<td>1.28 %</td>
</tr>
<tr>
<td>Kia</td>
<td>24,003</td>
<td>0.78 %</td>
</tr>
<tr>
<td>Saturn</td>
<td>11,667</td>
<td>0.38 %</td>
</tr>
<tr>
<td>VW</td>
<td>6,575</td>
<td>0.21 %</td>
</tr>
<tr>
<td>Porsche</td>
<td>4,272</td>
<td>0.14 %</td>
</tr>
<tr>
<td>BMW</td>
<td>3,185</td>
<td>0.10 %</td>
</tr>
<tr>
<td>Mercedes-Benz</td>
<td>2,236</td>
<td>0.07 %</td>
</tr>
<tr>
<td>Mazda</td>
<td>1,144</td>
<td>0.04 %</td>
</tr>
<tr>
<td>Audi</td>
<td>1,124</td>
<td>0.04 %</td>
</tr>
<tr>
<td>Dodge/Chrysler</td>
<td>88</td>
<td>0.00 %</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>3,087,421</strong></td>
<td><strong>100 %</strong></td>
</tr>
</tbody>
</table>

Fig. C.3  Total number of light-duty vehicles (LDVs) (passenger cars and light-duty trucks) in the USA over the twenty-first century

Gasoline-Powered Plug-in Hybrid Electric Vehicle (PHEV) Sales Projections

We have fewer data on PHEV sales, and since sales of the first commercial PHEV, the Chevy Volt only began in 2010. Through the 3rd quarter of 2014, approximately 42,500 PHEVs have been sold in the USA [C.3].

Caution is advised with this online “scorecard,” since they list non-plug-in pure battery EVs on the same chart as PHEVs.
quarter 2014 PHEV sales equal 3rd quarter sales, then total 2014 PHEV sales would grow to 56,770 vehicles. These historical sales of PHEVs in the USA along with the logistics model curve fit in the near term are shown in Fig. C.6. The logistics curve fit data for the PHEV are:

\[
A = 0.985 \\
G = 0.173, \text{ and} \\
Y_0 = 2045.
\]

The long-term PHEV sales are shown in Fig. C.7 over the twenty-first century.
Ethanol-Powered PHEV Sales Projections

No commercial OEM is currently selling ethanol-powered PHEVs, but the transition to such an AFV could be swift since a) the OEMs are producing many “flex-fuel” conventional vehicles that can run on gasoline or mixtures of gasoline and ethanol and b) there are thousands of fuel stations across the USA that sell ethanol/gasoline blends. According to the DOE’s Alternative Fuels Data Center, there are 2389 fuel stations in the USA that currently supply E-85, a mixture of 85% ethanol and 15% gasoline [C.4].

One major objection to using ethanol is the “food versus fuel” dilemma. Almost all ethanol in the USA is made today by fermenting corn grain. While the ethanol production plants use field corn, and not sweet corn normally consumed by humans, the field corn is fed to cattle and other animals that supply meat for human consumption. In the first decade of the twenty-first century, it was widely
expected that ethanol would soon be produced from lignocellulosic materials such as the non-food stalks and roots of corn plants (called “stover”) or switchgrass, the native prairie grass that is sometimes used in the farm belt to control runoff of agricultural chemicals.

Lignocellulosic ethanol not only alleviates the “food versus fuel” conundrum, but also substantially reduces greenhouse gas (GHG) emissions compared to ethanol made from corn. As shown in Fig. C.8, ethanol made from corn only reduces GHGs by 17–23% depending on the corn ethanol plant type, while lignocellulosic ethanol reduces GHGs by 64% [C.5].

Cellulosic ethanol would also significantly reduce the consumption of fossil fuels for transportation as shown in Fig. C.9 [C.5]. Thus, a gallon of
lignocellulosic ethanol that contains 76,350 Btu’s of energy would require 10.31 times less fossil fuel energy or only 7405 Btu’s of fossil fuel energy input, while corn ethanol would require 56,140 Btu’s of input fossil fuel energy. Electricity is the worst fuel in this regard, since on the average, electricity contains only 45% of the fossil energy used to make the electricity from fossil fuels. And gasoline contains only 81% of the energy in the crude oil used to make the gasoline. Hence, cellulosic ethanol requires much less fossil fuel than any other transportation fuel.

Despite these significant advantages of cellulosic ethanol, the commercial future of this biomass fuel is uncertain as of 2015. Several cellulosic ethanol plants were built in the 2008–2012 time period, but they have not yet proven to be economic. The National Renewable Energy Laboratory [C.6] estimates that the cost of cellulosic ethanol would be approximately $2.05/gallon; since ethanol has 32.8% lower energy content than gasoline, this would be equivalent to gasoline at approximately $3.11/gallon. For comparison, ethanol made from corn is estimated at a cost between $0.60 and $1.67/gallon.

Nonetheless, for this model, we assume that cellulosic ethanol does become economic over the century. As shown in Fig. C.10, we assume that all ethanol is made from corn initially, the current practice early in the century, shifting to corn stover and to switchgrass, until 96% of all ethanol is made from these two cellulosic sources by 2100.

The number of PHEVs fueled by E-85 instead of gasoline is governed by another logistics function with the parameters

\[ A = 0.95; \]
\[ G = 0.26; \]
\[ Y_o = 2065 \]

as shown in Fig. C.11. These are the fraction of PHEVs fueled by E-85, which leads to the first E-85 PHEVs OTR in 2018, e.g., the product of Fig. C.7, the number of PHEV sales times Fig. C.11 the fraction of PHEVs fueled by E-85.

Fig. C.10  Source of fuel ethanol production over the twenty-first century
Hydrogen-Powered Fuel Cell Electric Vehicle (FCEV) Sales Projections

Several major automobile companies have vowed to begin commercial production of FCEVs beginning in 2014 or 2015. Several hundred prototype FCEVs were produced for early testing programs, primarily in California, and the California Air Resources Board (CARB) is planning on providing the necessary hydrogen infrastructure so that the auto companies can begin introducing FCEVs as part of the CARB zero-emission vehicle (ZEV) program. The alternative vehicles necessary to meet the CARB goal of cutting GHGs to 80% below 1990 levels in California by 2050 are shown in Fig. C.12; they are projecting that 87% of all California cars will have to be electric vehicles (BEVs or FCEVs) by 2050 to meet their GHG reduction targets and that approximately 70% of all LDVs OTR will have to be hydrogen-powered FCEVs as shown in Fig. C.12 taken from a 2012 CARB staff report. [C.7]

The US Department of Energy conducted an in-depth on-road evaluation or “learning demonstration” of 183 FCEVs from four automobile companies19 and recorded the FCEV performance data for over 500,000 FCEV trips totaling 3.59 million miles, including 35,748 individual hydrogen fueling events without any major safety incident [C.8].

For this model, we used the actual FCEVs used in the learning demonstration program, along with the FCEVs that are projected for the ZEV program in California as summarized in Fig. C.13 for the near term. For the longer term, we used another logistics curve with these parameters

\[
A = 0.99; \quad G = 0.28 \quad Y_0 = 2038
\]

as shown in Fig. C.13 for the near term and in Fig. C.14 for the entire century.

\[19\text{Daimler, Ford, GM, and Hyundai-Kai.}\]
Battery-Powered Electric Vehicles (BEVs) Sales Projections

The sales of BEVs will be limited by several factors: short range between battery charges, long charging times, heavy vehicles even to meet minimal ranges, and the lack of a place to recharge batteries for many drivers. The range limitations of BEVs caused by mass compounding are discussed in detail in Appendix A, and the impacts of both range limitations and limited off-street parking are summarized.
in Appendix B. Carnegie Mellon University estimates that only 56 % of drivers have access to garages or off-street parking where BEVs could be charged [C.9]; many drivers live in large metropolitan areas where they have to search for a parking place every night and therefore do not have access to a fixed place to routinely charge their car batteries.

The historical BEV sales in the USA are summarized in Table C.2, starting with 19 Nissan Leaf BEVs sold in 2010, accelerating to 57,955 BEVs estimated for 2014.\(^{21}\)

\(^{20}\)Data were only available through the end of the third quarter of 2014; we have assumed here that fourth quarter 2014 BEV sales are equal to third quarter BEV sales for all BEV models.

\(^{21}\)The Tesla BEV sales are approximations, since Tesla is the only automaker that does not report annual sales for the USA. These Tesla numbers may also include some BEV sold overseas.
For the base case of 30% BEV maximum market penetration, the historical and projected BEV US sales are shown in Fig. C.15 for the near term and Fig. C.16 for the twenty-first century. The logistics function parameters for this curve fit are:

\[ A = 0.311 \]
\[ G = 0.245 \]
and \( Y_0 = 2030 \)
References


Appendix D
Marginal Grid Mixes

Introduction

When calculating the greenhouse gas (GHG) emissions from electrical power plants used to recharge batteries on BEVs or plug-in hybrid electric vehicles (PHEVs), some analysts use the \textit{average} grid mix for the local utility. But this often underestimates the actual GHGs generated when batteries are charged. The correct metric is the \textit{marginal} grid mix which takes into account the generator that is “on the margin” ready to be turned on when a new load such as a BEV or PHEV is added to the grid load.

Marginal Grid Mix Illustration

Consider a hypothetical utility that has only two generators: a coal power plant and a hydroelectric power plant, each serving half the peak load. Assume further that during the evening hours, the utility load is half the total capacity of these two generators. To minimize their costs, this utility would turn on the hydroelectric plant first, since it has the lowest operating cost. In the evening, with a 50\% load, the hydroelectric plant would supply all power.

If a new load (such as charging the batteries on BEVs and PHEVs) is added, then the utility would have to turn on the coal plant to supply this extra load.\footnote{In reality, a coal plant cannot be turned on and off quickly, since it takes many hours to heat up a coal plant. So in this example, the coal plant would have to on all the time in a “hot standby” mode, ready to ramp up whenever the load required more power than the hydroelectric plant could deliver.} The coal plant would be on the margin.

The average emissions from these two power plants are approximately 500 g of CO$_2$ per kWh generated, the average of 1000 g/kWh for the coal plant and zero for the hydroelectric plant.
An analyst using average emissions would therefore assign a GHG value of 500 g/kWh to a BEV or PHEV added to this grid, when in fact adding the BEV or PHEV would generate 1,000 g/kWh, the GHG emissions from the coal plant on the margin. In this hypothetical case, the average grid mix result would be twice the correct result from the marginal grid mix.

As stated in the Greenhouse gas protocol [D.1]:

An average emission rate is easy to calculate, but it provides only a rough approximation of marginal displaced emissions. A simple average emission rate may be necessary in situations where data are not available to perform a marginal rate methods. Because calculating a simple average is significantly less precise than other methods, however, it should only be used where other methods are not practicable.

Of course actual utility grid mixes are much more complicated than the hypothetical two-plant utility described above. Figure D.1 shows a more realistic mix of generators for a utility that represents the average generator sources of all US utilities. The generators are arranged in increasing operating cost from bottom to top. Thus, the generators with the lowest operating costs23 (Hydro, renewables, and nuclear) are shown in the bottom of the chart. Having low operating costs, these are the generators that are generally turned on first and run as baseload. Above these generators come generators with higher operating costs, such as coal plants, then natural gas combined cycle (NG CC) plants,24 and finally the most expensive to operate natural gas (single cycle) combustion turbines (NG CT). Also shown in Fig. D.1 are two hypothetical utility load profiles. The intersection of these load  

---

23Note that this metric ignores the capital cost of these generators. Thus nuclear plants are very expensive to build, but have low operating costs once they are constructed.

24Combined cycle plants have higher efficiency than single-cycle turbines or combustion turbines, so the combined cycle plants use less natural gas and have lower operating costs.
profiles with the stacked utility generator profiles defines the likely generators that will supply those loads—the marginal grid mixes. For load profile #1, all the electricity would be generated from natural gas plants: combined cycle plants around noon, and lower efficiency combustion turbines in the evening and late morning and afternoon hours.

Load profile #2 dips into the coal plant regime from early afternoon, through the night, until mid-morning, so the coal plants would supply a large fraction of the electricity for load profile #2, so GHGs would be much higher with load #2 compared to load #1. For BEVs and PHEVs charging at night, load profile #2 will generate more GHGs than load profile #1.

**Actual US Marginal Grid Mixes**

As stated in the GHG protocol above, calculating the marginal grid mix is much more complex than calculating the average grid mix, since calculating the marginal grid mix requires an hour-by-hour load profile for each utility system to determine which generators are on the margin, information that is not readily available. Fortunately, the scientists and engineers at the Oak Ridge National Laboratory have made such complex calculations for each of the major US electricity regions (See Fig. D.2 for map of the 2007 EIA regions) using data from the DOE’s 2007 Annual Energy Outlook [D.2]; we use their marginal grid mix data (top half of Table D.1) for 2020 in this model; we entered these utility marginal grid mix data into the GREET model to arrive at GHG emissions and petroleum consumption for both average and marginal grid mixes. Note that nuclear power (with zero GHG emissions) makes up more than 18% of the average LDV-weighted grid mixes, but the electricity from these nuclear plants is never on the margin in any region of the country and new loads such as BEVs would never lead to an increase in nuclear power production; therefore, any analysis that includes nuclear power in the calculation of GHG emissions from electric vehicles is flawed.

The differences between marginal and average grid mixes show up predominantly with BEVs and to a lesser extent with PHEVs. Table D.2 shows the results of BEV GHG emissions for the 14 grid regions mentioned above. In 8 of the 14 regions, GHGs for BEVs increase using the marginal grid mix compared to the average grid mix, and GHGs are lower for marginal average grid mixes in the other 6 regions.

---

25Note that the zero GHG generators (hydro, renewables, and nuclear) are never on the margin in this simplified example and are almost always run as baseload as the lowest operating cost generators; so a high percentage of zero-GHG generators at a given utility do not necessarily reduce the actual GHG emissions from these utilities when new loads such as BEVs or PHEVs are added.

26Nuclear power contributed more than 20% of all US power in this time period, but the weighting by LDV in each region results in the 18.3% estimate, meaning that those regions with high concentrations of registered LDVs tend to have lower concentration of nuclear power plants.
The last row in Table D.2 also shows the percentage of LEVs in each region.

The results of calculating the GHG emissions for all alternative fueled vehicles are shown in Table D.3. The results are obviously identical for AFVs that do not use any grid electricity. The LDV-weighted GHG estimate from the marginal grid data for BEVs is 9.86 % greater than the GHGs calculated using the average grid mixes in the 14 regions. The GHGs for PHEVs using the marginal grid mixes are from 3.6 to 5.3 % greater than the GHGs calculated using the LDV-weighted average grid mix.
Table D.1  Marginal and average electrical grid mixes from the Oak Ridge National Laboratory (first 13 regions) (Region 14 (Alaska and Hawaii) modeled manually by author)

<table>
<thead>
<tr>
<th>Region</th>
<th>Marginal grid mixes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>East Central Area Reliability Coordination Agreement—01 (%)</td>
</tr>
<tr>
<td>Coal</td>
<td>55.9                                                                 0.0                                                               25.5                                             62.0                                             22.7                                             4.0                                               14.8</td>
</tr>
<tr>
<td>Oil</td>
<td>0.3                                                                 0.0                                                               11.0                                             0.0                                               2.1                                               13.6                                              20.7</td>
</tr>
<tr>
<td>Gas ST</td>
<td>0.3                                                                 24.5                                                              0.2                                               0.5                                               0.2                                               12.8                                              0.8</td>
</tr>
<tr>
<td>Gas CC</td>
<td>20.0                                                                52.5                                                              57.4                                             9.2                                               30.1                                              52.5                                              49.4</td>
</tr>
<tr>
<td>Gas CT</td>
<td>19.9                                                                22.4                                                              8.1                                               28.2                                              36.8                                              16.9                                              5.4</td>
</tr>
<tr>
<td>Total natural gas</td>
<td>42.9                                                                99.4                                                              65.8                                             37.9                                             67.1                                              82.3                                              55.6</td>
</tr>
<tr>
<td>Renew</td>
<td>0.8                                                                 0.0                                                               0.0                                               0.0                                               0.0                                               0.0                                               0.0</td>
</tr>
<tr>
<td>Unserved</td>
<td>0.0                                                                 0.1                                                               0.1                                               0.0                                               0.0                                               0.0                                               0.0</td>
</tr>
<tr>
<td>Nuclear</td>
<td>0.0                                                                 0.0                                                               0.0                                               0.0                                               0.0                                               0.0                                               0.0</td>
</tr>
<tr>
<td>LDV % per region</td>
<td>13.7                                                                5.9                                                               9.1                                               8.8                                               3.6                                               5.4                                               5.2</td>
</tr>
</tbody>
</table>

(continued)
Table D.1 (continued)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>0.3</td>
<td>33.3</td>
<td>5.1</td>
<td>0.0</td>
<td>7.2</td>
<td>0.0</td>
<td>4.2</td>
<td>23.4</td>
</tr>
<tr>
<td>Oil</td>
<td>16.3</td>
<td>0.1</td>
<td>2.3</td>
<td>0.0</td>
<td>0.0</td>
<td>0.1</td>
<td>70.1</td>
<td>4.4</td>
</tr>
<tr>
<td>Gas ST</td>
<td>11.0</td>
<td>0.3</td>
<td>13.3</td>
<td>15.9</td>
<td>1.9</td>
<td>21.7</td>
<td>6.1</td>
<td>7.6</td>
</tr>
<tr>
<td>Gas CC</td>
<td>51.1</td>
<td>61.9</td>
<td>75.1</td>
<td>73.4</td>
<td>88.2</td>
<td>60.5</td>
<td>14.2</td>
<td>48.9</td>
</tr>
<tr>
<td>Gas CT</td>
<td>18.6</td>
<td>2.9</td>
<td>4.1</td>
<td>10.6</td>
<td>2.6</td>
<td>16.9</td>
<td>6.1</td>
<td>14.4</td>
</tr>
<tr>
<td>Total natural gas</td>
<td>80.7</td>
<td>65.1</td>
<td>92.5</td>
<td>100.0</td>
<td>92.6</td>
<td>99.2</td>
<td>26.4</td>
<td>71.0</td>
</tr>
<tr>
<td>Renew</td>
<td>0.6</td>
<td>1.5</td>
<td>0.0</td>
<td>0.0</td>
<td>0.2</td>
<td>0.5</td>
<td>0.0</td>
<td>0.5</td>
</tr>
<tr>
<td>Unserved</td>
<td>0.6</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.2</td>
<td>0.0</td>
<td>0.1</td>
</tr>
<tr>
<td>Nuclear</td>
<td>0.8</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>LDV % per region</td>
<td>5.5</td>
<td>17.1</td>
<td>2.9</td>
<td>5.1</td>
<td>3.0</td>
<td>13.4</td>
<td>0.6</td>
<td></td>
</tr>
</tbody>
</table>

(continued)
### Table D.1 (continued)

<table>
<thead>
<tr>
<th></th>
<th>East Central Area Reliability Coordination Agreement—01 (%)</th>
<th>Electric Reliability Council of Texas—02 (%)</th>
<th>Mid-Atlantic Area Council—03 (%)</th>
<th>Mid-America Area Interconnected Network—04 (%)</th>
<th>Mid-Continent Area Power Pool—05</th>
<th>Northeast Power Coordinating Council/New York—06</th>
<th>Northeast Power Coordinating Council/New England—07</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>78.3</td>
<td>32.1</td>
<td>49.3</td>
<td>53.1</td>
<td>73.3</td>
<td>13.1</td>
<td>11.5</td>
</tr>
<tr>
<td>Oil</td>
<td>0.0</td>
<td>0.0</td>
<td>1.0</td>
<td>0.0</td>
<td>0.1</td>
<td>1.1</td>
<td>2.1</td>
</tr>
<tr>
<td>Gas ST</td>
<td>0.2</td>
<td>4.2</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Gas CC</td>
<td>10.5</td>
<td>45.5</td>
<td>14.2</td>
<td>12.3</td>
<td>4.0</td>
<td>39.7</td>
<td>55.3</td>
</tr>
<tr>
<td>Gas CT</td>
<td>1.1</td>
<td>4.7</td>
<td>0.4</td>
<td>1.9</td>
<td>2.6</td>
<td>1.0</td>
<td>0.4</td>
</tr>
<tr>
<td>Total natural gas</td>
<td>11.8</td>
<td>54.4</td>
<td>14.7</td>
<td>14.2</td>
<td>6.6</td>
<td>41.7</td>
<td>55.8</td>
</tr>
<tr>
<td>Renew</td>
<td>1.1</td>
<td>0.4</td>
<td>3.4</td>
<td>1.5</td>
<td>5.9</td>
<td>17.5</td>
<td>10.9</td>
</tr>
<tr>
<td>Unserved</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Nuclear</td>
<td>8.8</td>
<td>11.0</td>
<td>31.3</td>
<td>11.4</td>
<td>11.4</td>
<td>26.1</td>
<td>19.7</td>
</tr>
</tbody>
</table>
Table D.1 (continued)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>34.7</td>
<td>51.9</td>
<td>67.8</td>
<td>35.0</td>
<td>66.3</td>
<td>30.1</td>
<td>12.2</td>
<td>46.6</td>
</tr>
<tr>
<td>Oil</td>
<td>3.2</td>
<td>0.3</td>
<td>0.3</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>56.0</td>
<td>0.9</td>
</tr>
<tr>
<td>Gas ST</td>
<td>3.5</td>
<td>2.9</td>
<td>2.0</td>
<td>0.3</td>
<td>0.7</td>
<td>5.0</td>
<td>6.4</td>
<td>1.8</td>
</tr>
<tr>
<td>Gas CC</td>
<td>47.0</td>
<td>8.4</td>
<td>20.9</td>
<td>16.8</td>
<td>17.3</td>
<td>27.3</td>
<td>7.9</td>
<td>21.6</td>
</tr>
<tr>
<td>Gas CT</td>
<td>4.4</td>
<td>0.5</td>
<td>0.7</td>
<td>0.6</td>
<td>0.5</td>
<td>4.4</td>
<td>3.6</td>
<td>1.8</td>
</tr>
<tr>
<td>Total natural gas</td>
<td>54.9</td>
<td>11.9</td>
<td>23.7</td>
<td>17.8</td>
<td>18.5</td>
<td>36.7</td>
<td>17.9</td>
<td>25.2</td>
</tr>
<tr>
<td>Renew</td>
<td>2.3</td>
<td>3.9</td>
<td>2.4</td>
<td>41.9</td>
<td>4.6</td>
<td>18.4</td>
<td>13.9</td>
<td>8.1</td>
</tr>
<tr>
<td>Unserved</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Nuclear</td>
<td>4.7</td>
<td>32.0</td>
<td>3.9</td>
<td>2.9</td>
<td>10.1</td>
<td>12.0</td>
<td>0.0</td>
<td>18.2</td>
</tr>
</tbody>
</table>
### Table D.2  GHG emissions in grams/mile for BEVs using average and marginal grid mixes, % change of marginal compared to average grid mix calculations, and % of LDVs in each of the 14 US geographic regions

<table>
<thead>
<tr>
<th>Region</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>Wgt’d Ave.</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEV Marginal GHGs</td>
<td>407</td>
<td>291</td>
<td>337</td>
<td>434</td>
<td>327</td>
<td>313</td>
<td>307</td>
<td>304</td>
<td>312</td>
<td>266</td>
<td>260</td>
<td>245</td>
<td>277</td>
<td>443</td>
<td>326.8</td>
</tr>
<tr>
<td>BEV Average GHGs</td>
<td>415</td>
<td>292</td>
<td>284</td>
<td>299</td>
<td>382</td>
<td>168</td>
<td>192</td>
<td>320</td>
<td>292</td>
<td>392</td>
<td>217</td>
<td>371</td>
<td>246</td>
<td>392</td>
<td>297.5</td>
</tr>
<tr>
<td>delta</td>
<td>−1.9</td>
<td>−0.6</td>
<td>18.6</td>
<td>45.2</td>
<td>−14.2</td>
<td>86.3</td>
<td>59.6</td>
<td>−4.8</td>
<td>7.0</td>
<td>−32.1</td>
<td>20.1</td>
<td>−33.8</td>
<td>12.8</td>
<td>12.9</td>
<td>14.5</td>
</tr>
<tr>
<td>of LDVs</td>
<td>13.7</td>
<td>5.9</td>
<td>9.1</td>
<td>8.8</td>
<td>3.6</td>
<td>5.5</td>
<td>5.3</td>
<td>5.6</td>
<td>17.2</td>
<td>3.0</td>
<td>5.2</td>
<td>3.1</td>
<td>13.5</td>
<td>0.6</td>
<td></td>
</tr>
</tbody>
</table>
Table D.3  LDV-weighted GHG emissions comparing average with marginal grid mixes and % increase of marginal GHGs relative to average GHGs

<table>
<thead>
<tr>
<th></th>
<th>GHG emissions (g/mile)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Marginal</td>
<td>Average</td>
<td>Marg/Ave (%)</td>
</tr>
<tr>
<td>Gasoline ICV</td>
<td>549.8</td>
<td>549.8</td>
<td>0.00</td>
</tr>
<tr>
<td>E-85 ICV</td>
<td>358.8</td>
<td>358.8</td>
<td>0.00</td>
</tr>
<tr>
<td>Gasoline HEV</td>
<td>339.0</td>
<td>339.0</td>
<td>0.00</td>
</tr>
<tr>
<td>NGV</td>
<td>488.1</td>
<td>488.1</td>
<td>0.00</td>
</tr>
<tr>
<td>NG HEV</td>
<td>309.8</td>
<td>309.8</td>
<td>0.00</td>
</tr>
<tr>
<td>Diesel ICV</td>
<td>474.4</td>
<td>474.4</td>
<td>0.00</td>
</tr>
<tr>
<td>Diesel HEV</td>
<td>307.9</td>
<td>307.9</td>
<td>0.00</td>
</tr>
<tr>
<td>E-85 HEV</td>
<td>309.8</td>
<td>309.8</td>
<td>0.00</td>
</tr>
<tr>
<td>BEV</td>
<td>326.6</td>
<td>297.3</td>
<td>9.86</td>
</tr>
<tr>
<td>FCEV</td>
<td>256.2</td>
<td>256.2</td>
<td>0.00</td>
</tr>
<tr>
<td>NG PHEV-40</td>
<td>300.1</td>
<td>297.3</td>
<td>0.93</td>
</tr>
<tr>
<td>FC PHEV-40</td>
<td>290.6</td>
<td>275.8</td>
<td>5.34</td>
</tr>
<tr>
<td>EtOH PHEV-40</td>
<td>361.9</td>
<td>349.4</td>
<td>3.57</td>
</tr>
<tr>
<td>Gasoline PHEV-40</td>
<td>285.9</td>
<td>273.5</td>
<td>4.56</td>
</tr>
</tbody>
</table>

References


Appendix E
Capital Cost of Equipment to Produce Hydrogen, Heat, and Electricity at Wastewater Treatment Plants

Introduction

One excellent source of hydrogen is from waste processed at municipal wastewater treatment plants (WWTPs). Several of these treatment plants are found in every major metropolitan area, and some are already equipped with anaerobic digesters (AD) that use microorganisms to break down the solid waste in the absence of oxygen to produce methane (CH₄), the main ingredient in natural gas, and a superb source of hydrogen.

The key components of a wastewater treatment plant hydrogen tri-generation system are illustrated in Fig. E.1 (heat exchangers not shown that would be used to capture the waste heat from the SMR and fuel cell systems to supply heat to the digester tanks).

Wastewater from the sewage system is concentrated in settling tanks, and the remaining sludge is placed into a set of anaerobic digester tanks. Microbes then convert part of the sewage waste into digester gas (primarily methane and carbon dioxide) in the absence of oxygen. A gas cleanup system then removes most of the carbon dioxide, hydrogen sulfide, and siloxides, leaving a gas made up primarily of methane. This methane is then fed to a steam methane reformer (SMR) that converts the methane and water to hydrogen, some carbon monoxide (CO), and carbon dioxide (CO₂):

\[
3\text{H}_2\text{O} + 2\text{CH}_4 = \text{CO} + \text{CO}_2 + 7\text{H}_2 \quad (E.1)
\]

A water gas shift reactor then converts most of the residual CO into more hydrogen and more CO₂:

\[
\text{H}_2\text{O} + \text{CO} = \text{H}_2 + \text{CO}_2 \quad (E.2)
\]

For a net reaction of:

\[
4\text{H}_2\text{O} + 2\text{CH}_4 = 2\text{CO}_2 + 8\text{H}_2 \quad (E.3)
\]

---

27Tri-generation refers to the three products from this plant: hydrogen, heat, and electricity.
So half the hydrogen comes from water and half from methane (8 hydrogen atoms each).

Finally, a pressure swing adsorption (PSA) system produces a very pure stream of hydrogen suitable for the stationary fuel cell system and the fuel cells onboard FCEVs, and the residual CO2 is released.

This ultra-pure hydrogen is then compressed and stored in a set of storage tanks at a nominal pressure in the range of 110 bar; this medium-pressure stored hydrogen could then be used to fuel the stationary fuel cell during a power outage or during plant downtime for maintenance, providing a very stable supply of electricity for the WWTP.28

To fill the hydrogen tanks on the FCEVs, a second compressor29 raises the pressure of some hydrogen to the range between 850 and 900 bar that is stored in a multitank cascade to fill the 700-bar FCEV car tanks.30 In the process of filling the high-pressure tanks, the hydrogen is heated, which reduces the amount of hydrogen that can be stored in the car tanks. To assure a full tank of hydrogen, the hydrogen is cooled prior to filling the car tanks.

28However, we have not included the cost of this backup electricity system in this analysis.
29Alternately, one compressor may have two or more stages, with the first stage compressing the hydrogen from the PSA to 110 bar and the second stage to boost the pressure to 850–900 bar for vehicle fueling.
30As indicated in the diagram, some of the 110-bar hydrogen is used initially to fill nearly empty car tanks, and then, higher and higher pressures are added until the car tanks are full at 700-bar pressure.
Table E.1 Available WWTPs in Los Angeles and Orange Counties, and the number of LDVs and population in these two counties, along with the number of FCEVs that could be supported by these 34 WWTPs

<table>
<thead>
<tr>
<th></th>
<th># of WWTPs</th>
<th>Available H2 (tonnes/year)</th>
<th># of FCEVs supported (M)</th>
<th>Population (millions)</th>
<th>Registered LDVs (M)</th>
<th>LDVs/WWTP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Los Angeles</td>
<td>23</td>
<td>10,000</td>
<td>57.51</td>
<td>9.82</td>
<td>7.2</td>
<td>311,261</td>
</tr>
<tr>
<td>Orange County</td>
<td>11</td>
<td>5,400</td>
<td>31.06</td>
<td>3.01</td>
<td>2.4</td>
<td>221,727</td>
</tr>
<tr>
<td>LA area Totals</td>
<td>34</td>
<td>15,400</td>
<td>88.57</td>
<td>12.83</td>
<td>9.6</td>
<td>282,294</td>
</tr>
</tbody>
</table>

**Available WWTPs in Los Angeles Area**

The National Renewable Energy Laboratory has analyzed the number of available WWTPs in the Los Angeles area (LA and Orange Counties). As shown in Table E.1, there are approximately 34 available WWTPs in these two counties that do not already utilize some or all of their biogas to produce either heat or electricity. These 34 plants could produce enough hydrogen to support more than 88,000 FCEVs. There are 9.6 million registered LDVs in these two counties or an average of 282,294 LDVs per WWTP.

One WWTP in Tulare, California, is already producing 1.2 MW of electricity with a molten carbonate fuel cell (MCFC) system supplied by Fuel Cell Energy. The Tulare plant processes 11.7 million gallons of waste per day (MGD), with 4.4 MGD from domestic waste from the city’s population of 59,278, and 7.1 MGD from industrial waste. This WWTP requires 2.7 MW of electrical power, so the 1.2 MW of fuel cell power from waste satisfies 45% of the electrical demand to run the WWTP.

**FCEVs Projected for the LA Area**

The projected number of FCEVs sold nationwide is derived in Appendix C. The resulting cumulative number of FCEVs OTR per wastewater treatment plant in the Los Angeles area based on this national average FCEV density is shown in Fig. E.2. The number of projected FCEVs is quite small in the early years of market expansion.

---

penetration. For example, the model predicts a national average of only 10 FCEVs OTR per WWTP in 2017 and 26 in 2020, based on the number of LDVs in the LA area.

But the expected number of FCEVs in California is much higher as shown in Table E.2 for two LA area counties.\textsuperscript{33} The CARB\textsuperscript{34} is estimating that there will be 6,650 and 18,465 FCEVs OTR by 2017 and 2020, or 2,178 and 6,048 FCEVs in the LA area based on LDV density in this area.\textsuperscript{35}

On the average, the number of FCEVs projected in the LA area per WWTP is 225 times\textsuperscript{36} the national average as shown in Fig. E.3, which shows the CARB estimates for 2017 and 2020 superimposed on the data national average data from Fig. E.2 multiplied by 225. So the density of FCEVs relative to LDVs in the LA area will be 225 times greater than the national average during the early years of FCEV deployment, due to the State of California actively promoting hydrogen fueling stations and FCEVs through their ZEV program.

\textsuperscript{33}Los Angeles and Orange counties.


\textsuperscript{35}The LA area is home to approximately 32.76% of all California vehicles (9.6 out of 29.3 million vehicles).

\textsuperscript{36}From a national average of 10 FCEVs in 2017 to 2178 in 2017 and from 26 to 6048 in 2020.

\textbf{Table E.2} Projected number of FCEVs in the 2017–2020 time period

<table>
<thead>
<tr>
<th></th>
<th>California</th>
<th>LA area</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017</td>
<td>6650</td>
<td>2178</td>
</tr>
<tr>
<td>2020</td>
<td>18,465</td>
<td>6048</td>
</tr>
</tbody>
</table>

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig_e.2.png}
\caption{Projected number of FCEVs per WWTP in California based on the conservative (low) national average FCEV density in the model}
\end{figure}
**Fig. E.3**  Number of FCEVs per WWTP from the CARB projections compared with 225 times the national average projection from Fig. E.2

**WWTP Tri-Gen Return on Investment**

The internal rate of return (IRR) or return on investment in a tri-generation system will depend on several variables including:

- The capacity of the stationary fuel cell system in terms of electrical output in kW.
- The demand for vehicle hydrogen which will depend on the number of FCEVs in the vicinity of the WWTP.
- The local price of fuels such as natural gas, electricity, and gasoline; the price of natural gas will determine the avoided cost of heating by using the waste heat from the SMR and stationary fuel cell system; the price of electricity will determine the cost savings from generating electricity onsite instead of buying it from the local utility, and the price of gasoline will determine the allowable price of hydrogen for FCEVs.
- The installed cost for all systems.
- The efficiencies of the various systems.

---

37Before taxes and current dollars.

38In the model, we assume that the price of hydrogen is set to a value such that the owner of a FCEV pays 10% less per mile (a variable) for vehicle fuel than he or she would pay for gasoline in a conventional vehicle to travel the same distance.
Fuel Cell Sizing

An existing hydrogen Tri-Gen system at the Orange County Sanitation District WWTP in Fountain Valley California produces 250 kW of electrical power, but we have assumed here that a set of automotive or bus style proton exchange membrane (PEM) fuel cell systems produces 1.3 MW (similar to the 1.2 MW fuel cell system at the Tulare WWTP described above) as a base case to maximize the savings by avoiding the costs of electricity consumed on-site. We are postulating the use of stationary PEM fuel cells produced by or for automobile and bus manufacturers as they ramp up production of FCEVs. Specifically, Brian James of Strategic Analysis, Inc. of Arlington, Virginia, recommends using bus PEM fuel cell stacks for this stationary application, since bus fuel cells are typically more durable due to higher catalyst loadings (0.4 mg of platinum per cm² compared to 0.15 mg of Pt/cm² for automotive stacks), and bus FC stacks typically operate at lower pressure (1.8 vs. 2.5 atmospheres). The bus PEM Fuel cell system analyzed in detail by James et al. has a power level of 160 kW in two stacks, so 8 or 9 bus FC systems would be used in this stationary 1.3 MW application.

SMR Sizing

The SMR must produce hydrogen for both the stationary fuel cell system and dispensing hydrogen to the FCEVs.

Hydrogen Required for the 1.3 MW Electrical Load

The stationary fuel cell will produce $1300 \times 24 = 31,200$ kWh per day. Assuming a FC efficiency of 48%, then the hydrogen required must have an energy content of:

$$31,200 \text{ kWh} / 0.48 = 65,000 \text{ kWh}.$$  
Since one kg of hydrogen has an energy content (lower heating value) of 33.31 kWh, then the SMR must produce 

$$65,000 / 33.31 = 1951 \text{ kg/day of hydrogen to run the stationary fuel cell system.}$$

---

39The Fuel Cell Energy DFC-300 molten carbonate fuel cell (MCFC) nominally has a 300-kW capacity, but is derated to 250 kW with the production of 125 kg/day of hydrogen.

Hydrogen Required for FCEVs

We assume in the model that vehicles travel an average of 11,876 miles per year, the US average for 2012. The National Laboratory-certified fuel economy of the Toyota Highlander SUV FCEV was 68.3 miles/kg of hydrogen, so each FCEV requires approximately

$$\frac{11,876}{68.3} = 173.9 \text{ kg of hydrogen per year or an average of approximately } 0.476 \text{ kg/day.}$$

The total hydrogen required then depends on how many FCEVs will be supported by each WWTP.

We assume that each WWTP station will support 60 FCEVs initially.

Note that a station that supports 60 FCEVs is not equivalent to a station that refuels 60 cars per day. For example, if we assume that a FCEV travels 11,876 miles per year (the US average for 2012) with a fuel economy of 68.3 miles/kg, then this FCEV would consume 0.48 kg/day as described above. If we further assume that the driver refuels his or her vehicle when it has used 85% of the hydrogen (15% remaining), then the driver will refill the car tanks approximately 35 times per year or an average of 10.4 days between refills. In this case, a station supporting 60 FCEVs will refuel an average of only 5–6 cars per day, which is very low compared to some gasoline stations that refuel hundreds of cars per day.

This station that supports 60 FCEVs will on the average dispense 28.6 kg/day.

Total Hydrogen Required

The SMR system must therefore be designed to produce over 1980 kg/day (1951 kg/day for the stationary 1.3 MW fuel cell system plus 28.6 kg/day for FCEV refueling.)

WWTP System Cost Estimates

The WWTP hydrogen station will have all the subsystems shown in Fig. E.1 plus heat exchangers to recover waste heat from the stationary fuel cell and SMR systems.

---


42Assuming a hydrogen tank designed to hold 5.9 kg for 400 miles range.
The Anaerobic Digester

We assume that the anaerobic digester is built as part of the WWTP

Anaerobic Digester Gas Cleanup System

Anaerobic digester gas (ADG) is typically composed of 50–60 % methane (CH\textsubscript{4}), 38–48 % carbon dioxide (CO\textsubscript{2}), with traces of inert gases such as nitrogen. But ADG also contains H\textsubscript{2}S and siloxanes that must be removed to avoid damaging downstream equipment. After removing the H\textsubscript{2}S and siloxanes, the percentage of methane should be increased using either a membrane separator or a PSA system that uses adsorbents that remove much of the CO\textsubscript{2} while letting the smaller methane molecules pass through. The gas flow must be reversed periodically once the adsorbents become saturated with CO\textsubscript{2}. Multiple adsorbent beds are used, so that one or more beds can be producing high concentrations of methane, while other beds are being cleaned of CO\textsubscript{2} by reverse flow. The Eastern Research Group\textsuperscript{43} estimated that the cost of gas fuel treatment for a 300-kW fuel cell plant power by ADG would be approximately $147,000. We use this estimate in the model with a 0.6 power scaling factor for other sizes of FC plants:

$$\text{Cost}_{\text{gas clean-up}} = 147,000 \left[ \frac{\text{Capacity}_{\text{FC}} (\text{kW})}{300} \right]^{0.6}$$

Heat Recovery System

The Eastern Research Group\textsuperscript{17} also estimated a cost of $23,200 for a heat recovery system for the 300-kW fuel cell plant. So we assumed a heat recovery system cost of

$$\text{Cost}_{\text{heat recovery}} = 23,200 \times \left[ \frac{\text{Capacity}_{\text{FC}} (\text{kW})}{300} \right]^{0.6}$$

Steam Methane Reformer System

A SMR converts methane (the main constituent of natural gas) and water into primarily hydrogen and carbon dioxide. An SMR can also convert the methane in ADG into hydrogen and carbon dioxide. A commercial SMR such as the one my company, H2Gen, developed and sold also contains a gas filter to remove H\textsubscript{2}S from the incoming gas stream and a compressor to raise the pressure of the methane into a range that is effective for reforming, nominally 13.8 bar. Finally, the SMR systems that we developed include a built-in PSA system to filter out all gases except hydrogen, producing an ultra-pure hydrogen stream suitable for powering PEM fuel cells. The estimated cost of such an SMR system is shown in

\textsuperscript{43}Eastern Research Group, “Opportunities for and Benefits of combined heat and power at wastewater treatment facilities,” prepared for the U.S. Environmental Protection Agency, December 2006.
Fig. E.4  Two estimates of SMR capital cost as a function of plant capacity in kg/day

![SMR Capex](image)

Table E.3  Markup factor to convert fuel cell cost to price

<table>
<thead>
<tr>
<th></th>
<th>Rate (%)</th>
<th>Markup</th>
</tr>
</thead>
<tbody>
<tr>
<td>Profit</td>
<td>15.0</td>
<td>1.15</td>
</tr>
<tr>
<td>Non-recurring engineering</td>
<td>8.0</td>
<td>1.08</td>
</tr>
<tr>
<td>Warranty</td>
<td>20.0</td>
<td>1.2</td>
</tr>
<tr>
<td>Contingency</td>
<td>5.0</td>
<td>1.05</td>
</tr>
<tr>
<td><strong>NET markup</strong></td>
<td></td>
<td>1.56</td>
</tr>
</tbody>
</table>

Fig. E.4, along with an estimate made by the National Renewable Energy Laboratory (NREL).\(^{44}\) A curve fit to the higher H2Gen estimated SMR system cost\(^{45}\) which we use in the model is given by

\[
\text{Cost}_{\text{smr}} = 30360 \times C \left(\text{kg/day}\right)^{0.48}, \text{where} \quad \text{"C" is the capacity of the SMR in kg/day.}
\]

**PEM Stationary Fuel Cell System Cost**

For the purposes of this calculation, we assume that the fuel cell companies building bus fuel cell systems are able to produce 160-kW systems for approximately $58,462 as projected by James et al., in production rates of 400 systems per year, or $365/kW at the cost level.\(^{46}\) This cost estimate must be marked up to account for profit, warranty, non-recurring engineering charges, and a 5% contingency as summarized in Table E.3. The total cost markup is by a factor of 1.56 or a fuel cell

---


\(^{45}\)Both the NREL and H3Gen cost estimates do not include a hydrogen gas precooling system that is required to fill 700-bar FCEV car tanks; a refrigeration system is added separately below.

system price of $365 \times 1.56 = $572/kW. The 1.3 MW stationary PEM FC system that we are proposing in this model will therefore cost approximately $743,343.

We assume that these stationary fuel cell systems will have a life of 40,000 h, which means that they must be replaced every 4–5 years. However, the cost of replacement will be less than the initial price since many of the parts can be salvaged each time a fuel cell system is refurbished. The net salvage value is estimated at approximately 45% or $26,381 as shown in Table E.4. So the cost to

---

Table E.4  Estimated salvage value for refurbished 160-kW fuel cell systems

<table>
<thead>
<tr>
<th>Part</th>
<th>Salvage %</th>
<th>Salvage $</th>
<th>Salvage %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stamped bipolar plates</td>
<td>50</td>
<td>$570</td>
<td></td>
</tr>
<tr>
<td>MEAs:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Membranes</td>
<td>0</td>
<td>$ -</td>
<td></td>
</tr>
<tr>
<td>Catalyst ink</td>
<td>90</td>
<td>$4362</td>
<td></td>
</tr>
<tr>
<td>GDLs</td>
<td>0</td>
<td>$ -</td>
<td></td>
</tr>
<tr>
<td>M&amp;E cutting and slitting</td>
<td>0</td>
<td>$ -</td>
<td></td>
</tr>
<tr>
<td>MEA Gaskets</td>
<td>0</td>
<td>$ -</td>
<td></td>
</tr>
<tr>
<td>Coolant gaskets</td>
<td>0</td>
<td>$ -</td>
<td></td>
</tr>
<tr>
<td>End gaskets (screen printing)</td>
<td>0</td>
<td>$ -</td>
<td></td>
</tr>
<tr>
<td>End plates</td>
<td>100</td>
<td>$133</td>
<td></td>
</tr>
<tr>
<td>Current collectors</td>
<td>90</td>
<td>$14</td>
<td></td>
</tr>
<tr>
<td>Compression bands</td>
<td>0</td>
<td>$ -</td>
<td></td>
</tr>
<tr>
<td>Stack insulation housing</td>
<td>0</td>
<td>$ -</td>
<td></td>
</tr>
<tr>
<td>Stack assembly</td>
<td>0</td>
<td>$ -</td>
<td></td>
</tr>
<tr>
<td>Stack conditioning</td>
<td>0</td>
<td>$ -</td>
<td></td>
</tr>
<tr>
<td>Stack total</td>
<td></td>
<td>$5078</td>
<td>24.8</td>
</tr>
<tr>
<td>2 stacks</td>
<td></td>
<td>$10,156.60</td>
<td></td>
</tr>
<tr>
<td>Stack $/kW</td>
<td></td>
<td>$255.70</td>
<td></td>
</tr>
</tbody>
</table>

 Balance of plant

<table>
<thead>
<tr>
<th>Component</th>
<th>Salvage %</th>
<th>Salvage $</th>
<th>Salvage %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air loop</td>
<td>100</td>
<td>$7499</td>
<td></td>
</tr>
<tr>
<td>Humidifier and water recovery</td>
<td>50</td>
<td>$610</td>
<td></td>
</tr>
<tr>
<td>High-temperature coolant loop</td>
<td>95</td>
<td>$1643</td>
<td></td>
</tr>
<tr>
<td>Low-temperature coolant loop</td>
<td>95</td>
<td>$206</td>
<td></td>
</tr>
<tr>
<td>Fuel loop</td>
<td>100</td>
<td>$950</td>
<td></td>
</tr>
<tr>
<td>System controller</td>
<td>95</td>
<td>$506</td>
<td></td>
</tr>
<tr>
<td>Sensors</td>
<td>95</td>
<td>$3947</td>
<td></td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>95</td>
<td>$864</td>
<td></td>
</tr>
<tr>
<td>BOP total</td>
<td></td>
<td>$16,224</td>
<td>94.3</td>
</tr>
<tr>
<td>Assembly and Testing</td>
<td>0</td>
<td>$ -</td>
<td></td>
</tr>
<tr>
<td>Total system</td>
<td></td>
<td>$26,381</td>
<td>45.1</td>
</tr>
</tbody>
</table>

---

replace the fuel cells every 4 to 5 years is 55% of the original price of $743,343 or approximately $407,909.

In addition, the model includes an annual operation and maintenance budget of 5.5% of the initial price of the fuel cell system or approximately $40,900 per year; over the four years between fuel cell replacements, then, the project spends an additional $163,500 over the $407,900 spent to refurbish the fuel cell systems.

_Hydrogen Cooling System_

Hydrogen must be cooled to avoid overheating\textsuperscript{48} while filling the FCEV car tanks at 700 bar, the pressure now used by most auto companies for their FCEVs. The cost of the refrigeration system as a function of station capacity is estimated by the Argonne National laboratory\textsuperscript{49} as shown in Fig. E.5. We use the logarithmic curve fit to estimate the cost of the cooling system for hydrogen flows greater than 250 kg/day and $69,000 each for lower capacity stations.\textsuperscript{50}

\textsuperscript{48}This overheating is not a safety issue, but it does preclude the complete filling of a hydrogen tank since the warm hydrogen expands and takes up more space than the design quantity of hydrogen at room temperature.


\textsuperscript{50}The logarithmic curve fit to the ANL refrigeration cost curve goes negative for station capacities less than approximately 40 kg/day, while ANL estimated a cost of $69,000 for both 100 and 200 kg/day stations.
Inverter

The direct current from the stationary fuel cell must be converted to alternating current with a DC to AC inverter. Figure E.6 shows a curve fit to DC to AC inverter costs taken from commercial inverter prices on the Internet in October 2014.

Hydrogen Compressors

Hydrogen compressors are needed to fill medium-pressure (110-bar) hydrogen storage tanks and to boost the pressure of hydrogen to the 850 bar to 950 bar range to fill 700-bar FCEV tanks.51

Hydrogen must be stored on-site at medium pressure to provide hydrogen for refueling vehicles that will arrive at irregular intervals. Elgowainy et al. at the Argonne National Laboratory, based on detailed analyses to minimize costs, recommend that low-pressure storage be provided for at least 15% of the daily hydrogen load52 or 4.3 kg of low pressure based on the daily consumption of 28.6 kg/day derived in Sect. 6.2 above.

---

51These two functions could be achieved with different stages of a single compressor, but we assume two separate compressors in this model which should be conservative relative to cost.

Table E.5 Compressor cost parameters from Yang and Ogden

<table>
<thead>
<tr>
<th>Source</th>
<th>Base cost</th>
<th>Scale factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAS-forecourt-current</td>
<td>$7237</td>
<td>0.8</td>
</tr>
<tr>
<td>NAS-forecourt-future</td>
<td>$2279</td>
<td>0.8</td>
</tr>
<tr>
<td>Yang and Ogden</td>
<td>$1888</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Yang and Ogden at the Institute of Transportation Studies at the University of California at Davis\textsuperscript{53} have analyzed various estimates of hydrogen compressor costs based on the compressor power required, given by:

\[ P_{\text{comp}} = \frac{Q Z R T N}{\eta \times (\gamma - 1)} \times \left\{ \left( \frac{P_o}{P_i} \right)^{\frac{\gamma - 1}{\gamma N}} - 1 \right\} \]  

(E.4)

where

- \( Q \) hydrogen flow rate (Nm\(^3\)/s)
- \( Z \) compressibility of hydrogen
- \( R \) universal gas constant = 8.3146 J/Kmol
- \( T \) temperature (°K)
- \( N \) number of compressor stages,
- \( \eta \) adiabatic efficiency of compressor (65 % here)
- \( \gamma \) ratio of specific heats (1.41 for hydrogen)
- \( P_o \) output pressure (Pa), and
- \( P_i \) input (suction) pressure (Pa)

The system is designed to support 60 FCEVs, each of which consumes an average of 0.48 kg/day of hydrogen or 6.52 kg/h = 0.0201 Nm\(^3\)/s. We assume that the bulk of the hydrogen for refueling is stored at 110 bar, with a 3-tank high-pressure cascade with the highest pressure at 850 bar to 950 bar. The pressure out of the PSA is 200 psig or 13.8 bar. From Eq. E.4, the power required from the low-pressure compressor (13.79–110 bar) is 66.2 kW and the high-pressure compressor (110–850 bar) requires 38.7 kW for a total power draw of 105 kW.

Yang and Ogden\textsuperscript{16} have also summarized the cost of compressors dependent on their power rating as shown in Table E.5,

\[ C_p = C_b P(kW)^{a} \]

where \( C_p \) refers to the 2004 National Academy of Sciences report on hydrogen.\textsuperscript{54} They considered 2020 as “future” in this 2004 study, which will be here by the time large-scale deployments of FCEVs are completed, so we averaged the current and

\textsuperscript{53}C. Yang & J. Ogden, “Hydrogen delivery and refueling infrastructure” the Institute for Transportation Studies, the University of California at Davis, provided for the California Energy Commission Advanced Energy Pathways (AEP) Project, June 2007.

future NAS projections along with the Yang and Ogden estimates to arrive at an average compressor cost as shown in Table E.6.

The total estimated cost for the two compressors is $255,190 as shown in Table E.6. This calculation assumes an intermediate bulk storage pressure of 500 bar. Compressor costs could be reduced further with lower bulk storage pressures, but then, the bulk storage costs would increase along with the required storage volume.

### Hydrogen Dispenser Cost

Some analysts have suggested dispenser costs in the $50,000 range, but the NREL independent peer review team\(^{55}\) estimated that the dispenser would cost $165K as an optimistic case and $189K for their base case, due to the much higher operating pressures for hydrogen compared to natural gas compressor and the need to dispense cold hydrogen. We use the optimistic estimate of $165K for this model.

### Electricity Consumption

The SMR and hydrogen compressors both consume electricity, which will reduce the electricity from the stationary PEM fuel cell that could be sold or used to displace electricity previously purchased from the local utility.

---

SMR Electricity Consumption

The HGM-10,000 SMR system\textsuperscript{56} consumes 1.48 kWh/kg of hydrogen produced. Most of this electricity is used in the natural gas compressor. Compressor power is directly proportional to the gas flow rate as shown by Eq. E.4. So this electricity per kg value will increase with increased hydrogen flow. We assume that the SMR compressor will consume:

$$\text{SMR electricity consumption} = \frac{1.48 \text{ kWh/kg}}{C(\text{kg/day})/567 \text{ kg/day}},$$

where $C(\text{kg/day})$ is the capacity of the SMR.\textsuperscript{57} For the base case of a 1.3-MW stationary PEM fuel cell system, the required hydrogen flow is approximately 1951 kg/day plus 23.8 kg/day for the FCEVs, which increases the SMR electrical consumption to 5.17 kWh/kg.

The SMR then consumes approximately 10,276 kWh/day or 3.62 million kWh/year with a 96 % system annual availability factor.

Hydrogen Compressor Electricity Consumption

The hydrogen compressors only compress the hydrogen needed for refueling FCEVs. The hydrogen used to run the stationary PEM fuel cell system is fed directly to the fuel cell; there is no need to store hydrogen for the stationary fuel cell system.\textsuperscript{58} So compressors are only needed for the hydrogen used for FCEV refueling. The model assumes that the hydrogen fueling station is designed to accommodate 60 FCEVs. Each FCEV consumes an average of 0.48 kg/day, so a station designed to support 60 FCEVs will require a hydrogen flow of 28.6 kg/day on the average. The low-pressure compressor must operate continuously to fill the 500-bar storage tanks at a power level of 131.5kW or an annual electricity demand of 184,400 kWh/year. The high-pressure compressor (500–900 bar) requires 21.7 kW, but only operates 105 h per year when one of the 60 FCEVs is being filled, or a total electricity demand of 2210 kWh/year for a total annual demand of 86,600 kWh/year from both compressors, which is just 1.7 % of the annual 1.3 MW FC output of 11.05 million kWh/year.

\textsuperscript{56}The HGM-10,000 is the commercial SMR developed by H2Gen, Inc. that produced 10,000 standard cubic feet of hydrogen of hydrogen per hour or approximately 567 kg/day.

\textsuperscript{57}To the degree that some of the electricity in the SMR is used for controls and devices that do not increase with hydrogen flow rate, this adjustment of electricity consumption is conservative.

\textsuperscript{58}Although some WWTP operators might want to store some hydrogen to serve as an emergency backup system in case of a power outage. Hydrogen could also be stored to be used to cover annual maintenance downtime on the SMR system.
Table E.7  Summary of hydrogen station costs for a WWTP in thousands of dollars

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas pretreatment</td>
<td>$354.3</td>
</tr>
<tr>
<td>1.3-MW PEM FC</td>
<td>$743.3</td>
</tr>
<tr>
<td>SMR system</td>
<td>$1171.2</td>
</tr>
<tr>
<td>Low-pressure compressor</td>
<td>$208.0</td>
</tr>
<tr>
<td>High-pressure compressor</td>
<td>$47.2</td>
</tr>
<tr>
<td>Low-pressure storage</td>
<td>$10.6</td>
</tr>
<tr>
<td>High-pressure Cascade storage</td>
<td>$44.5</td>
</tr>
<tr>
<td>Refrigeration system</td>
<td>$69.0</td>
</tr>
<tr>
<td>Dispenser</td>
<td>$165.0</td>
</tr>
<tr>
<td>DC/AC inverter</td>
<td>$358.3</td>
</tr>
<tr>
<td>Heat recovery system</td>
<td>$55.9</td>
</tr>
<tr>
<td>Electrical and controls</td>
<td>$161.3</td>
</tr>
<tr>
<td>Mechanical and piping</td>
<td>$166.7</td>
</tr>
<tr>
<td>Total Capex</td>
<td>$3555.39</td>
</tr>
<tr>
<td>Installation costs (20 %)</td>
<td>$711.1</td>
</tr>
<tr>
<td>Total installed costs</td>
<td>$4266.5</td>
</tr>
</tbody>
</table>

**Installation Costs**

The cost of installation is a significant fraction of the total project costs. The NREL technical peer review team\(^\text{18}\) recommended installation costs between 20% (Optimistic case) and 30% (base case) of the project capital costs. We use an installation factor of 20% in the model.

**Summary Costs**

The total system capital costs of $3.6 million are summarized in Table E.7, with a total installed cost of $4.27 million.