

Wind-to-Wheel Energy Assessment

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Abstract

Hydrogen generation, battery electric storage, and compressed air energy storage are compared on an efficiency basis for effectively applying renewable electric energy to transportation goals. Results are presented as a driving range, in kilometers, achievable with a uniform input of 100 MJ of wind-generated, AC electricity to each type of energy storage technology. Lithium-ion battery electric vehicles can achieve up to 133 km of range with this input. In contrast, compressed air cars and fuel cell vehicles achieve 46 and 42 kilometers, respectively, with the same 100 MJ of input electricity. The vehicle ranges are compared for Taurus-class vehicles driving in a standard urban drive cycle.

Introduction

Renewable energy technologies are quickly penetrating the energy generation market, principally in response to an urgent need to reduce greenhouse gases (GHGs) released into the atmosphere. Central energy generators like megawatt-scale wind turbines, run-of-the-river hydroelectric plants, tidal and wave stations are well-suited to integrate into the electric grid. But how can these new resources be best used to displace the GHGs produced by the worldwide fleet of gasoline and diesel-fueled vehicles?

Even solar photovoltaic energy, well-suited for distributed applications, cannot power an independent, consumer-friendly vehicle directly. The energy density required for the automotive performance expected by consumers is simply too high to be available through commercially achievable photovoltaic products. Vehicles restricted to tracks can utilize energy transmitted from larger solar power installations or other renewable technologies, but independent vehicles always require energy storage.

As pressure grows to curtail the GHG emissions of vehicles, most of the resources considered for the purpose will be the same electric generating technologies currently being added to the power grid. So the questions and answers that will guide new vehicle development boil down almost entirely to comparative analyses of energy *storage* technologies.

In this paper, we demonstrate such a comparative analysis by placing various energy storage technologies in the context of a single system boundary that begins at the terminals of any electric generator, and ends at a uniform work product: moving a Ford Taurus-class car through an urban drive cycle.

System Boundary

The inputs of the evaluated transportation systems are at the AC electric output terminals of the wind turbine or equivalent electric generator. To create a fair comparison of the transportation systems, all are assumed to consume 100 MJ at the terminals.

The presumption is that the electric output is highly variable depending on wind conditions, such that all input energy must be stored aboard the vehicle. This makes the analysis valid for nearly any renewable energy technology having electricity as its native output. Most renewable resources qualify for this criterion, with the exception of liquefied biomass (biofuels). The environmental impacts of biofuel manufacture are not directly comparable with those of the electric-generating resources and are not considered in this article.

The outputs of the evaluated transportation systems are the quantity of kilometers traveled in a standardized, urban driving cycle. Accordingly, the output/input performance of each technology can be expressed as an “overall fuel efficiency” in km/MJ, with higher fuel efficiency values representing higher performance.

The presumption is that all vehicles are the same, Taurus-class vehicle. Hence, the boundary of each *unique* energy storage technology ends at the vehicle drive shaft. In theory, the output/input performance of each technology could be expressed as a unitless ratio (MJ at the drive shaft)/(MJ at the wind turbine) and the ratios between results would remain unchanged. The additional factor of the uniform MJ-to-km translation associated with the Taurus-class vehicle simply makes the physical values of the outcomes more intuitive to the reader.

Energy Storage Technologies

Three methods of energy storage are evaluated for this comparison: chemical storage in the form of hydrogen gas, electrical storage in batteries, and mechanical storage in compressed air. System diagrams representing the three paradigms are presented in Figure 1. For each, we briefly describe efficiency losses in the associated fuel chain, from the wind turbine to the automobile’s drive shaft.

Hydrogen Vehicles

The two hydrogen vehicles evaluated share an assumption of hydrogen generated by electrolysis at local “filling” stations. A previous analysis [1] demonstrated that the efficiency differences between local and centralized hydrogen production are inconsequential and can be ignored. Specifically, compressed hydrogen gas can flow through large pipelines with a loss of about 0.77% per 100 km [2], while high voltage DC experiences a loss of perhaps 0.6% per 100 km [3].

The two types of hydrogen vehicle considered are a fuel cell vehicle (FCV) and a hydrogen-burning, internal combustion engine vehicle (ICEV). FCVs extract the chemical energy in the hydrogen gas through controlled oxidation process in an electrochemical cell. IC-EVs extract the energy from hydrogen using a traditional, spark-ignition heat engine to combust the gas in the same manner as modern cars are fuelled by gasoline. IC-EVs are not considered a likely, ultimate technology for extracting transportation energy from hydrogen gas, but could play an important, intermediate role before FCVs become commercializable.

Figure 2 shows the energy losses on the fuel path from original wind energy to a typical FCV's driveshaft. Electrolysis is assumed to be 80% efficient, based on an intermediate value between the 74% reported for the most efficient commercial electrolyzer available today [4] and the 90% reported in the most optimistic projections of achievable efficiency (e.g. [5]). Hydrogen compression to 350 bar is calculated from first principles to be 92% efficient, an intermediate value between single-stage adiabatic compression and the isothermal ideal. The fuel cell is assumed to transform 50% of the hydrogen's chemical energy to electricity, the highest realistically achievable value [6].

Battery Electric Vehicles

Battery electric vehicles (BEVs) are presumed to be charged directly from the same electric grid that supports the hypothetical wind turbine energy source. In fact a large, grid-connected BEV fleet can perform an important grid service by providing direct energy storage for intermittent, renewable energy resources like wind.

Two types of battery are considered in this analysis: nickel metal hydride (NiMH) and lithium ion (Li-ion). NiMH batteries are the current favored battery chemistry for automotive applications; Li-ion batteries are a less mature technology with significantly better characteristics that most analysts believe is the likely, ultimate chemistry for long-range automotive applications [7]. Li-ion batteries are quickly maturing, driven primarily by the portable electronics market that already favors them for nearly every application.[8]

Figure 3 shows the energy losses associated with a BEV fuel chain, again beginning with the basic assumption of original wind power. There are no losses equivalent to the electrolysis and compression associated with hydrogen, because it is not necessary to convert the native electric output of wind turbines to a different energy form. There is an additional 6% loss due to electric distribution, since BEVs are charged on a completely distributed (residential) electric grid, while hydrogen is generated at local filling stations that can be located on high-voltage trunk or feeder lines. Another 5% loss is due to heat generated by the rectifier that converts the grid AC power to DC needed for charging the car battery.

The car battery has a native loss known as self-discharge, that is strongly dependent on use patterns. We assume an 8% self-discharge loss, a very high value equivalent to leaving a Li-ion vehicle standing one to two months between drives.

Air Cars

One other technology that has been receiving attention recently is compressed air energy storage. The paradigm would most likely be implemented similarly to the hydrogen paradigm, in which electric energy is transmitted to local filling stations that compress air and transfer it to vehicles. Compressing air produces substantial heat which is lost to the atmosphere, but some of this heat can be recovered when the car operates. The compressed air powers the car with expansion turbines; the air exhausting from the turbines is extremely cold due to the basic thermodynamics associated with rapid expansion of a gas. By using a multi-stage expansion turbine with heat exchangers between the stages, the cold air can be reheated at each stage to extract energy from the ambient atmosphere before being expanded through the next turbine.

Designing a commercially acceptable air car will still require overcoming engineering hurdles associated with ice formation and inter-stage heat exchange efficiency. Both of

these problems can be solved by cofiring the compressed air with a combustible fuel; the more complex efficiency analysis associated with this arrangement is not treated in this paper.

For our analysis we presume a very optimistic fuel chain, based on an air compression pressure of 300 bar, four-stage air compression with intercooling and four-stage expansion with heat exchange from the ambient air. Figure 4 shows the energy losses associated with such a compressed-air vehicle. Compression to 300 bar is an energy-intensive operation that leaves only 46% of the energy used present in the final compressed air (once it has cooled to ambient temperature). In comparison, the four-stage expansion turbine operates much more efficiently at 84%, since most of its thermodynamic losses can be recovered from heat in the ambient air [9].

Note that compression of air appears profoundly less efficient than compression of hydrogen in our analysis. This is an illusion. Electrical energy is stored in hydrogen by electrolysis of water. Relatively small volumes of the energetic gas have to be compacted for better handling. On the other hand, electrical energy is stored by pressurizing large volumes of air. Air compression is the energy storage, while the compression of hydrogen is a matter of convenience. However, because of the different densities hydrogen compression requires 15 times more energy than air compression for identical initial volumes and identical pressure limits. For hydrogen, the main losses are associated with electrolysis and fuel cell, while the heat generated in the process of compacting air is considered a loss in this context. However, the waste heat could be recovered and used for water and space heating by operating the compressor in a cogeneration mode.

Application to Vehicles

To compare the performance of these fuels we begin with Taurus-class vehicle modeling published in 2001 by DeLucchi & Lipman [10]. Their modeling approach accounts for the complex interactions of the vehicle's physical behavior and on-board energy consumption, with the primary energy source. DeLucchi & Lipman focused on electric vehicles, and our calculated BEV ranges are based directly on their conclusions. For FCVs and air cars, we couple the energy storage component efficiencies described above with the Taurus-class shaft energy requirements calculated by DeLucchi & Lipman.

Results

The results for all five vehicles evaluated are displayed in Figure 5. For each hypothesized vehicle the figure displays the driving distance achieved with the same 100 MJ of original electricity. 100 MJ is an arbitrarily chosen quantity that allows an intuitive comparison of the technologies. The length of each horizontal bar in the figure is proportional to the driving distance possible in the U.S. Environmental Protection Agency's urban driving cycle, with each technology after energy transmission and storage.

The NiMH and Li-ion battery electric technologies, able to drive 127 and 133 kilometers respectively, stand out in their performance over the others. In contrast, a nominal, high-performance FCV achieves only 42 km of range with the same input energy. Despite our optimistic estimates of FCV component efficiencies, our results may seem to fall short of some of the more hopeful figures published in the literature. For instance, Ogden,

Williams & Larson [11] report an efficiency for FCVs that would yield a range of 69 km when treated in our analysis. The main reason for the discrepancy is that our analysis uniformly assumes a very heavy, Taurus-class vehicle, while Ogden *et al* and other authors assume smaller vehicles in their work. It is the relative ranges that matter; repeating this study using a smaller nominal vehicle would produce roughly the same performance ratios between the different technologies.

Compressed air vehicles, if engineering hurdles can be overcome, promise an efficiency equal to that of FCVs. However, the lower energy density of compressed air will limit the maximum range of such cars to values appropriate only for in-city commuting.

Conclusions

Renewable energy resources still make up a relatively small fraction of generation, and need to be put to use as effectively as possible. This analysis makes clear that in the transportation sector, the most effective method for getting wind energy to the road is a battery-electric fuel chain. Specifically, Li-ion batteries show promise for cars that can perform 60% better (on a range basis) than the prevailing, NiMH battery type, and that can achieve three times the range of a fuel cell vehicle, on the same original wind turbine output.

It is also worth noting that even the most benign energy resources still have environmental impact; for instance wind energy has well-known visual impacts, can lead to unwanted roads development, and implemented on massive scale is likely to alter regional climates.[12] A 100-turbine wind farm that supports a Li-ion BEV fleet, would need to be replaced with a 300-turbine farm to support an equally sized FCV fleet. Clearly, there are both economic and environmental reasons to question the wisdom of such a choice.

References

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Figures

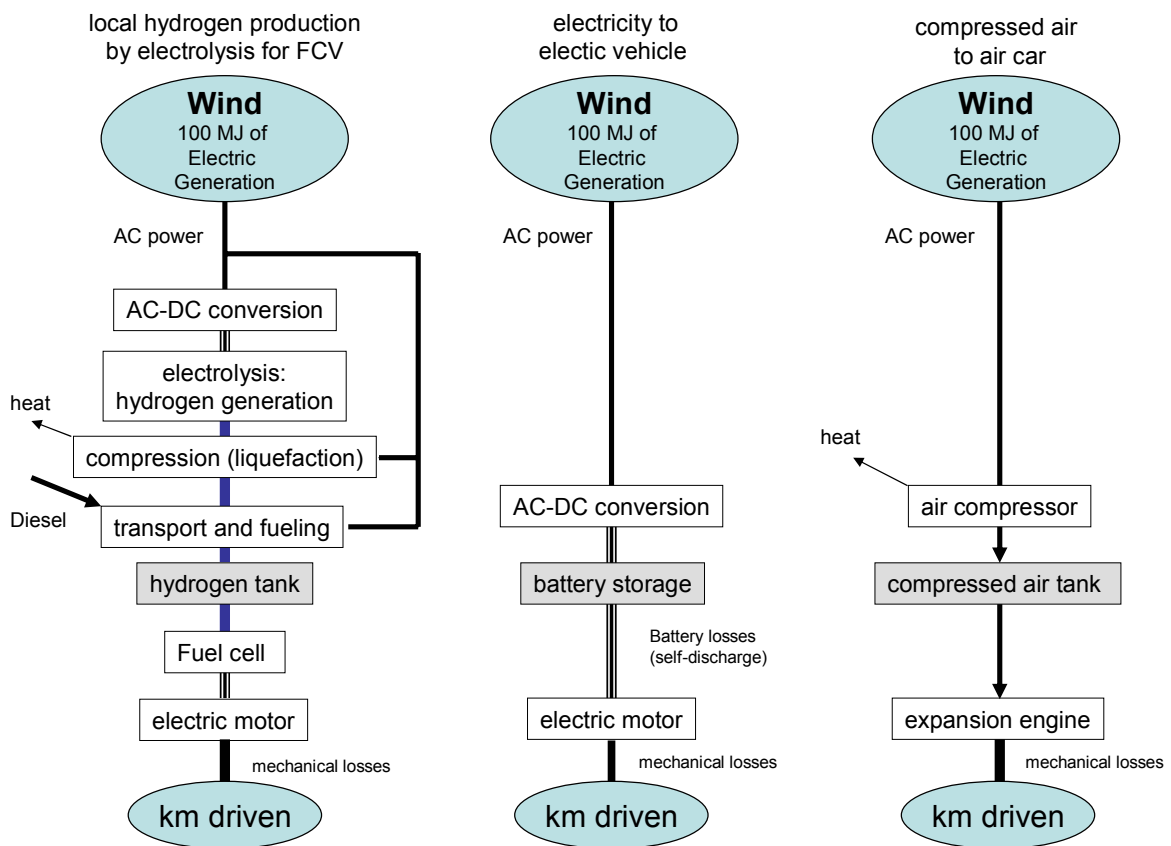


Figure 1 System diagrams describing vehicle fuel cycles for hydrogen, battery and compressed air energy storage

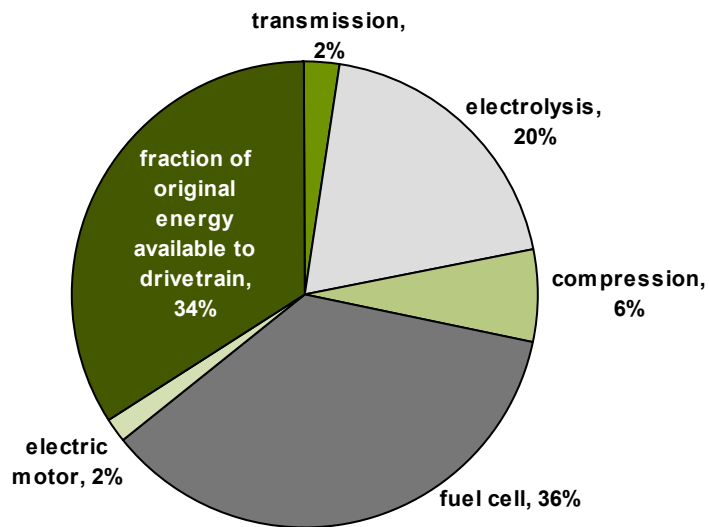


Figure 2 Energy losses on the FCV fuel path. Because the efficiencies multiply along the fuel chain, each step's *apparent* efficiency depends on its position in the chain: the further down the chain, the smaller that step's toll on overall efficiency

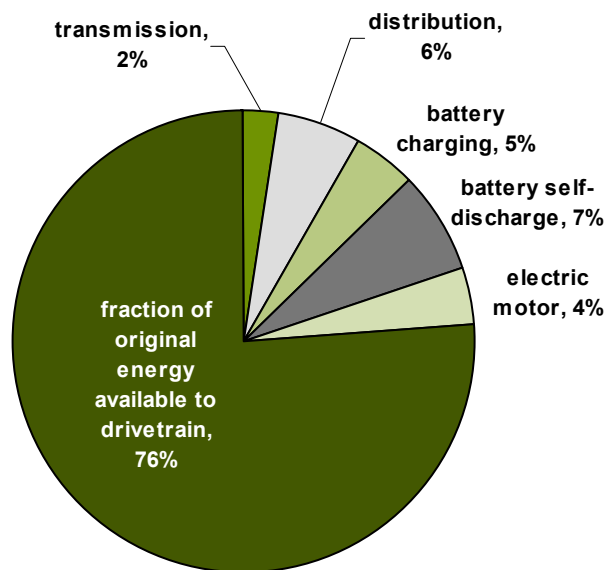


Figure 3 Energy losses on the Li-ion BEV fuel path

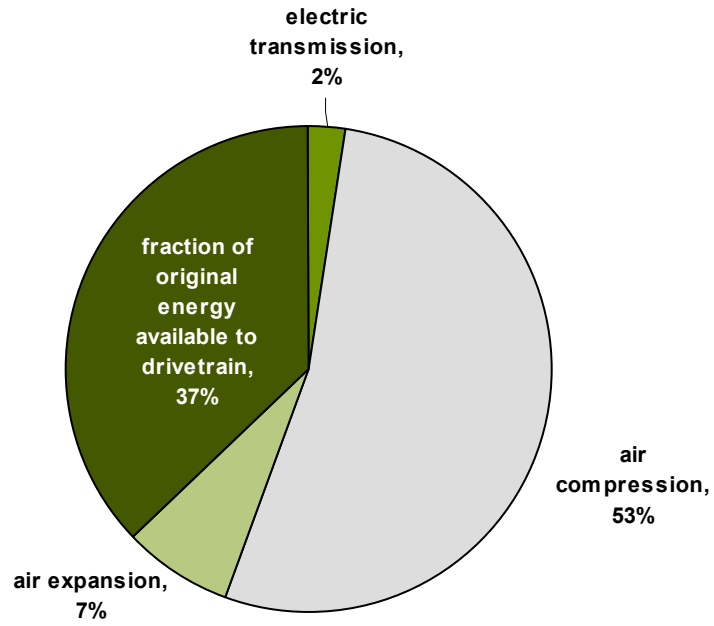


Figure 4 Energy losses on the compressed air car fuel path

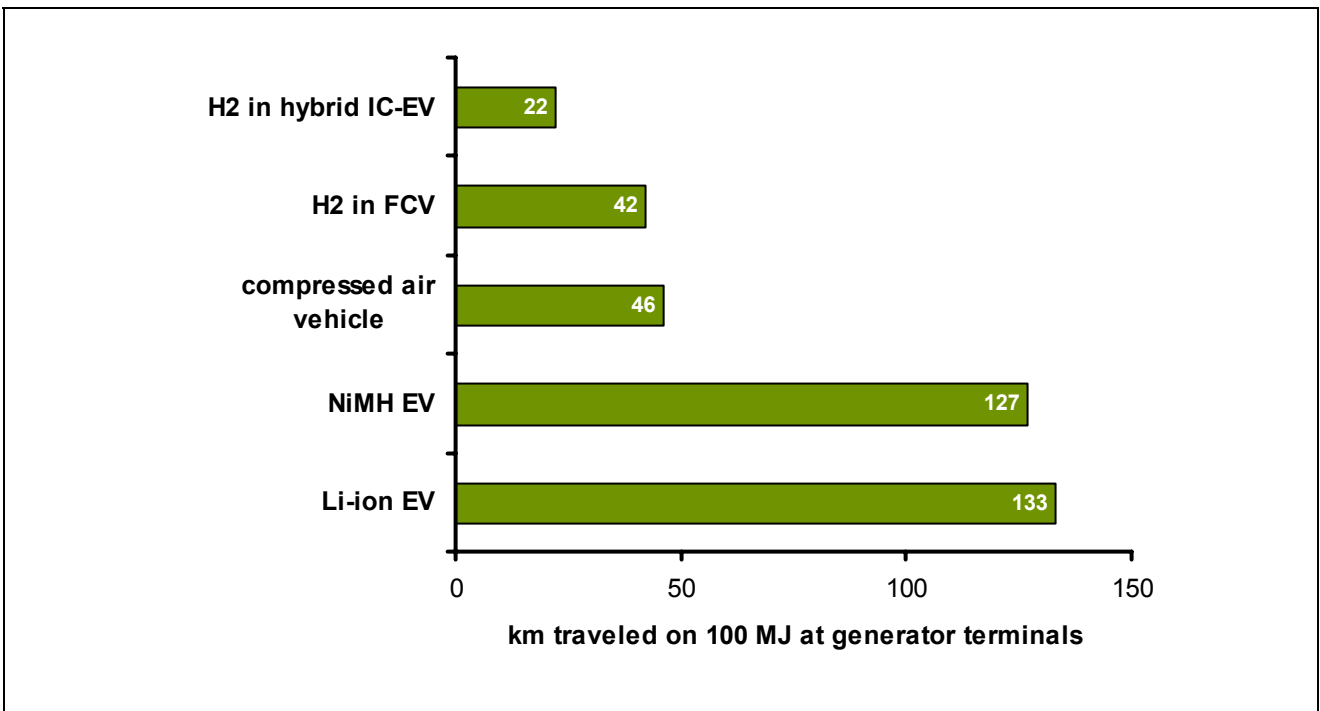


Figure 5 Kilometers traveled on an equal amount of original electricity