CHAPTER NINE

Fuel Cell Electric Vehicles, Battery Electric Vehicles, and their Impact on Energy Storage Technologies: An Overview

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1. INTRODUCTION

In contrast to vehicles powered by a conventional fossil fuel- or biofuel-based ICE, the energy storage system is of crucial importance for electric vehicles (EVs). Two major options exist: one is the storage of electrical energy using batteries, the other one is the storage of energy in form of hydrogen.

The development of such EV concepts has a very long tradition at General Motors (GM) and Opel, regardless whether fuel cell electric vehicles (FCEVs), pure battery electric vehicles (BEVs), or hybrid variants are concerned. For instance, the world's first fuel cellEV, the GM Electrovan of 1966 was developed and designed by GM. Over the course of the late 1990s, this technology was revived and reintroduced within the framework of a large-scale development program. These efforts lead to the development of the current GM HydroGen4 fuel cell car, a mid-sized crossover vehicle based on the Chevrolet Equinox.

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Also during the 1990s, a large development effort on pure BEVs was initiated. These automobiles were deployed to large-scale demonstration projects (e.g., the Opel Impuls to the so-called "Rügen-Projekt" on the German island of Rügen in the Baltic Sea, and to the Aachen area [1]). But also mass-produced EVs were designed and brought to the market on a lease basis, namely, the GM EV1.

The depletion of the fossil resources and the climatic change caused by anthropogenic CO_2 emissions have again made the development of zero-emission vehicles get more and more important in the last few years. For all projects carried out by Opel and GM in this field, the GM Alternative Propulsion Center Europe in Mainz-Kastel (Germany) played an important and central role [2]. In the context of this chapter, the latest vehicle projects like the GM HydroGen4 and the Chevrolet Volt (as well as the respective VOLTEC powertrain system) are introduced and discussed. The effects on the fuel infrastructure will also be evaluated.

2. THE BROADER CONTEXT FOR AUTOMOTIVE TECHNOLOGY DEVELOPMENT

Approximately 900 million vehicles worldwide are on the roads today. About 96% of the fuel used for propulsion purposes is thereby produced from fossil sources of energy. There are estimates for the year 2020 that the number mentioned above will increase to approximately 1.1 billion vehicles, in particular due to the economic expansion and industrial development of India and China. This will inevitably have consequences for global crude oil demand and for the worldwide CO_2 emissions. Since an increase in demand of oil and CO_2 production proportional to the projected number of vehicles is not sustainable for financial, ecological, and political reasons, every implementation strategy must aim at the replacement of fossil fuels as a source of energy for automotive applications.

Therefore, a key element of GM's advanced propulsion strategy is the electrification of the automobile, respectively, the displacement of gasoline by alternative energy carriers (see Figure 9.1). That leads to reduced fuel consumption, reduced emissions, and also to increased energy security via geographic diversification of the available energy sources. At GM, this strategy has its roots with the introduction of the first modern EV, the 1996 GM EV1. The EV1 was a pure BEV produced in small series for the "average Joe" driver. Unfortunately, the market experience with the EV1 and its initial lessees indicated that further significant improvements in BEV technology were needed. Some EV1 drivers coined the term "range anxiety" describing their omnipresent concern or even fear of becoming stranded with a discharged battery in a limited-range vehicle, away from the electric infrastructure. Hence, improvements in onboard energy storage (directly proportional to vehicle range) and, in particular, charging time were assessed to be essential for a more widespread deployment of BEVs. Due to these constraints, pure BEVs have not reached the commercial mass market until now. However, most of the EV-enabling electric

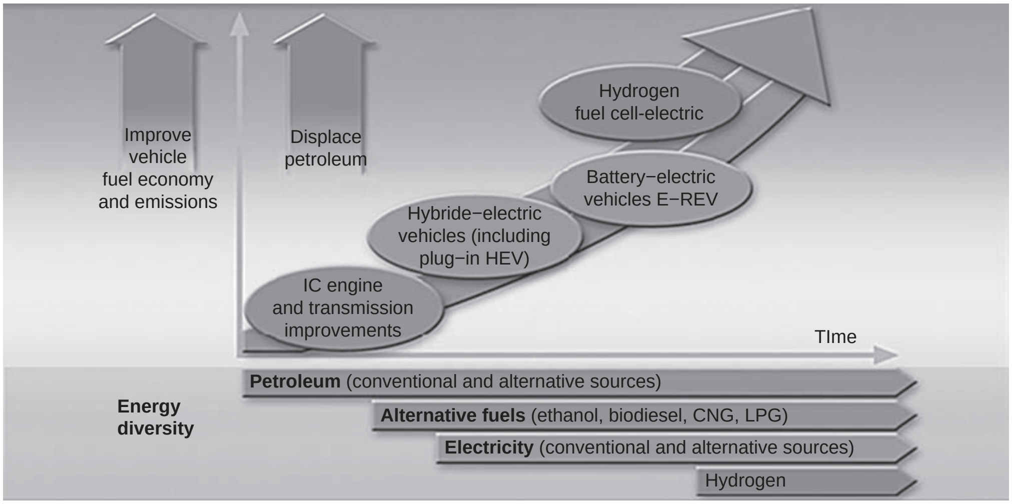


Figure 9.1 GM's advanced propulsion strategy.

components and systems have found utility in the meantime by adapting them for the usage in mild and full hybrid electric vehicles (HEVs). Such vehicles do not provide full power by exclusively using the electric motor, and therefore the power and energy level requirements for the system components are reduced in comparison to a conventional BEV. In addition, while conventional hybrids (both mild and full) improve vehicle efficiency (thus reduce gasoline consumption, and thereby, CO_2 emissions), all the energy they consume is generated from an onboard liquid medium. The onboard electrical engine and the storage system are only used to shift the operating point of the ICE to a more favorable point on the efficiency map and to enable recuperation. Thus, HEVs provide unfortunately not any additional pathways to utilize CO_2-neutral renewable energy sources. Partially, these drawbacks may be resolved by introducing so-called extended-range electric vehicles (E-REVs) that are discussed in the following sections.

Zero-emission vehicles using an electric powertrain system based on hydrogen fuel cells or purely battery–electric systems that are fully competitive to conventional vehicles regarding performance and ease-of-use represent the ultimate target of the GM strategy (see Figure 9.1). A further important step into this direction is the start of mass production of the Chevrolet Volt at the end of 2010, as well as the introduction of other vehicles like the Opel Ampera which are also based on the VOLTEC technology [2].

3. FCEV AND BEV—TWO COMPETING CONCEPTS?

Within the general public and also within the automotive and fuels community very often the impression is created that an exclusive decision has to be made between FCEV and BEV, as question of either/or. However, this is definitely not the case since

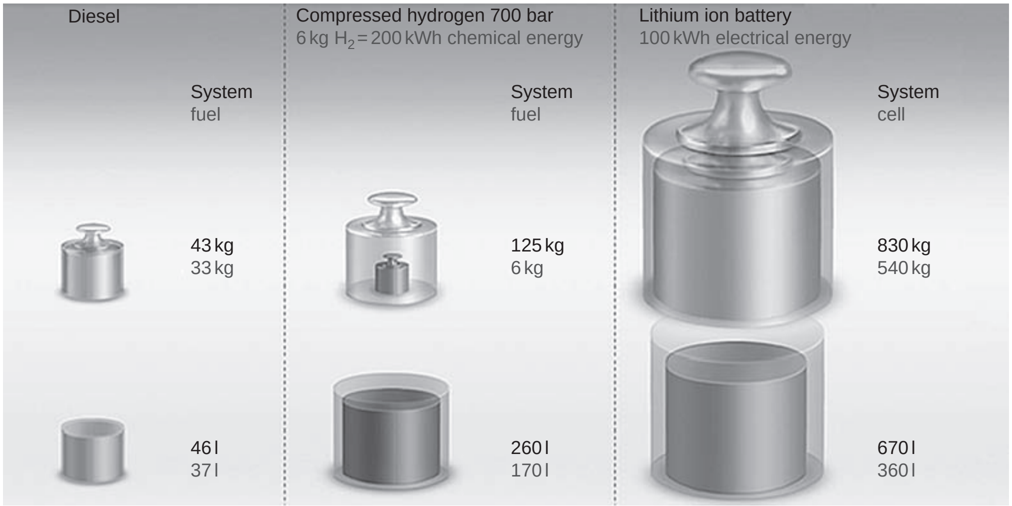


Figure 9.2 Energy storage system weight and volumes for various energy carriers.

these technologies address different areas of the vehicle market. This is due to the extremely different energy densities of the applied energy carriers (see Figure 9.2).

To realize a vehicle with a range of 500 km, using today's diesel technology, a tank system that weighs approximately 43 kg and requires a volume of just less than 50 l is needed. To realize a corresponding zero-emission vehicle on hydrogen basis, one has to build on a system weighing about 125 kg (based on a 700 bar compressed gaseous hydrogen vessel). The energy storage gets even heavier if a future highly advanced lithium-ion (Li-ion) battery system (usable system energy density: 120 Wh/kg; current technology is closer to 85 Wh/kg) would be implemented (see Figure 9.2): the weight of the energy storage system would be just below one metric ton to provide a range of 500 km. Furthermore, a hydrogen tank can be refilled completely within 3–5 min, very similar to a conventional diesel tank. In contrast, recharging a battery can take—depending on the available infrastructure and battery size—from hours (50 kW fast charging point) up to many hours or even to a whole day (conventional 230 V/16 A electrical outlet).

Projections show that a hydrogen tank system for a vehicle range of 500 km could be manufactured for approximately US$ 3,000 at high-volume production; on the other hand, a comparable 100 kWh battery would cost approximately US$ 50,000.

Therefore, it makes sense to develop and use a BEV for a driving and duty cycle for which a smaller battery and a lower range is sufficient and viable. The impact of the energy storage densities and drive cycles, respectively, duty cycles on an appropriate propulsion technology is shown in Figure 9.3. The pure battery vehicle is the technology of choice for small urban vehicles with ranges up to 150 km. A so-called E-REV such as

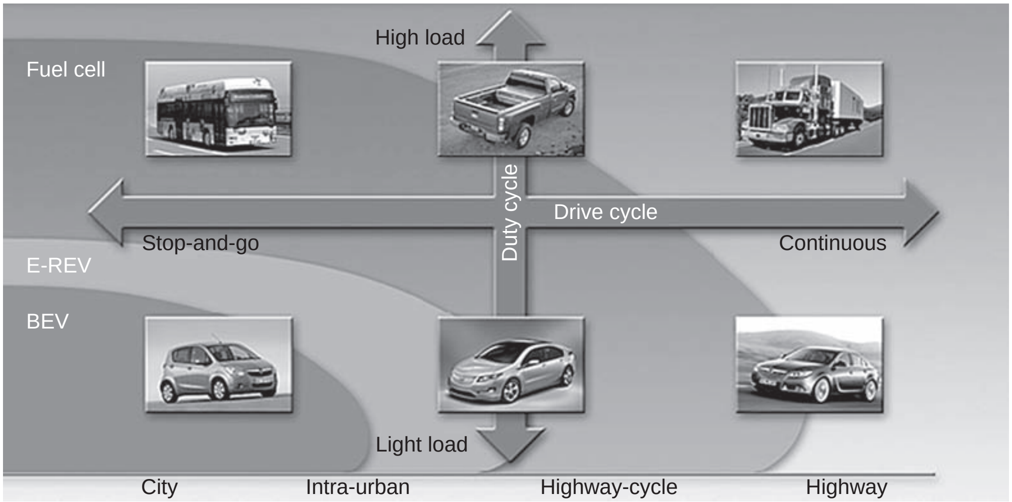


Figure 9.3 Application map for various EV technologies.

the Chevrolet Volt or the Opel Ampera is perfectly suited for those customers who need sometimes—but not too often—longer ranges of up to 500 km; and for those who are willing to accept a small ICE in order to ensure the range beyond the initial 60 km of pure EV operation. On the other hand, hydrogen fuel cell vehicles offer a different kind of advantages: they are always operated as zero emission, can be refueled within 3–5 min, and offer a long range of about 500 km at full performance for family-sized cars.

Due to its comparatively high-energy density of 1600 Wh/kg of tank system weight, hydrogen is the ideal energy carrier to serve as intermediate store of fluctuating renewable energy such as solar and wind power, and to enable the usage of this green energy as transportation fuel. Early commercialization of the automotive fuel cell technology is planned to start in between 2015 and 2020.

Hence, depending on the required operating range, a future electric powertrain will either be combined with just a battery (BEV), or the needed energy for longer ranges will be provided by an ICE-generator set (E-REV) or by a high-performance fuel cell (FCEV). These latter concepts will be introduced and discussed in detail in Sections 4 and 5.

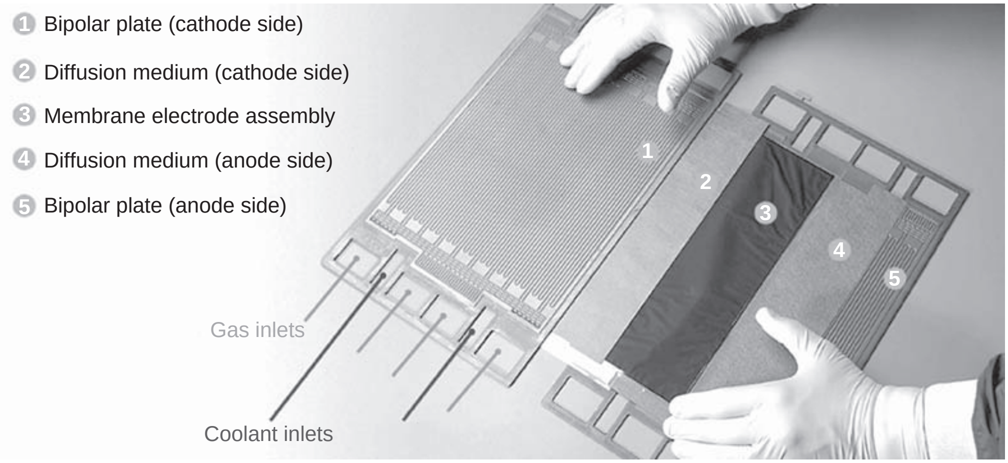
4. FUEL CELL ELECTRIC VEHICLES

As already mentioned, GM has a long history of innovations within the field of hydrogen technology: the world's first fuel cell car, the Electrovan (1966), was developed by GM. This vehicle was equipped with an alkaline fuel cell (AFC) and two cryogenic tank vessels for liquid hydrogen and liquid oxygen [3].

The fuel cell stack represents the core component of the complete fuel cell power system. There is a wide range of fuel cells available, including mid- and high-temperature fuel cells. However, only low-temperature fuel cells working with a proton-conducting polymer membrane (proton exchange membrane, PEM) are viable for automotive applications. PEM fuel cells combine a comparatively low operating temperature, typically between 60 and 80°C, with a high-power density, the option of conventional air operation, and the potential of being manufactured at low cost. PEM fuel cell-based power systems provide similar performance features as ICEs, with which they are competing. The fuel cell stack is built up from hundreds of single cells (see Figure 9.4a) and—like a battery—it directly converts chemical energy into electrical energy.

The "fuel," however, is not contained in the electrode, but supplied to the electrode from a separate subsystem. As long as fuel and oxidant are supplied to the fuel cell at sufficient quantities, the generation of electrical energy is ensured. The challenge consists in evenly supplying all single cells of the stack with fuel and also in removing the reaction (or waste) products properly. In the case of a hydrogen PEM fuel cell, the waste product is just pure water.

(A)



(B)

(a) Acidic electrolyte, e.g. in case of a PEMFC:		(b) Alkaline electrolyte, e.g., in case of an AFC:
$H_2 \rightarrow 2H^+ + 2e^-$	anode reaction	$H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$
$2H^+ + 2e^- + 1/2O_2 \rightarrow H_2O$	cathode reaction	$1/2O_2 + 2e^- + H_2O \rightarrow 2OH^-$
$H_2 + 1/2O_2 \rightarrow H_2O$		$H_2 + 1/2O_2 \rightarrow H_2O$

Figure 9.4 (A) Setup of PEM fuel cell; (B) chemical reactions at the electrodes.

After the technology transition from AFCs to PEM fuel cells, the various generations of HydroGen1 to HydroGen4 were developed. The integration of the fuel cell system into vehicles can be done similarly to the integration of ICEs. It has been demonstrated that sufficiently powerful and compact drivetrains could be realized. The fuel cell system and the electric traction system of the GM HydroGen3 were packaged in a way that they fitted into the same volume as an ICE propulsion module; even the same mounts could be used. Such an integrated fuel cell module (population dresss-up module, PDU) allows the simple and cost efficient vehicle assembly in existing facilities. Thus, PDUs are a probable technology scenario for the introduction of volume production on the basis of existing platforms. There is, however, no technical restriction that would rule out a completely different configuration of the fuel cell powertrain components on board of the vehicle.

The scalability of fuel cell systems also facilitates the adaptation to different vehicle sizes (see Figure 9.5). One example is the fuel cell system that was originally developed for the GM HydroGen3 van, and afterward was adapted to a small vehicle, the Suzuki MR Wagon FCV, using a shorter fuel cell stack with reduced cell count. Eventually, it was adapted to a GMT800 truck by doubling the stack and some other components [2].

Here 70 MPa CGH_2 (compressed gaseous hydrogen) storage systems are state of the art since the public presentation of the HydroGen3. As shown in Figure 9.2, 1,600 Wh/kg can be achieved for such a single-vessel tank system. Typically, 4–7 kg of hydrogen have to be stored onboard. This remains to be a significant issue for the vehicle integration. Furthermore, cylindrical vessels are required for CGH_2 fuel storage. In existing vehicles, without modifications, there is not enough space for hydrogen storage devices that could provide a range comparable to conventional vehicles. Hence, rear body modifications are necessary to integrate the hydrogen storage vessel(s). In an extreme case, one could imagine concepts where the car is built around the hydrogen storage. Vehicle designers at GM have developed the Chevrolet Sequel concept car (see Figure 9.6a) providing enough space for three large 70 MPa CGH_2 vessels (total fuel capacity: 8 kg of hydrogen). By doing so, for the very first time, an FCEV operating range of significantly more than 300 miles could be achieved and demonstrated even on public roads between suburban Rochester and New

Figure 9.5 The GM HydroGen3 system architecture (60 kW at the wheels) has been scaled down for the integration into a Suzuki MR Wagon FCV (38 kW at the wheels), and scaled up for the propulsion of a Chevrolet Silverado military truck (120 kW at the wheels).

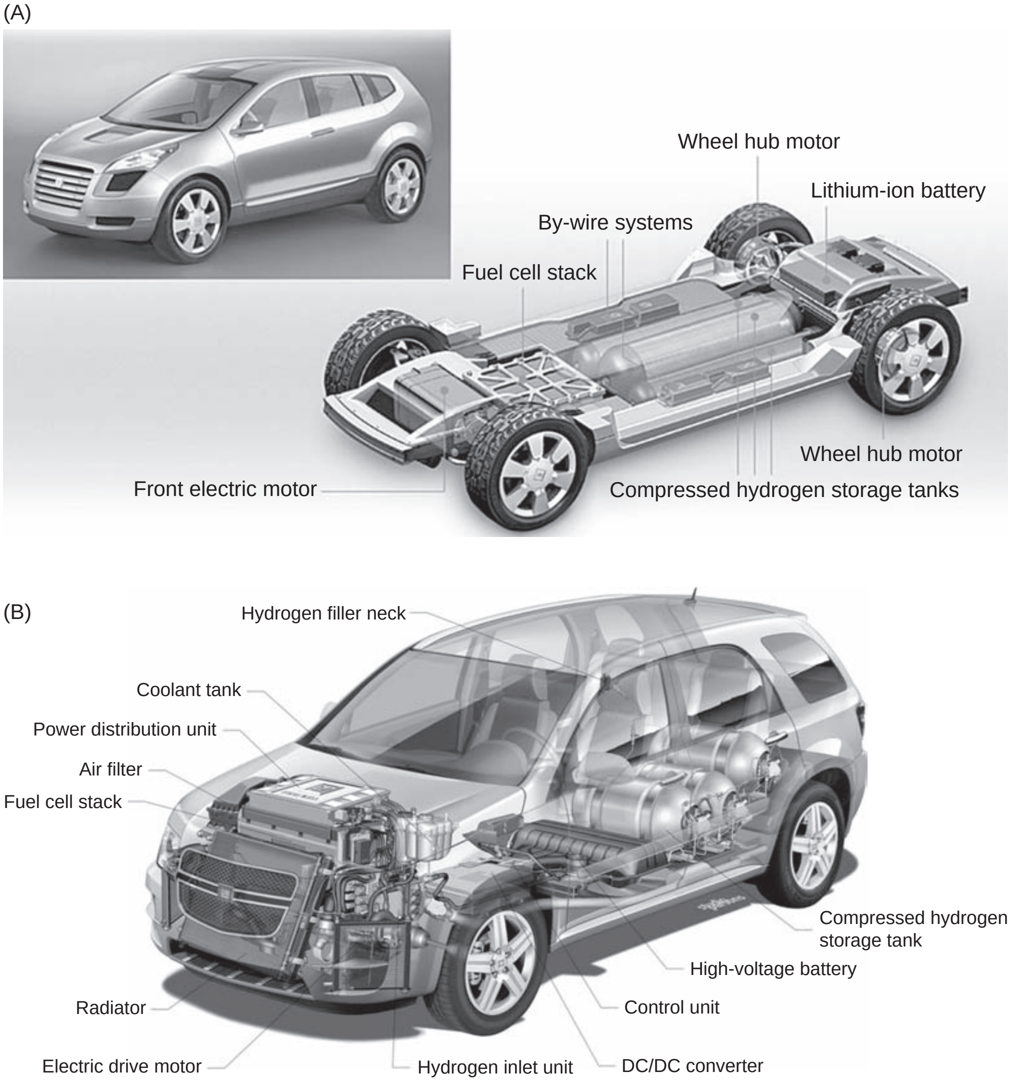


Figure 9.6 (A) GM Sequel and the skateboard chassis; (B) GM HydroGen4 vehicle.

York City in May 2007. The fuel cell system of the Sequel has been packaged into the vehicle underbody as well, offering flexibility for the interior design. Although the Sequel is only a concept vehicle with no production intent at this time, one may imagine that vehicles one day will be developed and optimized for the specific characteristics and opportunities that fuel cells and H_2 can offer.

Since autumn 2007, within the framework of "Project Driveway", more than 100 cars of the current generation HydroGen4 (Figure 9.6b) were deployed to demonstration projects all over the world (e.g., in the United States and in Germany). These

Table 9.1 Technical specifications of the GM HydroGen4

GM HydroGen4	
Vehicle type	Five-door, crossover vehicle, front-wheel drive, based on the Chevrolet Equinox
Dimensions	
Length	4,796 mm
Width	1,814 mm
Height	1,760 mm
Wheelbase	2,858 mm
Trunk space	906 Liter
Weight	2,010 kg
Payload	340 kg
Hydrogen storage system	
Type	3 Type IV CGH_2 vessels
Operating pressure	70 MPa
Capacity	4.2 kg
Fuel cell system	
Type	PEM
Cells	440
Power	93 kW
Battery system	
Type	Ni-MH
Power	35 kW
Energy content	1.8 kWh
Electric propulsion system	
Type	Three-phase, synchronous motor
Continuous power	73 kW
Maximum power	94 kW
Maximum torque	320 Nm
Performance	
Top speed	160 km/h
Acceleration (0–100 km/h)	12 s
Range	320 km
Operating temperature	-25°C to +45°C, vehicle can be parked at ambient temperature <0°C (without external heating)

vehicles offer an improved everyday capability and a higher performance than their predecessors (see Table 9.1). For instance, the cars can be both operated and started at very low temperatures, down to −25°C.

The electrical propulsion system provides a maximum torque of 320 N m at the motor and accelerates the HydroGen4 in less than 12 s from 0 to 100 km/h. The continuous power output of the electric motor of 73 kW is sufficient for a maximum speed of 160 km/h; the maximum performance is 93 kW. Three carbon-fiber tanks onboard store 4.2 kg of hydrogen and enable a range of 320 km. The empty hydrogen storage system can be completely refilled within 3 min (according to SAE (Society of Automotive Engineers) J2601 and SAE J2799). To further improve the agility of the vehicle and to increase the efficiency by enabling recuperation, a nickel metal-hydride battery (Ni-MH) with an energy content of 1.8 kWh is also installed onboard.

More than 10,000 customers in four countries drove the 115 HydroGen4 vehicles (10 of these are operated within the "Clean Energy Partnership" in Berlin); more than 80 mainstream drivers have used vehicles for extended periods of 2–3 months. The vehicles went through a total road performance of over 1,600,000 km (status: September 2008). A fuel cell system durability of about 30,000 miles has been demonstrated within Project Driveway, and an updated HydroGen4 system is projected to reach 80,000 miles. Further improvements will be achieved for the 2015–2020 early commercialization timeframe.

The vehicles proved to be more efficient than the comparable conventional Chevrolet Equinox vehicle with gasoline engine by a factor of 2 (EPA (Environmental Protection Agency) Composite cycle, 4.6 l/100 km of gasoline equivalent in comparison with 9.6 l/100 km of gasoline for the Equinox, see Figure 9.7). Particularly passenger vehicles are mostly operated at loads significantly below their rated power: for such operating conditions, the gain in efficiency offered by fuel cells is maximum. However, at very low-power output, even the fuel cell system efficiency sharply drops, while the fuel consumption increases. This is attributed to many balance-of-plant components, such as the air compressor, as they have to be operated even at idle power. At full load, similar to ICEs, the fuel consumption is significantly higher, but the relative drop in efficiency is stronger than for ICEs.

For a detailed discussion of the fuel cell vehicle efficiency and the corresponding values for key components, the authors recommend Ref. [4]. Many aspects of hydrogen storage technology (including alternative storage options) are summarized in Ref. [5].

5. EXTENDED-RANGE ELECTRIC VEHICLES

On the occasion of the North American International Auto Show in 2007 the Chevrolet Volt (see Figure 9.8 and Table 9.2) and the VOLTEC technology were presented for the first time [2]. The Volt is an EV equipped with an additional gasoline engine that is just used to extend the vehicle range beyond the electric range when required (E-REV). Main energy storage is a Li-ion battery with a nominal energy content of 16 kWh (depth-of-discharge is about 50%, i.e., 8 kWh are usable) and a pure battery-electric range of 60 km. The T-shaped battery consists of four modules with more than 220 cells and the complete automotive battery pack weighs approximately 180 kg. That energy storage system was developed by GM in cooperation with the Korean battery cell manufacturer LG Chem.

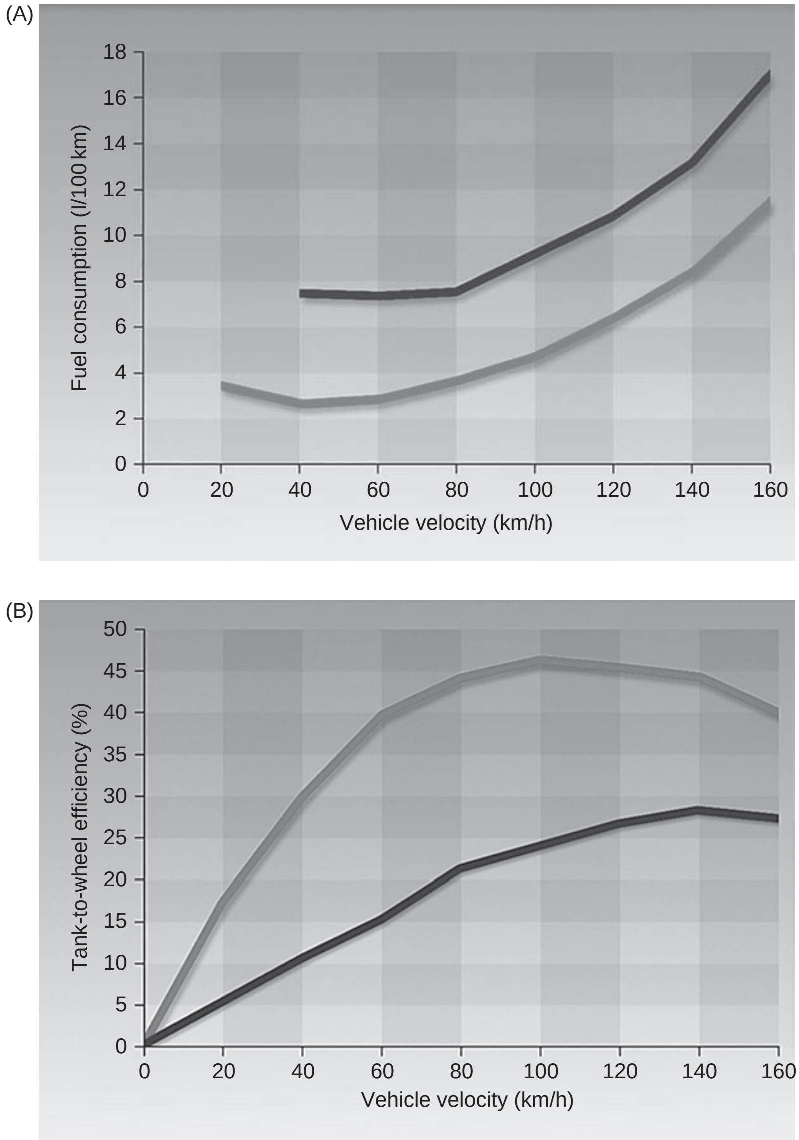


Figure 9.7 (A) Fuel consumption versus vehicle speed for the GM HydroGen4 (lower line) and the conventional ICE version of the Chevrolet Equinox (upper line); (B) efficiency versus vehicle speed for HydroGen4 (upper line) and Equinox (lower line).

The electric powertrain offers a maximum power output of 111 kW and a maximum torque of 370 N m at the motor. This is sufficient to accelerate the Volt from 0 to 100 km/h in less than 9 s and the VOLTEC powertrain enables a top speed of 160 km/h. The nominal size of the battery of 16 kWh was derived from the fact that a vehicle range

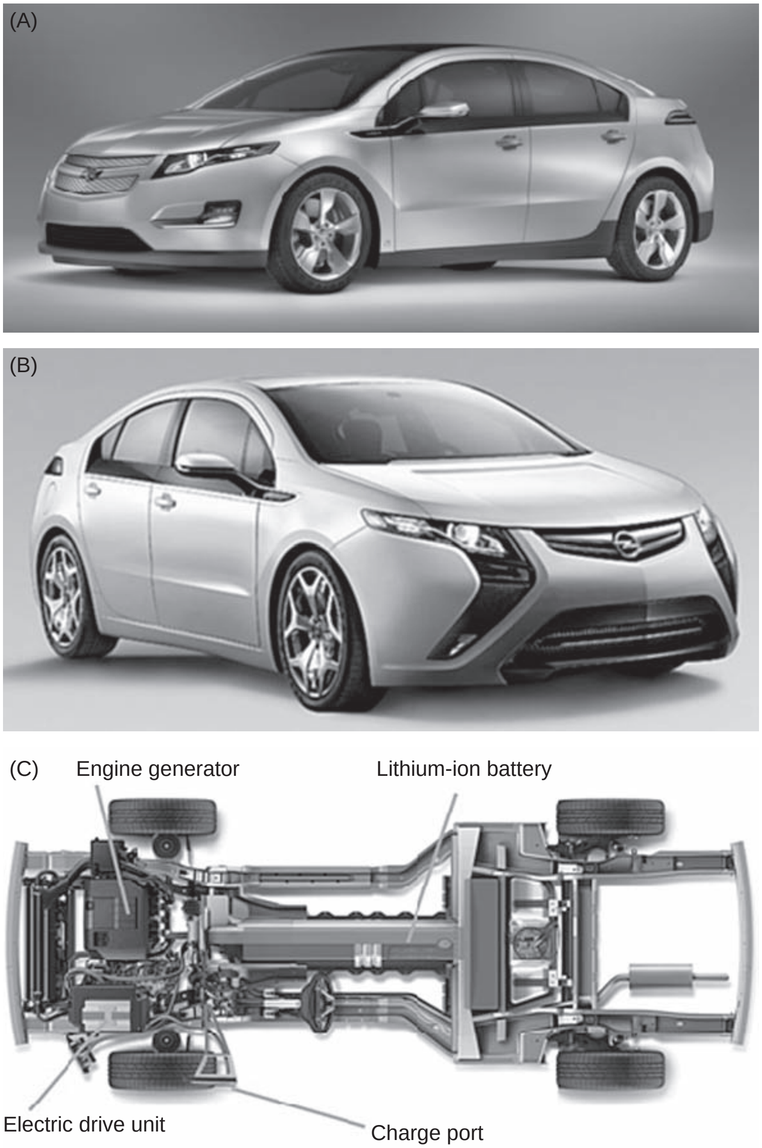


Figure 9.8 (A) Chevrolet Volt, (B) Opel Ampera, and (C) T-shaped battery.

of about 50–60 km is needed to cover at least 80% of the daily driving profiles of regular customers in many countries (as an example data for Germany is given in Figure 9.9). For these distances, the vehicle is operated as a pure electric car and therefore as a zero-emission vehicle. This operating mode is, hence, called "charge-depleting" mode or "EV mode." By limiting the battery size, it is possible to integrate such an extended-range drivetrain concept into GM's global compact architecture (see Figures 9.8 and

Table 9.2 Technical specifications of the Chevrolet Volt

Chevrolet Volt	
Vehicle type	BEV, front-wheel drive; range extender; charging via electrical grid using a standard wall outlet
Dimensions	
Length	4,404 mm
Width	1,798 mm
Height	1,430 mm
Wheelbase	2,685 mm
Battery system	
Type	Li-ion battery
Cells	>220
Weight	180 kg
Length	1.8 m, T-shaped
Power	Provides full performance
Energy content	16 kWh (8 kWh usable)
Electric propulsion system	
Type	Three-phase induction motor
Maximum Power	111 kW
Torque	370 N m
Range extender	
Type	Gasoline, naturally aspirated, 1.4 l displacement, family 0-derivative
Power	53 kW
Performance	
Maximum speed	160 km/h
Acceleration (0–100 km/h)	9 s
Range	Electric range: 60 km; approximately 500 km with range extender

9.10). Doing so, also the total battery costs can be limited since these costs are more or less proportional to the nominal energy content (see Section 3).

An additional advantage of a battery of such dimensions is that the usable 8 kWh of electrical energy could be recharged in just a few hours in Europe, but also in the United States (US standard wall outlet 110 V/16 A: about 6 h; European standard wall outlet 230 V/16 A: about 3 h). On the vehicle side, both Volt and Ampera are equipped with a socket according to SAE J1772. The required cord-set (SAE J1772 plug → country-specific home plug) is carried in the vehicle. In contrast, due to their bigger batteries, pure battery EVs would be dependent on off-board chargers (or even quick-charging stations) applying higher voltage and current levels in order to achieve such acceptable recharging times.

A naturally aspirated family-0 gasoline engine with a displacement of 1.4 l generates 53 kW of electric power that can be utilized when the state of charge drops below a

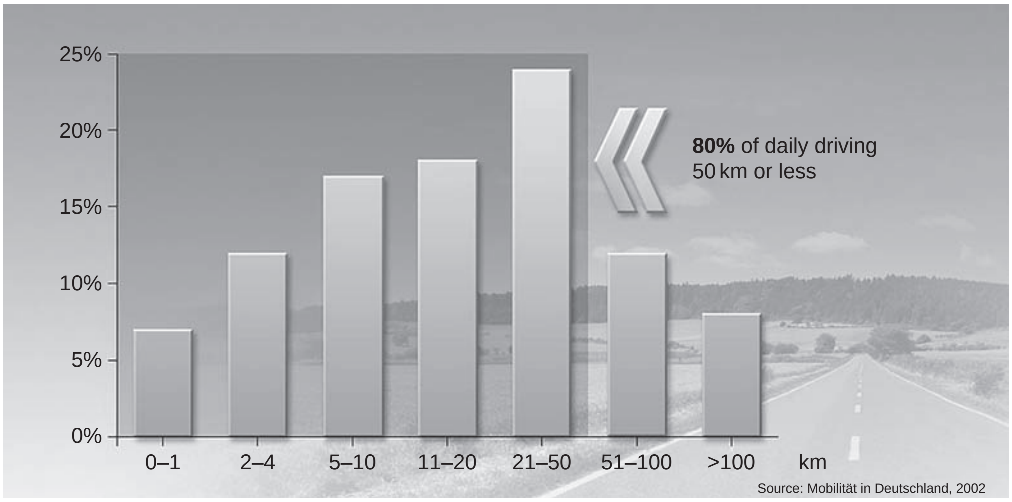


Figure 9.9 Daily driving distances in Germany.

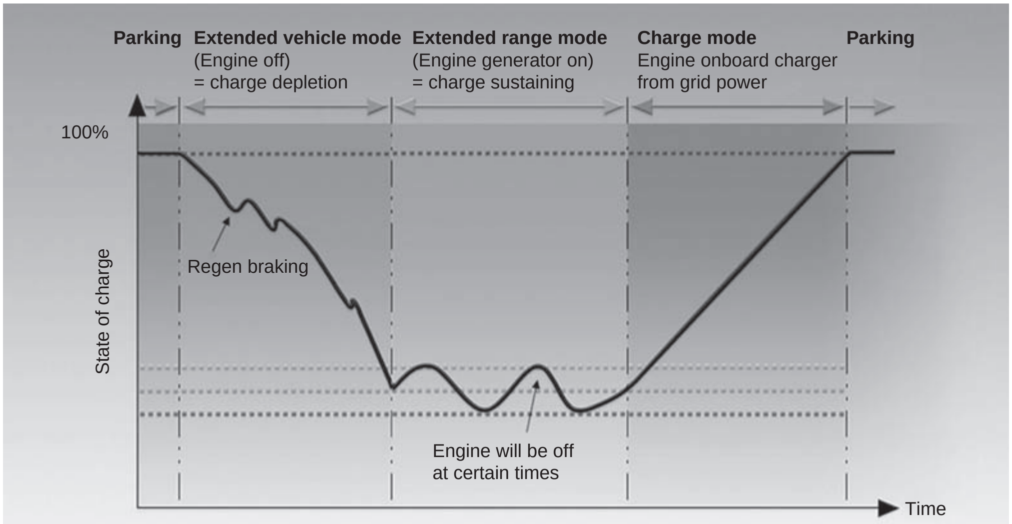


Figure 9.10 E-REV operating concept, approximately 50% of the nominal battery energy content is used.

certain value: this operating mode is called "charge-sustaining" or "extended-range" mode. By adding the ranges of both charge-depleting and charge-sustaining modes, a total vehicle range of more than 500 km can be achieved. For the normal daily driving profiles, it is nevertheless ensured that the VOLTEC vehicles are driven without any fossil fuel consumption and the related issues. For an annual electric driving distance of 13,000 km, the Chevrolet Volt or an Opel Ampera would require only 1730 kWh of electrical energy. This value corresponds to a level of just about 40% of the annual energy consumption of an average four-person household in Germany (4500 kWh) .[6] Considering the New European Driving Cycle (NEDC) (ECE R101), less than 40 g CO_2/km would be emitted by an Opel Ampera.

As mentioned before, the Chevrolet Volt and the VOLTEC propulsion technology have been presented for the first time in January 2007. In the same year, the decision was made to initiate the product engineering and to introduce the Volt as a volume production vehicle. The first battery packs were already assembled in late 2007, and the first components in vehicle tests were started. In 2008, the first packs were mounted on mule vehicles for early tests of the production-intent propulsion system, and the first vehicle crash tests were successfully performed (see Figure 9.11). Till early summer 2009 about 80 Volt prototypes were built. The series production of the Chevy Volt will start at the end of 2010; the volume production of the Opel Ampera with the same VOLTEC powertrain technology is set to begin about 1 year later.

6. INFRASTRUCTURE ISSUES

To set up a sufficiently dense (and sufficiently consumer-friendly) hydrogen filling station infrastructure, for example, in the United States, approximately 12,000 gas stations need to be built. The underlying model [7] assumes that in the 100 biggest metropolitan areas of the United States (comprising about 70% of total population) the

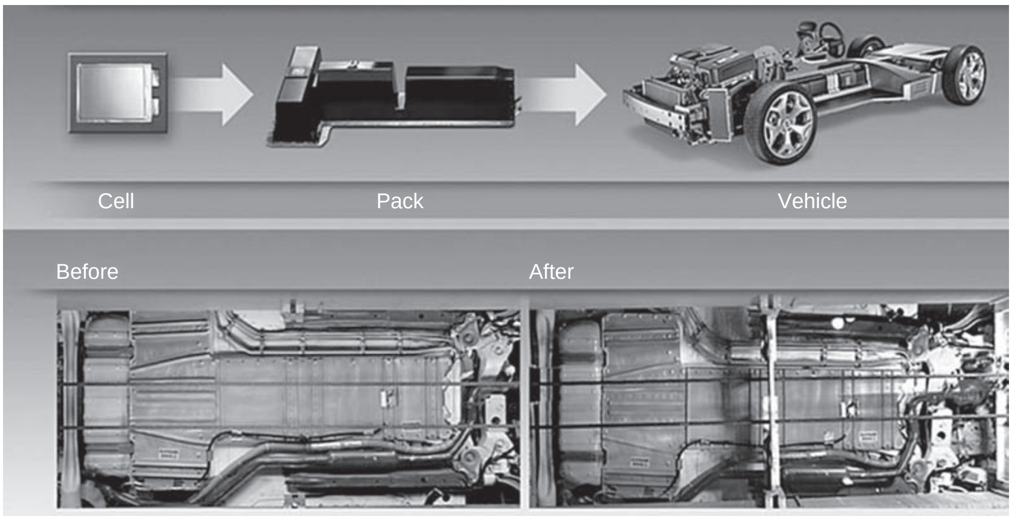


Figure 9.11 (Up) Integration of battery cells into modules and vehicle; (down) first crash test: the T-shaped battery is visible.

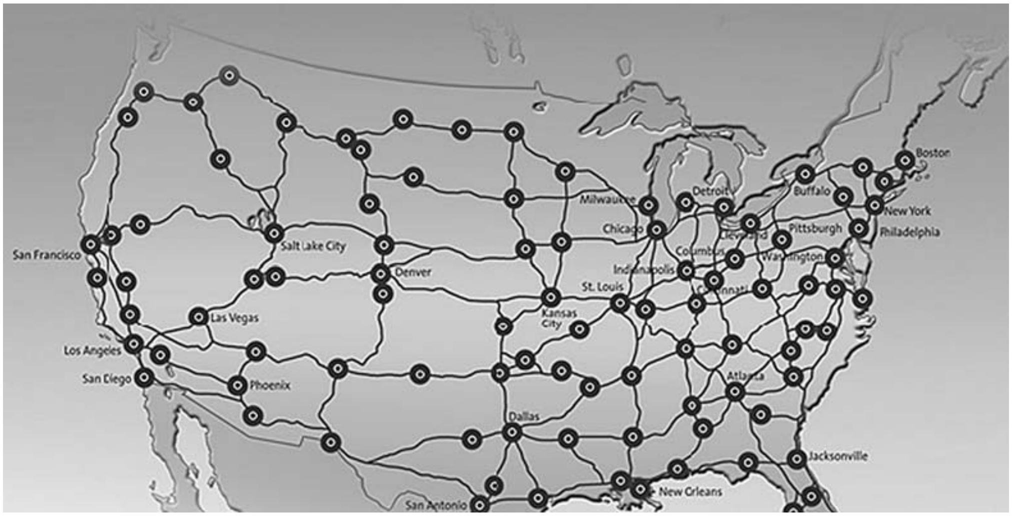


Figure 9.12 100 largest US metropolitan areas and interconnecting corridors.

maximum distance between two filling stations would not exceed 2 miles, resulting in 6,500 intraurban stations.

On the freeways connecting these large conurbations, a filling station would have to be installed every 25 miles [7]. This highway network would correspond to 5,500 additional stations. Such a comprehensive filling station network (see Figure 9.12) could serve about 1 million hydrogen vehicles and would cost approximately US$10–15 billion over a time period of 10 years.

Similar to today's gasoline infrastructure, a hydrogen gas station would be able to serve hundreds of vehicles per day, since just 3–5 min are needed to refill a hydrogen car. This is not the case for pure BEVs: for battery technology and electric grid stability reasons, charging times of at least one to several hours or even longer periods are required, that is, a standard public charging point becomes blocked for hours by just one customer. Hence, such a station could only serve a few vehicles per day. For EVs, there exists a strong interdependency between two normally distinct activities, namely "parking" and "refueling." Furthermore, the typical customer does not want to wait at the vehicle until it is recharged. On the other hand, the charging points are comparatively cheap even at low volumes (US$5,000–10,000 including installation) leading to low initial costs for early fleet demonstrations. This is in particular valid when the conventional 230V/16A technology (e.g., chargers, connectors, and wall outlets) can be used.

Although a single charging point is much less expensive than an H_2 fueling station, considering an ultimate scenario with an increasing penetration of the vehicle fleet with EVs (i.e., >1 million zero-emission vehicles in Germany), the cost for the implementation of a local battery recharging infrastructure under these assumptions approaches the initially much higher cost of a more centralized hydrogen infrastructure. This is caused by the high number of required charging pole installations: in fact, the ratio of public charging points per vehicle needs to be close to 1 or even higher. However, for small- to mid-sized fleets of zero-emission vehicles, the infrastructure for pure battery or E-REVs can be set up more simply due to the better scalability and the lower initial cost for a sufficiently dense network.

On the other hand, hydrogen offers a different and very important advantage: due to its high-energy density, hydrogen as an energy carrier is the ideal partner for the intermediate storage of fluctuating, renewable energies. Doing so, excess amounts of sustainable energy sources such as solar and wind power can be made available not only for stationary but also for automotive applications. Let us consider, for example, the North German electric power grid, the so-called "E.ON Kontrollzone Nord": in October 2008, the power fed into the grid by wind mills fluctuated (sometimes within a few hours, sometimes within days) between a maximum of approximately 8,000 MW and virtually zero. It is evident that it would be very helpful to "buffer" energy in intermediate stores to handle these fluctuations, that is, to absorb energy during a certain time period from the grid or, vice versa, to provide the required energy back to the grid.

Today, this "buffer" is realized as pumped hydro stores (the largest facility in Germany, Goldisthal, offers a maximum storage capacity of 8,000 MWh) or in compressed air reservoirs (typically a salt cavern, with a volume of 2 million cubic meters, and a maximum storage capacity of 4,000 MWh). If hydrogen would be used as medium instead of compressed air, up to 600,000 MWh energy could be stored in the identical salt cavern. Unlike conventional technology, hydrogen therefore offers not only a buffer store for short time periods ranging from a few minutes to hours. Such a large-scale hydrogen store could absorb the excess wind energy of several days. The stored gas eventually could be either converted back into electric energy or could simply be used as a fuel for hydrogen vehicles. In contrast, even large fleets of pure battery EVs are not able to provide a competitive energy storage dimension: if 5 kWh of the usable energy content of an EV battery (for operating lifetime and customer ease-of-use considerations, 10% of the total nominal energy content should not be exceeded) could be subscribed to and utilized by the electric utility, just to replace the pumped hydro store of Goldisthal, 1.6 million EVs would be needed.

7. CONCLUSIONS

GM's long-term advanced propulsion strategy consists in displacing gasoline and diesels as energy sources for the automotive application. This will be achieved by a continuously increasing electrification of the powertrain. However, the energy density of current and future automotive batteries unfortunately provides limitations for the development of pure battery electrical vehicles as soon as a longer vehicle ranges significantly beyond 100 miles are required. Therefore, GM and Opel pursue the

E-REV and FCEV concepts for this application field. Ranges of 500 km can be achieved with hydrogen fuel cell vehicles and 700 bar CGH_2 tanks; moreover, hydrogen can be produced at large scale at competitive prices. In the area of longer-range sustainable mobility, the future of automotive propulsion seems to rely mostly upon E-REV and FCEV vehicles and for some urban applications also upon small-sized BEV. During the early commercialization phases, all of these vehicles will be more expensive than comparable conventional vehicles; therefore, the support and cooperation of all involved stakeholders is indispensable during this initial phase. The most important players thereby are primarily car manufacturers, energy companies, and the governments. But also the end consumer should accept these innovative vehicles, despite the initial cost, considering the reduced fuel consumptions and the environmental concern.

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LIST OF ABBREVIATIONS

AFC	alkaline fuel cell
BEV	battery electric vehicle
CNG	compressed natural gas
CGH_2	compressed hydrogen gas
DC	direct current
E-REV	extended-range electric vehicle
EV	electric vehicle
EPA	Environmental Protection Agency
FCEV	fuel cell electric vehicle
GM	General Motors
HEV	hybrid electric vehicle
ICE	Internal Combustion Engine
Li-ion	lithium-ion battery
LPG	liquefied petroleum gas
NEDC	New European Driving Cycle
Ni-MH	nickel metal-hydride battery
PEM	proton exchange membrane
PEMFC	proton exchange membrane fuel cell
PDU	propulsion dress-up module
SAE	Society of Automotive Engineers

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