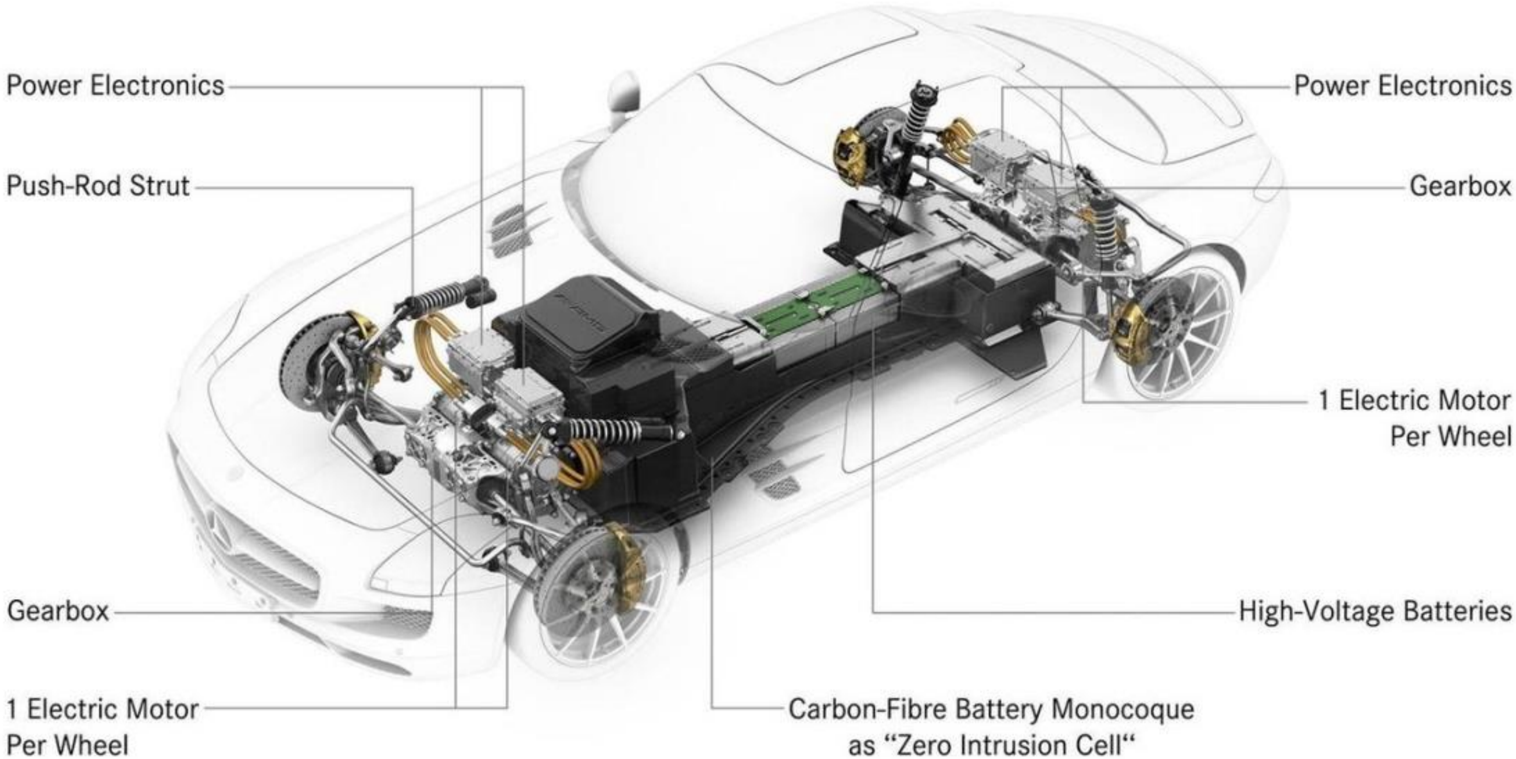
Chapter 1:

Electric Vehicle (EV): introduction, general types, and structure



1.1. EV definition, merits and limitations

An Electric Vehicle (EV) is a vehicle that is powered or propelled, at least in part, by electricity.

❑ Main merits of an EV:

- ✓ Contribution in reducing Green House Gas (GHG): in 2009, the transportation sector emitted 25% of the GHGs produced by energy related sectors;
- ✓ Quiet operation (reducing noise pollution urban);
- ✓ Provides the total torque from startup (high instant torque: preferable for motor sports);
- ✓ Does not require trips to the gas station;
- ✓ Can use various Energy Storage Systems (ESSs) such as batteries, Ultra-Capacitors (UCs), Fuel Cells (FCs), and flywheels;
- ✓ High efficiency in power converting from the ESS to the wheels tractive effort;
- ✓ Use minimum stored energy or cause any emission while idling;
- ✓ Is a major contributor for smart grids;
- ✓ Have regenerative braking to recover the kinetic energy of the vehicle while braking;
- ✓ Capable for frequent start-stop driving.

❑ Main limitations of EV:

- ✓ High costs specially due to the high ESS price;
- ✓ Relative high volume and weight of the ESS pack (like battery);
- ✓ Short drive range per charge (relative low energy density of the ESS pack);
- ✓ Long charging time (limitation on chargers power and the ESS charge acceptance rate) ;
- ✓ Loading a high demand on power grid.

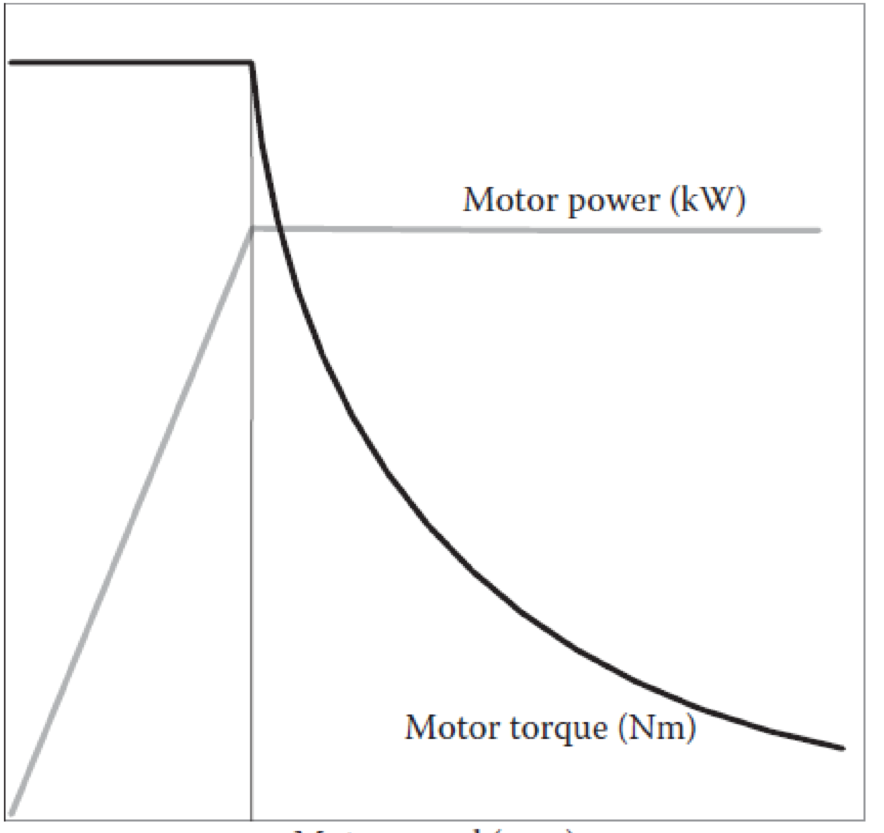


Fig. 1. Ideal performance characteristics for vehicular power plants.

- **For vehicular applications**, the ideal performance characteristic of a power plant is a **constant power output over the full speed range**. Consequently, the **torque varies with speed hyperbolically**. With this ideal profile, the maximum power of the power plant will be available at any vehicle speed, therefore yielding optimal vehicle performance. However, in practice, the torque is constrained to be constant in low speed, so as not to be over the maxima limited by the adhesion between the tire–ground contact area. This **constant power characteristic will provide the vehicle with high tractive effort at low speeds** where demands for acceleration, drawbar pull, or grade climbing capability are high.

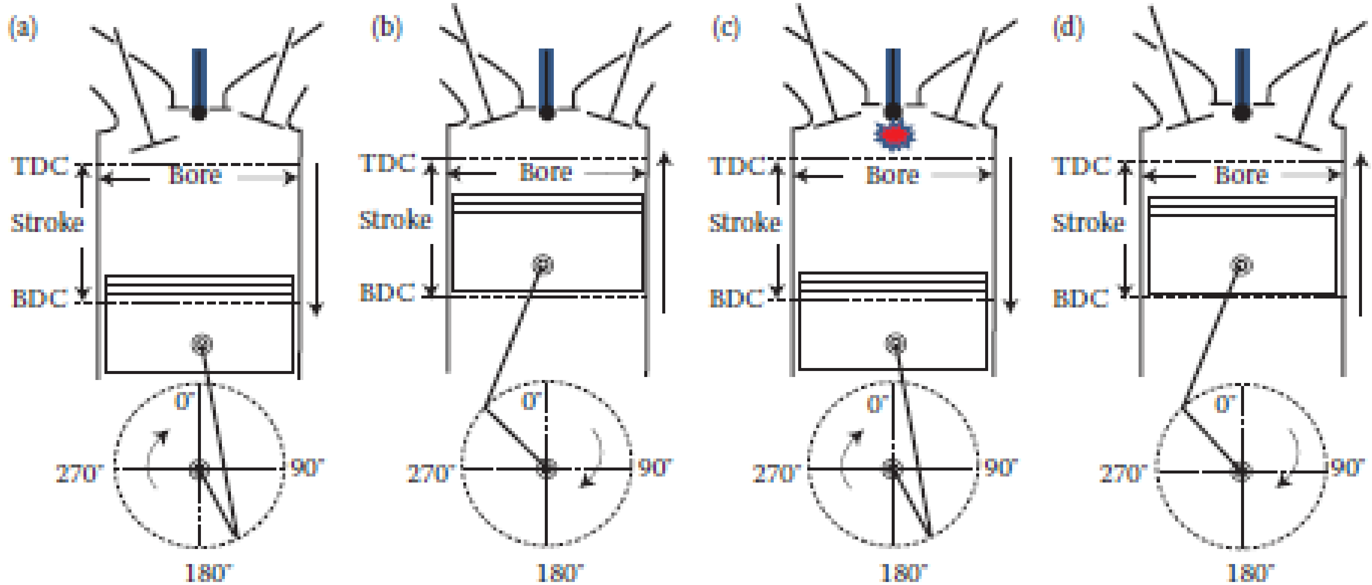


Fig. 2. Four-stroke cycle. (a) Intake; (b) compression; (c) power; (d) exhaust.

❑ The four strokes are:

1. Intake stroke: The intake stroke is from Top Dead Centre (TDC) to Bottom Dead Centre (BDC). In this stroke, fresh charge is drawn into the cylinder through intake valves. Typically, the intake valve opens slightly before TDC and closes after BDC to increase the inducted charge.

2. Compression stroke: The compression stroke is right after the intake stroke. In this stroke, both intake and exhaust valves are closed and charge in the cylinder is compressed. The cylinder pressure increases during the compression. When it is close to the end of the compression stroke (near TDC), combustion is initiated through SI engines or fuel injection and compression (CI engines).

3. Power stroke: After compression stroke, the cylinder pressure increases rapidly due to the combustion. The mixture gas with high pressure and temperature pushes the piston downward and enhances the crank rotation. In this stroke, the power is generated through combustion and transferred into the mechanical work in the form of crank rotation.

4. Exhaust stroke: At the end of the power stroke, the piston is around BDC. Then the exhaust valve starts to open and the exhaust gas is pushed out when the piston moves from BDC to TDC.

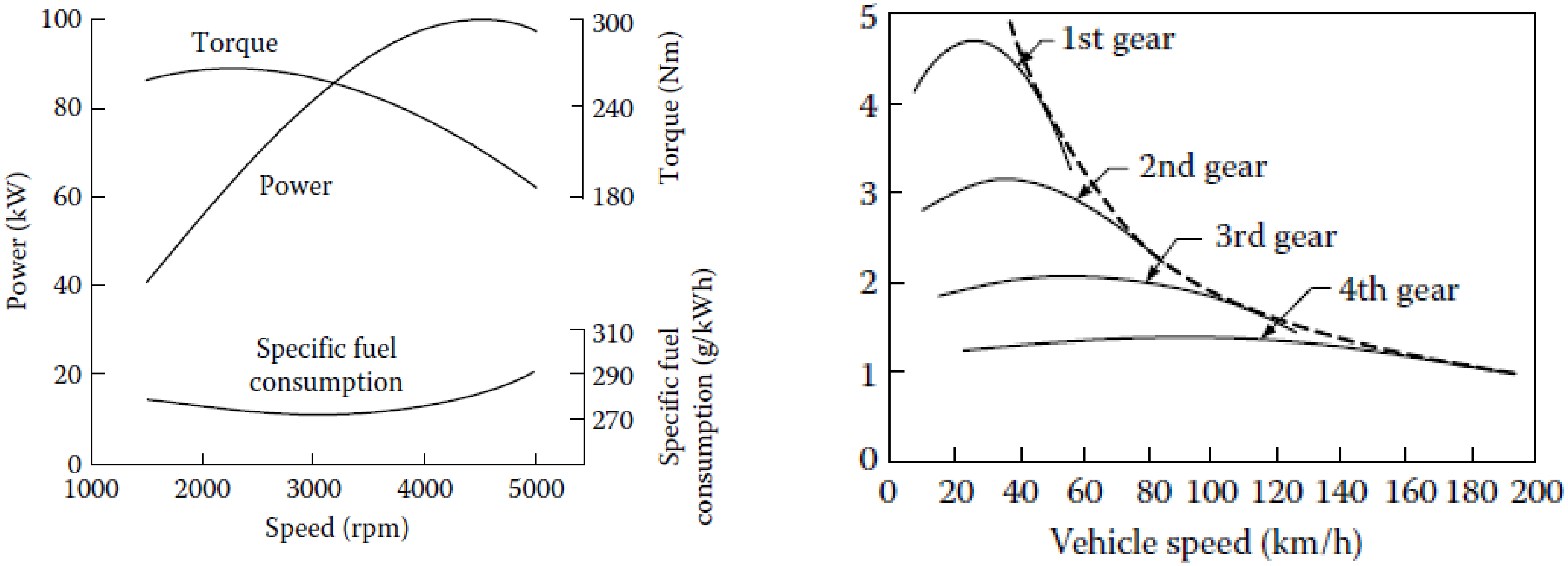


Fig. 3. Typical performance characteristics of an Internal Combustion Engine (ICE): power and torque versus speed (left); tractive effort and a multigear transmission vehicle versus vehicle speed (right).

- **An ICE** has torque–speed characteristics far from the ideal performance characteristic required by traction. It starts operating smoothly at the idle speed. **Good combustion quality and maximum torque are reached at an intermediate engine speed. As the speed further increases, the torque decreases due to less air induced into the cylinders**, caused by the growing losses in the air-induction manifold and grossing power losses caused by mechanical frication and hydraulic viscosity. Power output, however, increases to its maximum at a certain higher speed. Beyond this speed, the engine power starts declining. In vehicular applications, the maximum permissible speed of the engine is usually set just a little above the speed of the maximum power output. **The ICE has a relatively flat torque–speed profile** (as compared with an ideal power plant). Consequently, **a multigear transmission is usually employed to modify it**.

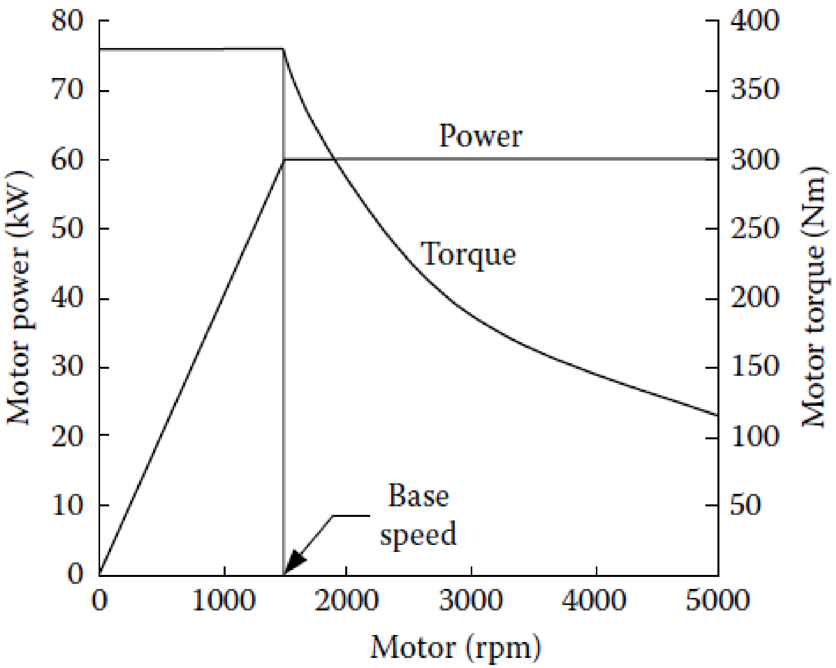


Fig. 4. Typical performance characteristics of an Electric Motor (EM) for traction.

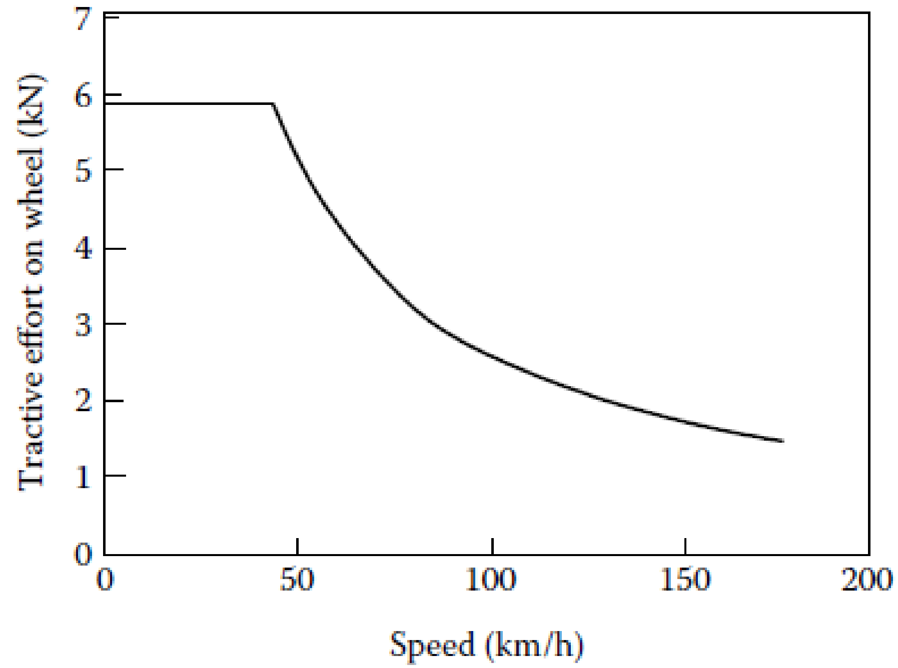


Fig. 5. Tractive effort of a single-gear EV versus vehicle speed.

- **An Electric Motor (EM)** is another candidate as a vehicle power plant. EMs with good speed adjustment control **usually have a speed–torque characteristic that is much closer to the ideal**. Generally, the EM starts from zero speed. **As it increases to its base speed, the voltage increases to its rated value while the flux remains constant.** In this speed range of zero to base speed, the electric motor produces a constant torque. **Beyond the base speed, the voltage remains constant and the flux is weakened.** This results in a constant output power while the torque declines hyperbolically with speed. Since the speed–torque profile of an electric motor is close to the ideal, **a single-gear or double-gear transmission may be employed to meet the vehicle performance requirement**.

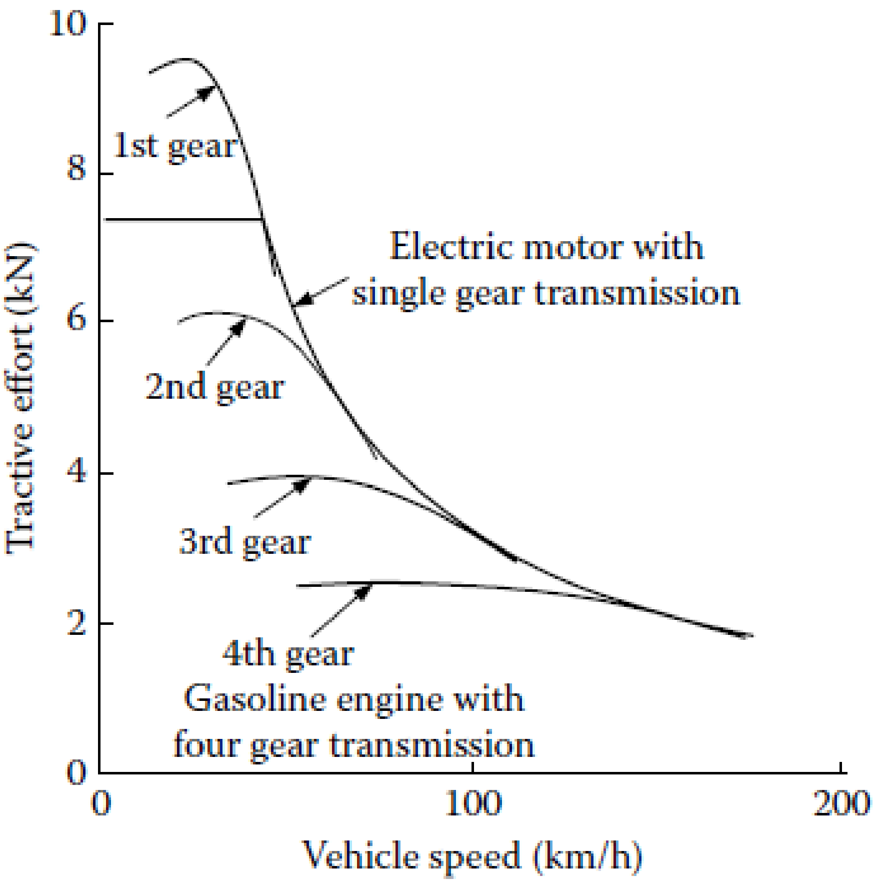


Fig. 6. Tractive efforts of a gasoline engine vehicle with a four-gear transmission and EV with a single-gear transmission.

- **The EMs** with favorable torque–speed characteristics can satisfy the tractive effort with **a simple single-gear transmission. An ICE has to use multigear or continuously varying transmission to multiply its torque at low speed.** The term transmission here includes all those systems employed for transmitting the engine power to the drive wheels. For automobile applications, there are usually two basic types of transmission: manual gear transmission and hydrodynamic transmission.

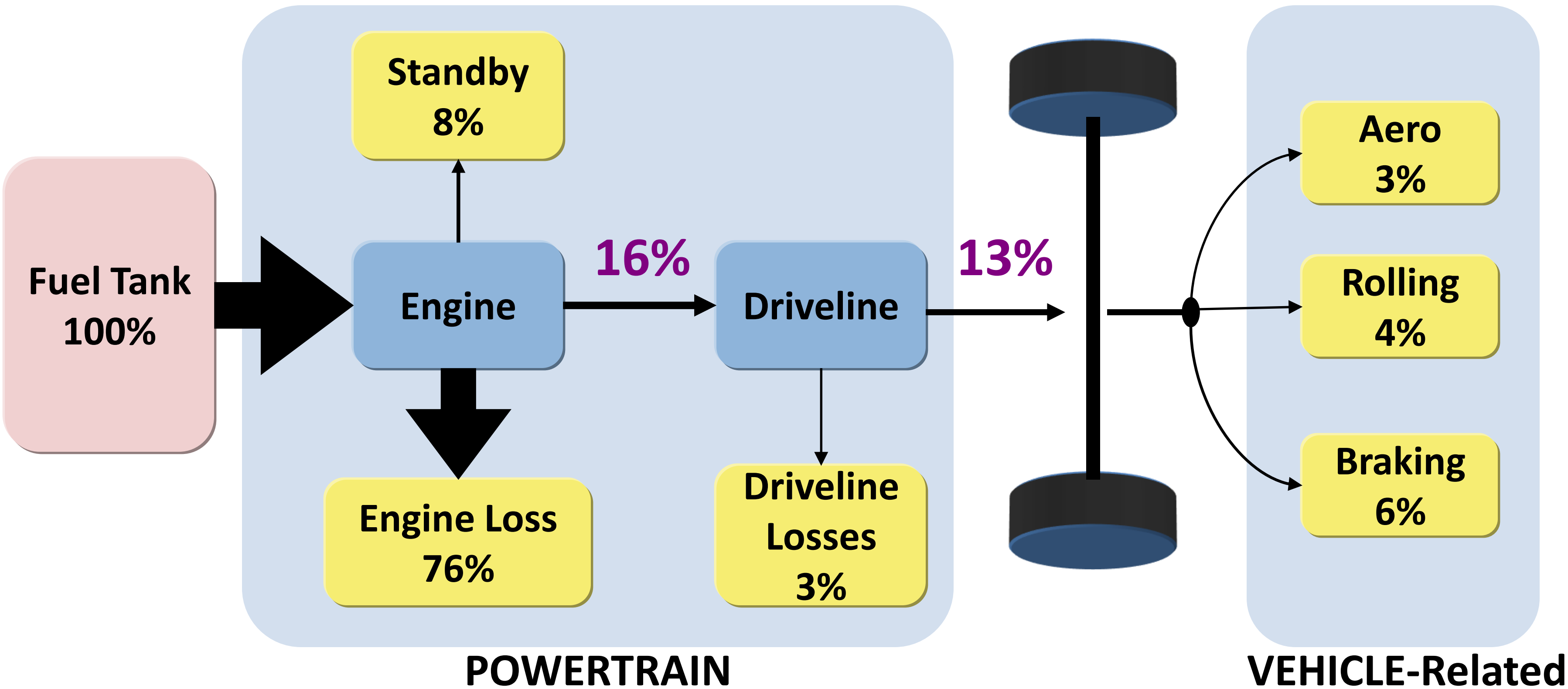


Fig. 7. Input to output (tank-to-wheel) efficiency of a typical ICE vehicle, 2005 3 L Toyota Camry, in city driving condition.

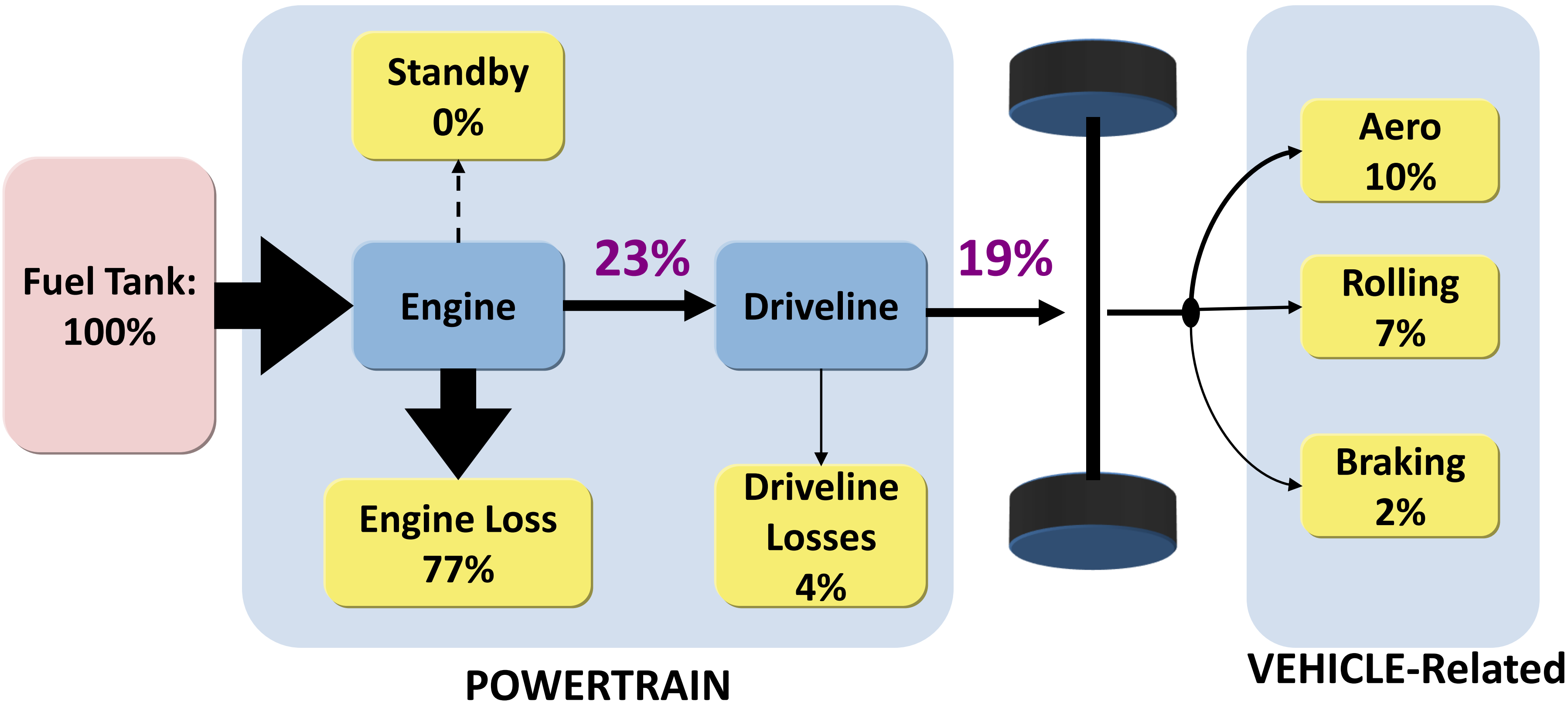


Fig. 8. Input to output (tank-to-wheel) efficiency of a typical ICE vehicle, 2005 3 L Toyota Camry, in highway driving condition.

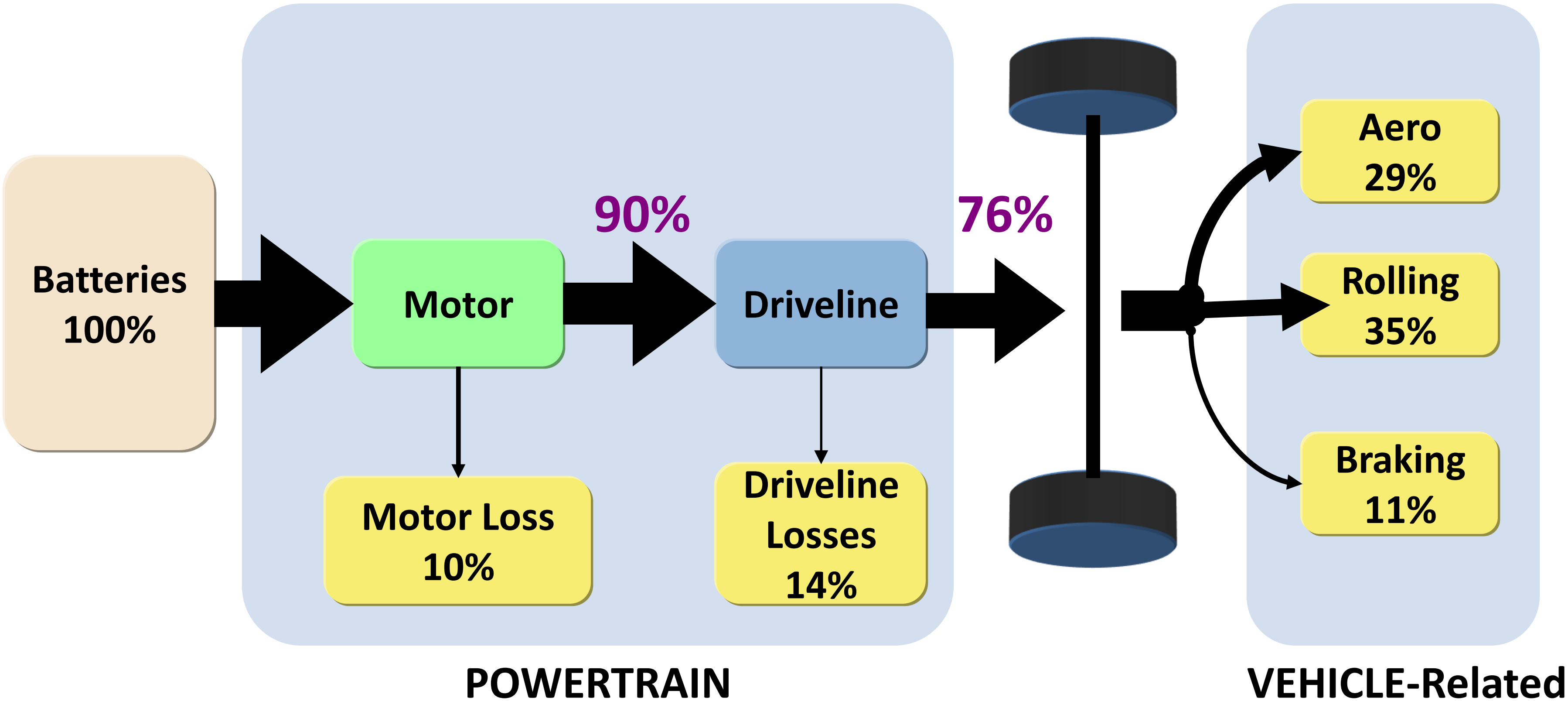


Fig. 9. Input to output (plug-to-wheel) efficiency of a typical EV in city driving condition.

- A comparison between well-to-wheel chain efficiency in both EVs and Internal Combustion Engine (ICE) vehicles demonstrate that **an EV has higher chain efficiency.**

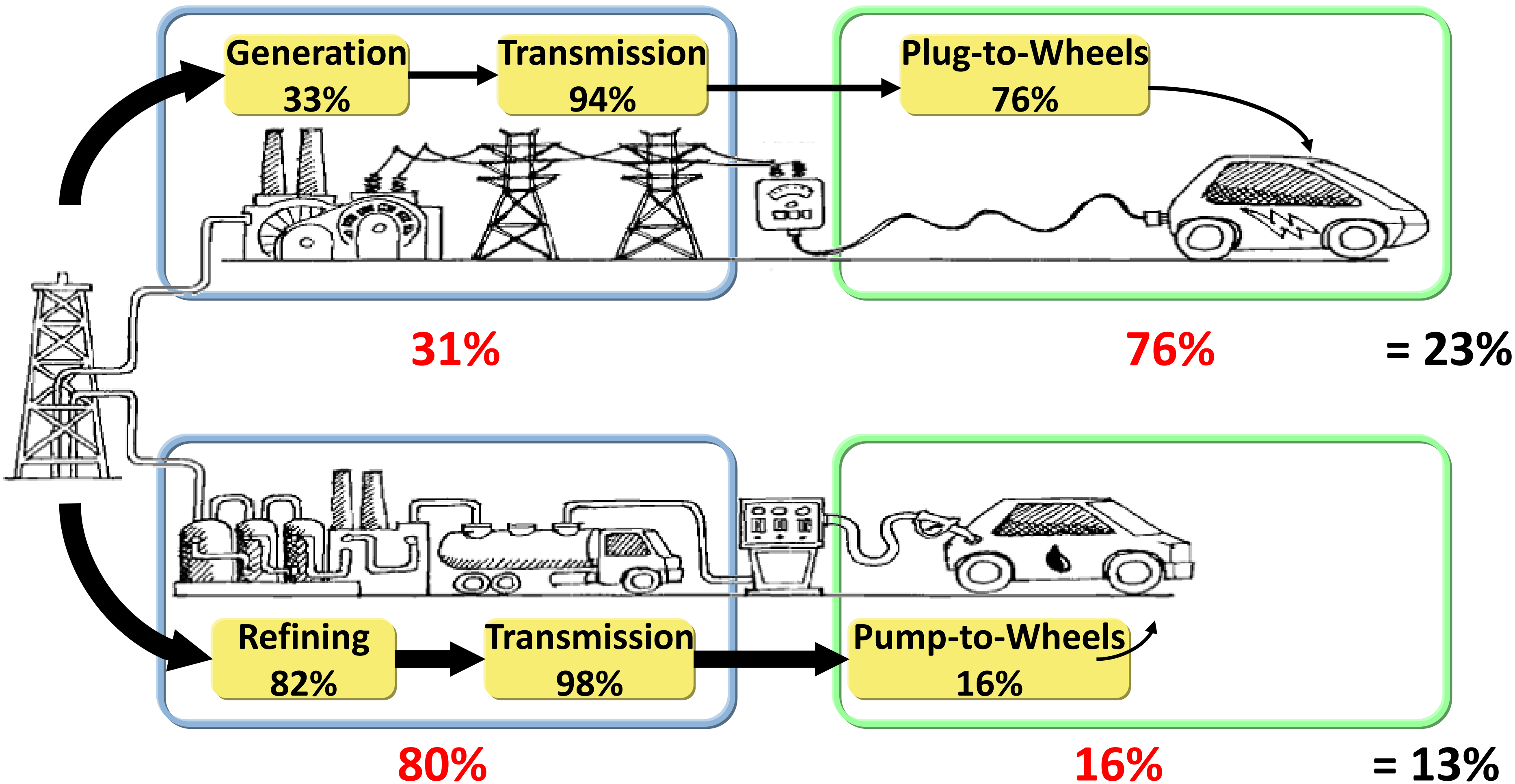


Fig. 10. Well-to-wheel efficiency comparison between the EVs and ICE vehicles.

- A comparison between well-to-wheel chain efficiency in both EVs and Internal Combustion Engine (ICE) vehicles demonstrate that **an EV has higher chain efficiency.**

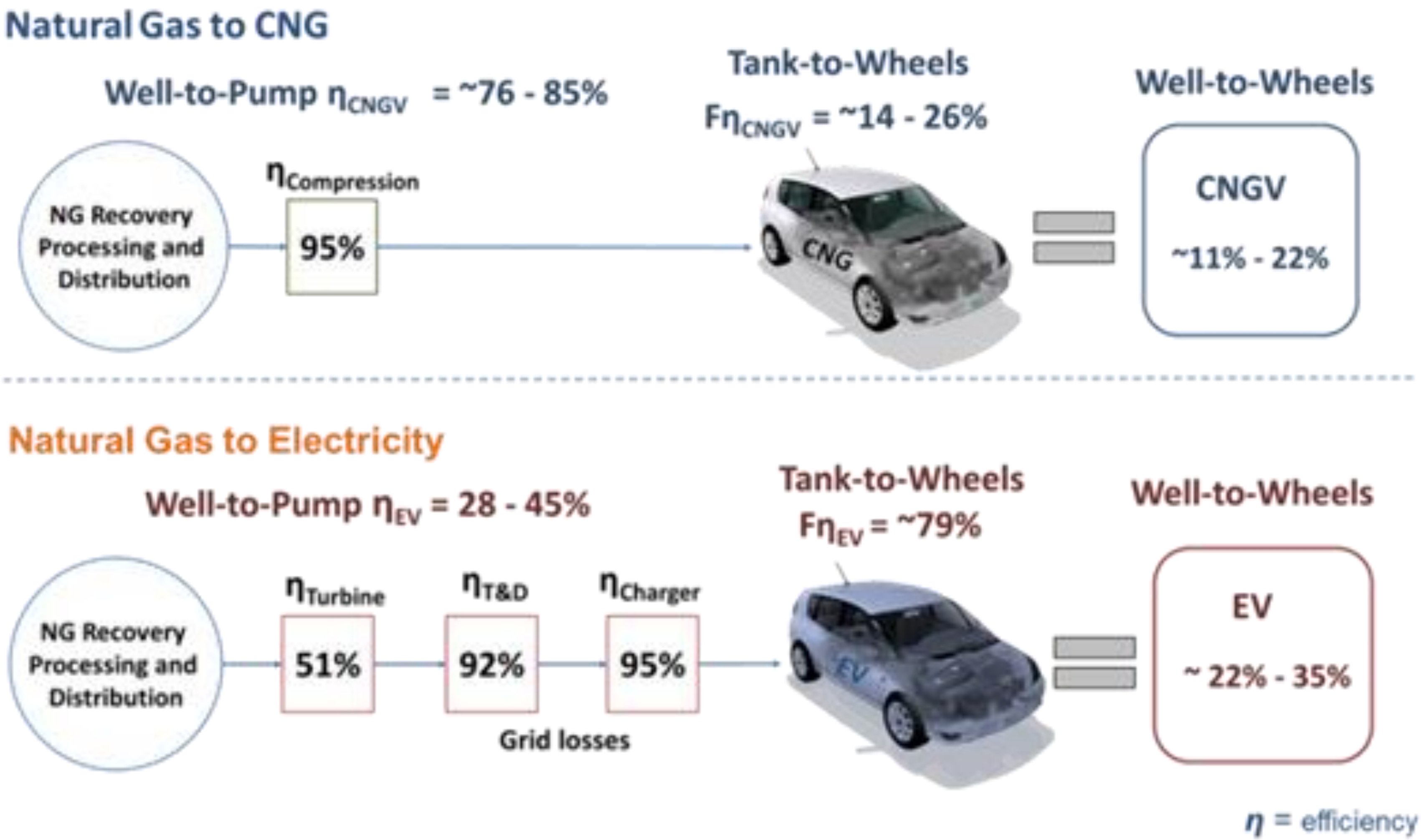


Fig. 11. Well-to-wheel efficiency comparison between the EVs and ICE vehicles in case of NG applying as the energy resource.

1.2. Statistic of EV trend in the world

- Some of most **famous EV manufacturers** are: Nissan, Mitsubishi, Chevrolet, Tesla, BYD.

Table 1. Some of the most famous highway-Capable EVs and Light Utility EVs with their sale number in a definite time.

Model	Market Launch	Global Sales	Sales Through
Nissan Leaf	December 2010	83,000	September 2013
Mitsubishi i-MiEV family	July 2009	>26,000	September 2013
Tesla Model S	June 2012	18,200	September 2013
Renault Kangoo Z.E.	October 2011	11,069	September 2013
Chery QQ3 EV	March 2010	9512	October 2013
Renault Zoe	December 2012	6605	September 2013
Mitsubishi Minicab MiEV	December 2011	4972	September 2013
BYD e6	May 2010	3220	October 2013
Tesla Roadster	March 2008	~2500	December 2012
Bolloré Bluecar	December 2011	2300	September 2013
Ford Focus Electric	December 2011	2167	September 2013

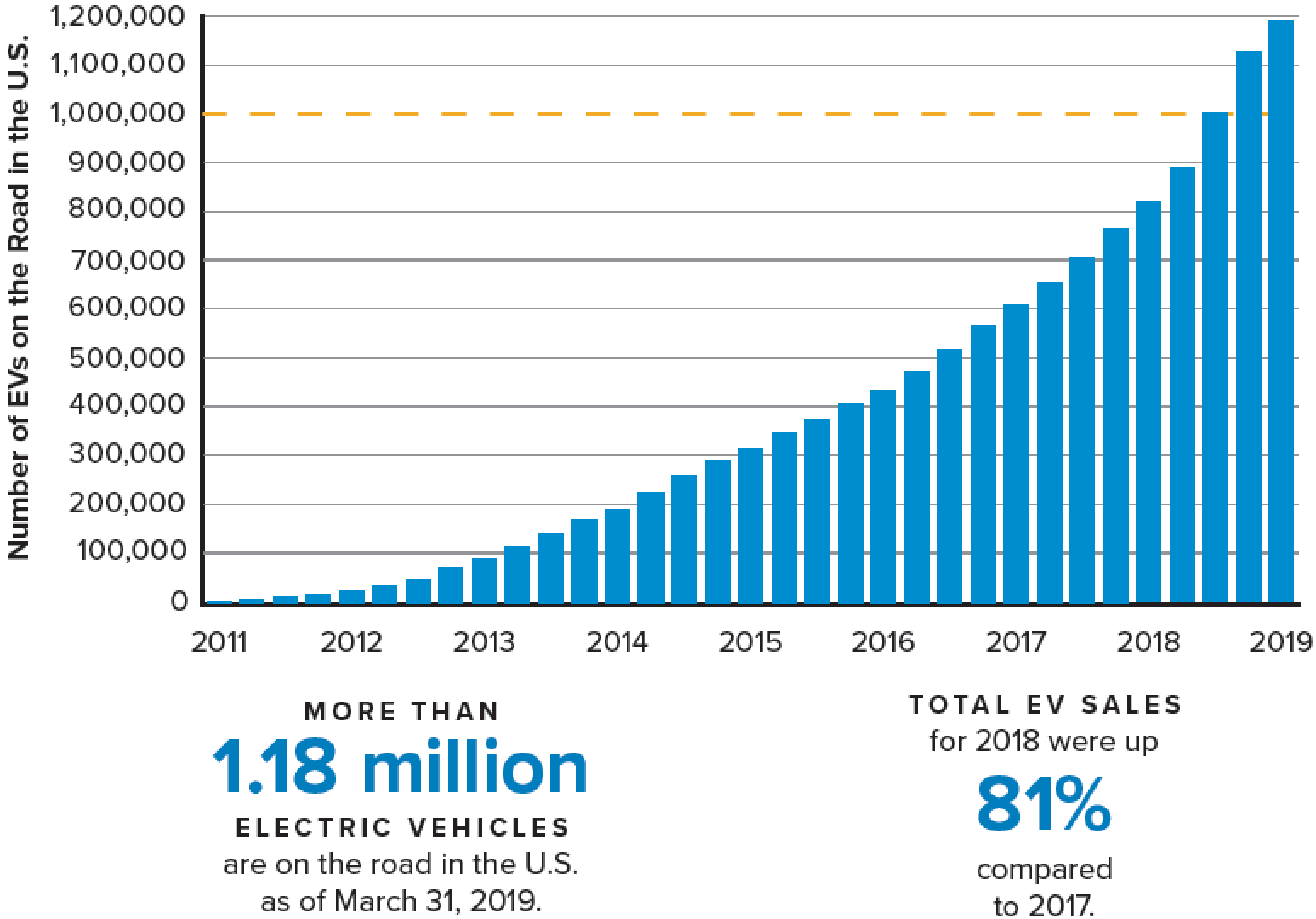
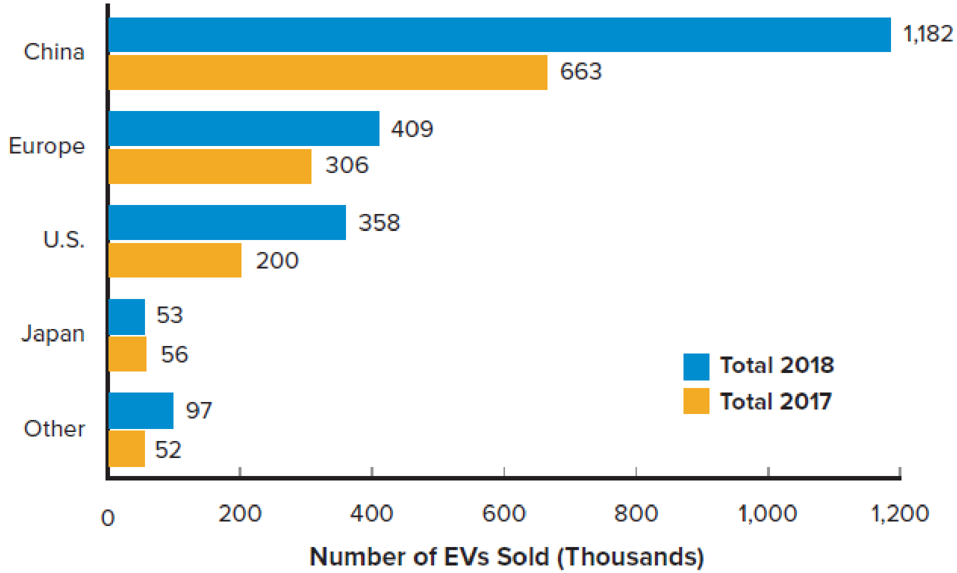


Fig. 12. Number of EVs on the road in the U.S.

Fig. 13. A comparison between EV sale in the various countries from 2017 to 2018.



KEY FACTS

- Global EV sales totaled about 2.1 million for 2018, an increase of 64% compared to the total sold in 2017.
- 2018 EV sales increased 79% in the U.S., 78% in China, and 34% in Europe compared to 2017.
- U.S. EV sales represented approximately 17% of global EV sales in 2018.

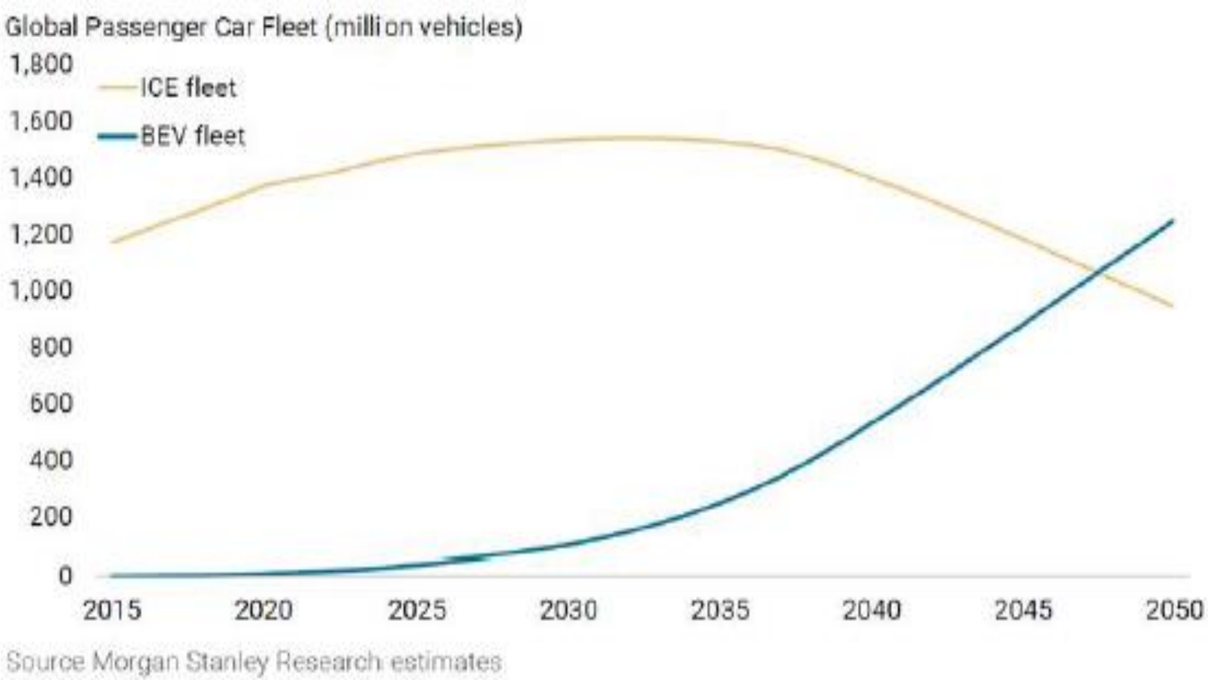


Fig. 14. Number of EVs and ICE Vehicles in a trend to 2050 (Bloomberg).

1.3. EV history

- By the 1900s, EVs had captured a notable share of the leisure car market. Among the 4200 automobiles sold in the United States in 1900, **38% were electric** and only **22% were gasoline**, while another **40% were still steam driven**. Why ICE conquered the market and EVs got lost into oblivion?

- ✓ Very low oil price;
- ✓ Simple operation of Vehicle starter;
- ✓ Problems in battery technology (low energy density cause to short driving range; and low life cycle)
- ✓ Weak chargers technology;

$$\eta_{W-W} = \eta_{W-T} \times \eta_{T-W}$$

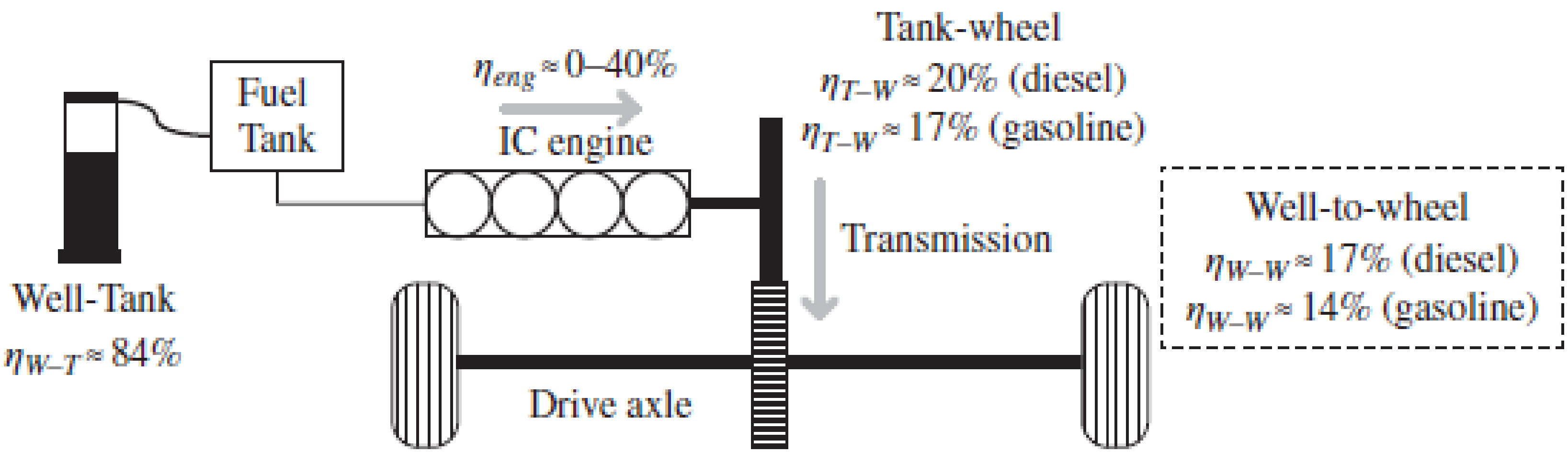


Fig. 15. An ICE-based vehicle architecture and energy flow efficiency.

A few decades stagnation of EVs

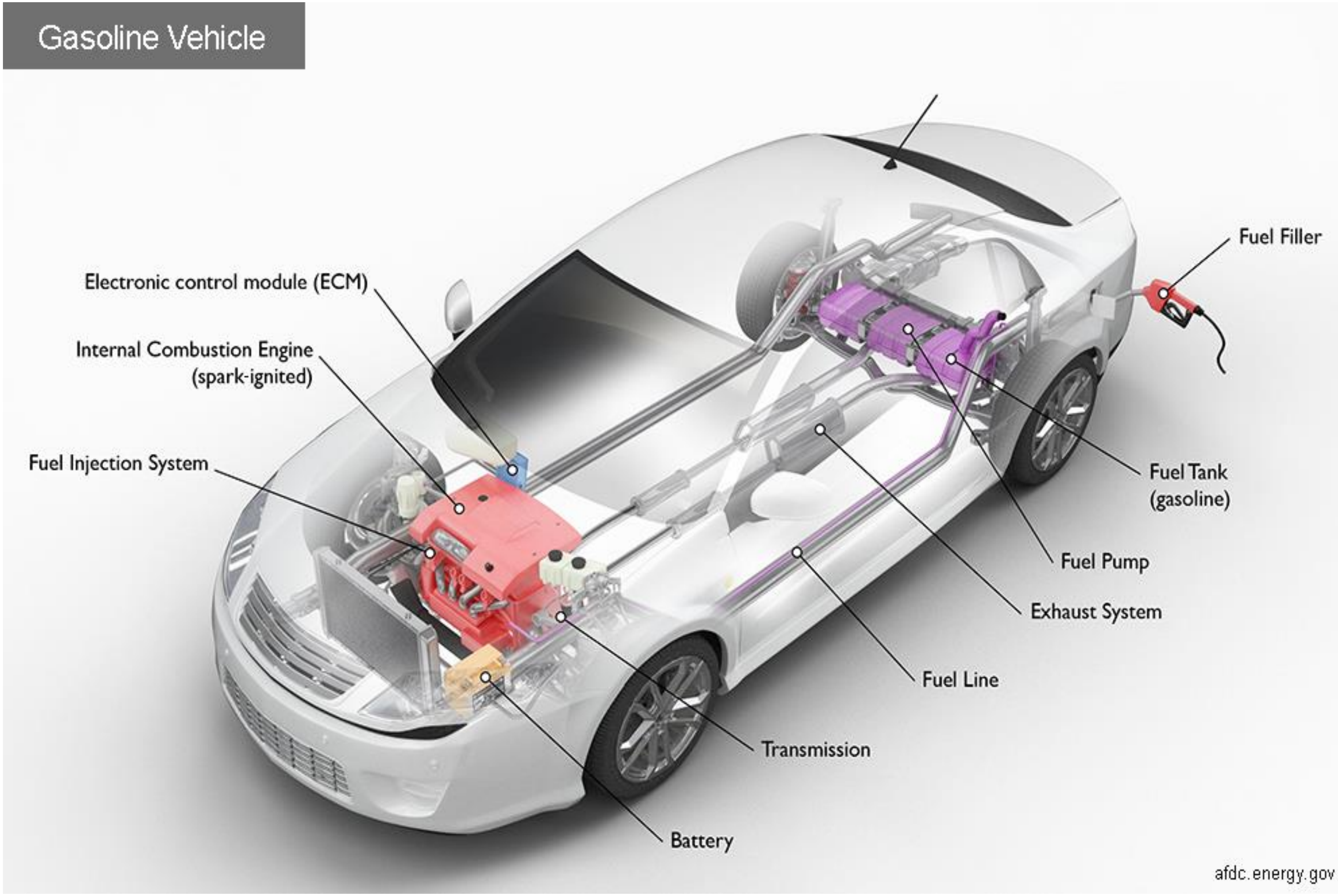
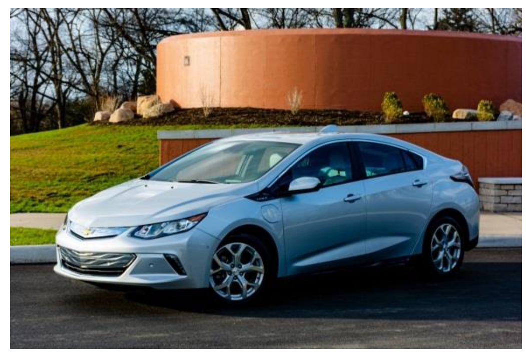


Fig. 16. Conceptual presentation of a typical ICE vehicle instruments.

- EV resurrection began with **General Motors EV1** production **in 1996** and quickly became very popular. Other carmakers, **Ford**, **Toyota**, and **Honda** presented their own EVs as well. **Toyota Prius**, was the first commercial Hybrid Electric Vehicle (HEV), **launched in Japan in 1997**, with **18,000** units sold in the first year of production.
- Nowadays, the market is dominated by **Nissan Leaf**, **Chevrolet Volt**, **Tesla Model S**, and **BYD** (mostly in Chinese market).



1.4. EV general subsystems

- **An EV is made of** different subsystems, which interact (more or less) with each other to make the EV work. It is the combined work of all these systems that make an EV operate.

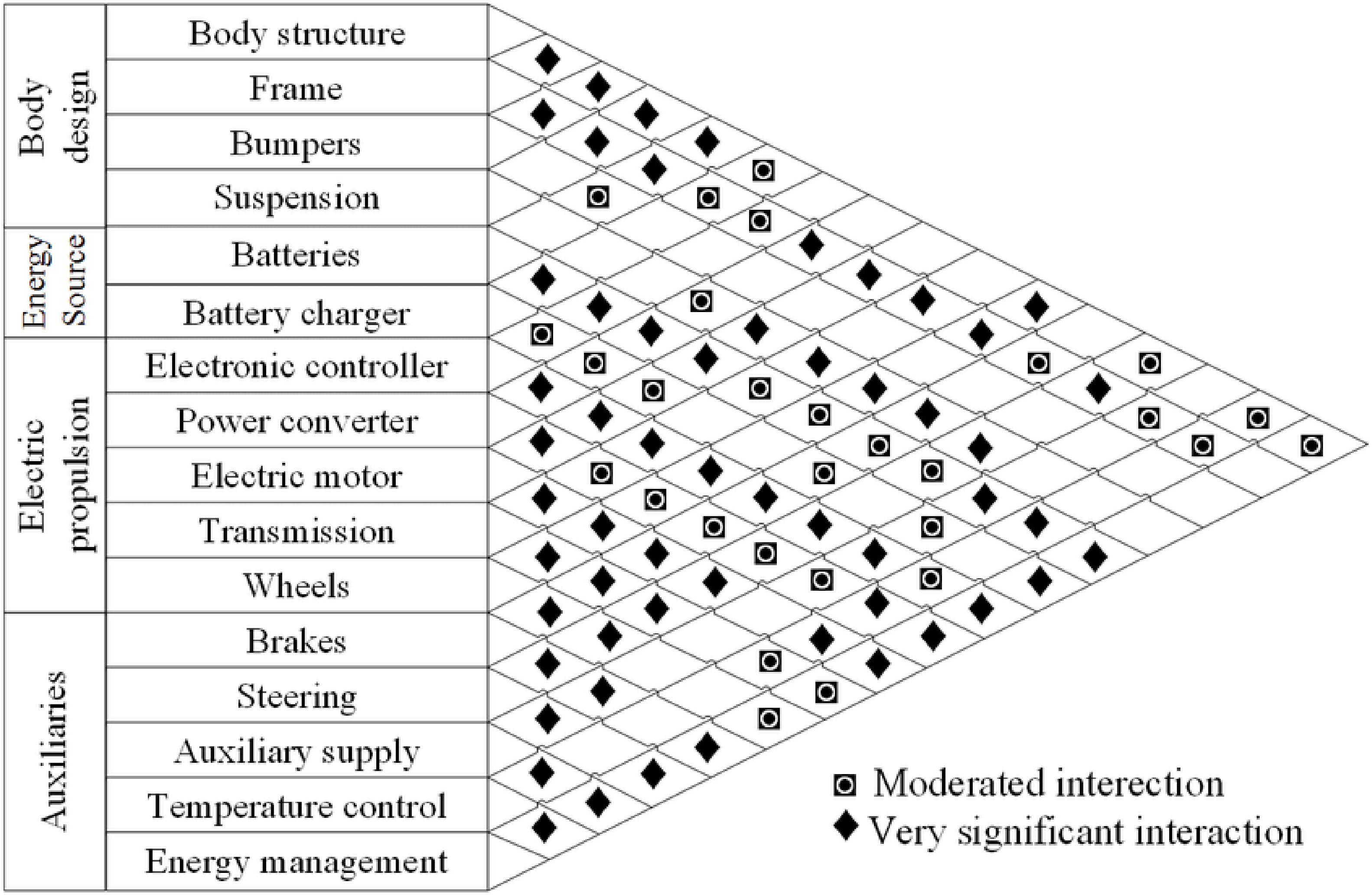


Fig. 17. Major EV subsystems and their interactions for EV working.

- ❑ An EV, unlike its counterparts ICE vehicle, **is quit flexible** because of the **absence of intricate mechanical arrangements** that applied in conventional vehicles (only controlled EM and a power supply in different arrangements).
- ✓ For the HEV, the ICE and EM can work in conjunction to turn the wheel.
- ❑ The three main subsystems of an EV are: **energy source**, **propulsion**, and **auxiliary**:

a) Energy source subsystems:

- ✓ Energy source ;
- ✓ Refueling system;
- ✓ Energy management.

b) Propulsion subsystems:

- ✓ EM;
- ✓ Power converter;
- ✓ Vehicle control Unit (VCU);
- ✓ Transmission;
- ✓ Driving wheels.

c) Auxiliary subsystems:

- ✓ Auxiliary power supply;
- ✓ Temperature controller;
- ✓ Power steering unit.

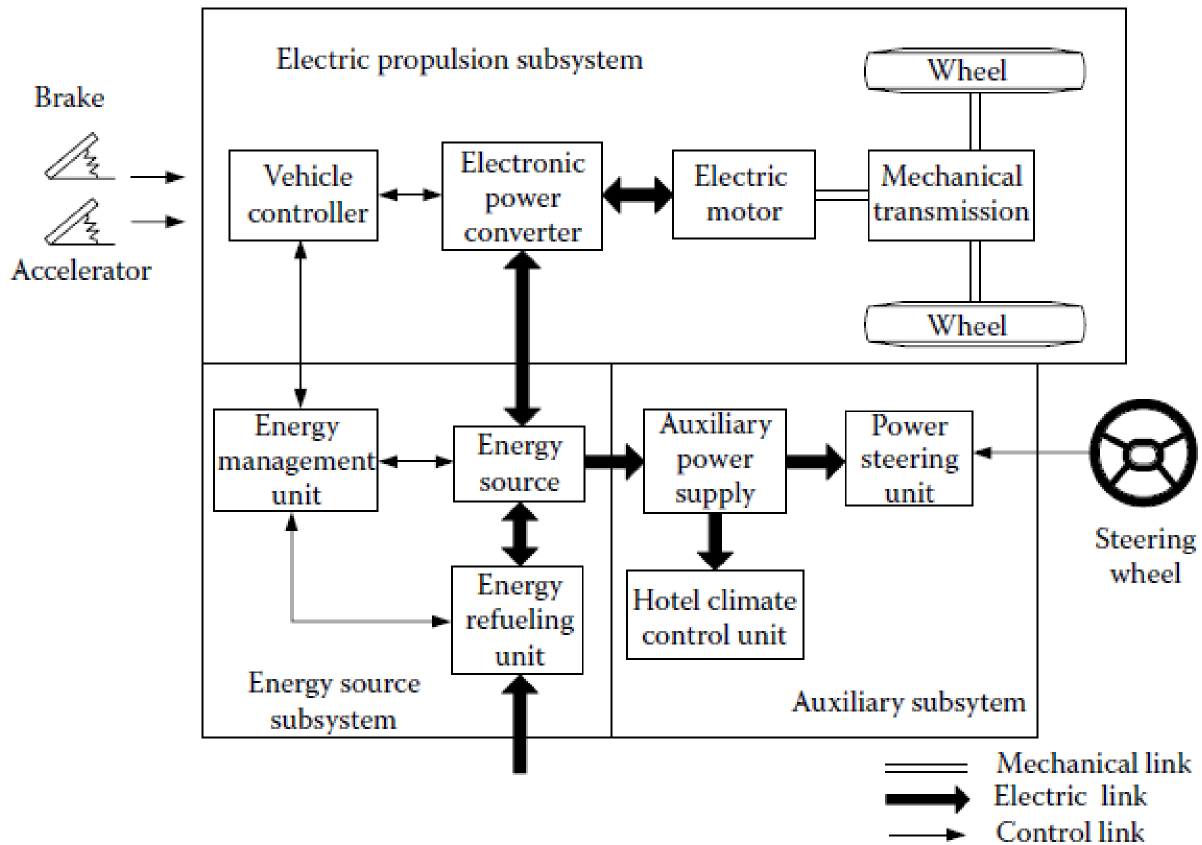


Fig. 18. An EV general subsystem.

- ❑ **A backward flow of power can be created by regenerative actions like regenerative braking.**

1.5. General types of EVs

- EVs can run **solely on electric propulsion** (Electrical Motor (EM), battery/Fuel Cell (FC), and converter). They can have **an ICE working alongside it** named as Hybrid EV (HEV). Therefore, common types of EVs are:

a) **Battery Electric Vehicle (BEV):** a battery pack applied as the ESS of the EV;

b) **Hybrid Electric Vehicle (HEV):** a battery/UC pack is applied with the ICE in an EV together ;

c) **Plug-in Hybrid Electric Vehicle (PHEV):** HEV with the capability for ESS charging by the power grid;

d) **Fuel Cell Electric Vehicle (FCEV):** the main ESS in the EV is FC;

- **Note:** various types of ESSs can work together. They are also named as types of EVs.

1.5.1. Battery Electric Vehicle (BEV)

- **EVs with only batteries to provide power** to the drive train are known as **BEVs**. Therefore, the **range** of such vehicles **depends directly on the battery capacity**.
- Based on nowadays battery technology, a typical BEV can cover 200–500 km on one charge. These ranges depend on **driving style, vehicle configuration, road condition, climate, battery type and age**.

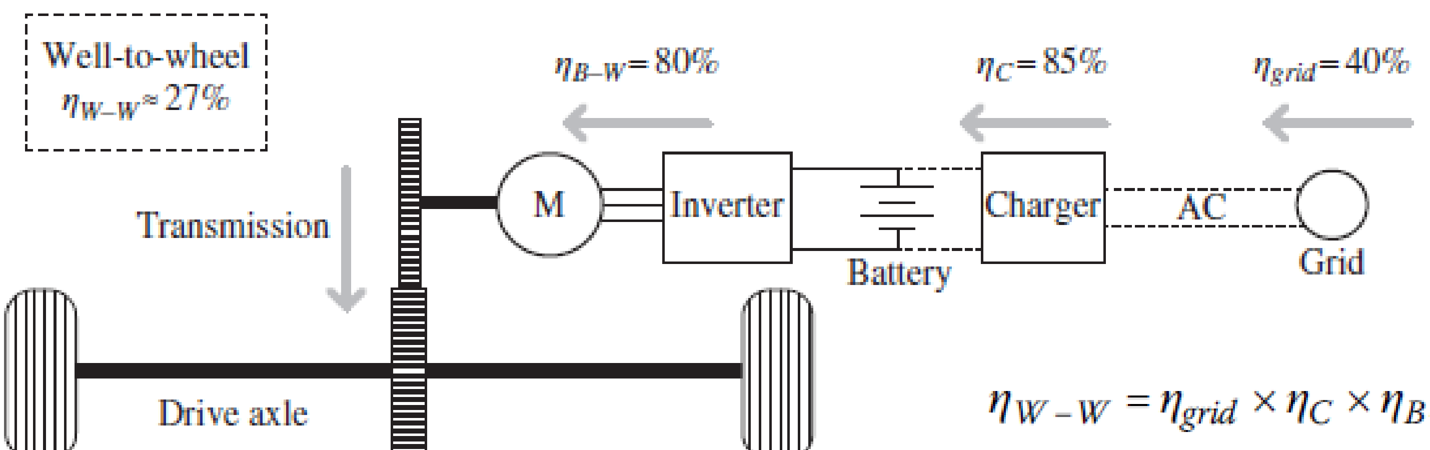


Fig. 19. Conceptual structure of a BEV with outer connection to chargers.

$$\eta_{W-W} = \eta_{grid} \times \eta_C \times \eta_{B-W}$$

BEV merits:

- ✓ Simple construction and operation;
- ✓ Do not produce GHG;
- ✓ Do not create any noise and therefore beneficial to the urban environment;
- ✓ High torques, even at low speeds. A Vehicle in urban driving requires running at slow or medium speeds, which demand a lot of torque (more than 125 Nm).

BEV limitations:

- ✓ Once the battery pack depleted, recharging takes quite a lot of time (a few hour) compared to refueling a conventional ICE vehicle (a few minutes). Charging time depends on the **charger power level and battery technology**;
- ✓ Lower range (mileage) in comparison with the ICE vehicles;
- ✓ High price of the battery pack and therefore, relatively high price of the BEVs.
- ✓ Relatively low cycle life of the batteries.

- ❑ Most famous **BEV productions in 2020** are: **Nissan Leaf** (62kWh battery capacity and 37.000$ price), **Tesla Roadster** (200kWh battery capacity and 200.000$ price), and **Tesla Model Y** (50kWh battery capacity and 39.000$ price).

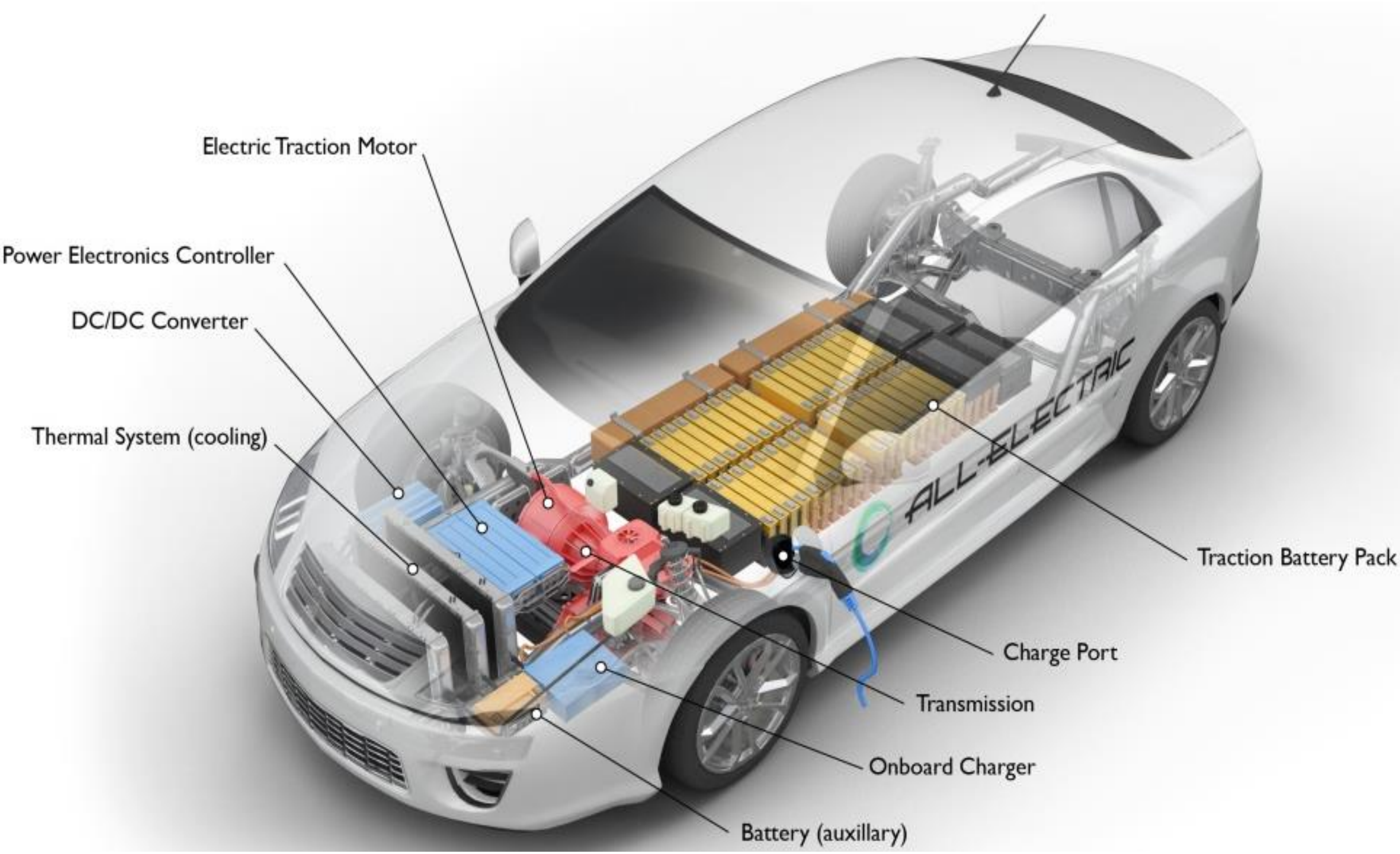


Fig. 20. Conceptual presentation of a typical BEV instruments.

1.5.2. Hybrid Electric Vehicle (HEV)

- **HEVs Employ both ICE and an Electric Power Train (EPR)** as the propulsion system of the vehicle. These two are combined in different forms (**for mileage improving or performance enhancing**):
- ✓ An HEV **uses the electric propulsion** system when the **power demand is low** (urban environment). Also, in **idling periods**, for example traffic jams, the fuel consumption eliminated since the engine stays totally off (reducing GHG). When **higher speed is needed**, the HEV switches to the **ICE**. The two drive trains can also work together to improve the performance and torque boosting.
- ✓ The **power has been splatted between the ICE and the EM** by considering the vehicle speed, driver input, State Of Charge (SOC) of the battery, and the motor speed to attain maximum fuel efficiency.

- Hybrid power systems are used to reduce or to remove turbo lag in turbocharged cars, like the Acura NSX.

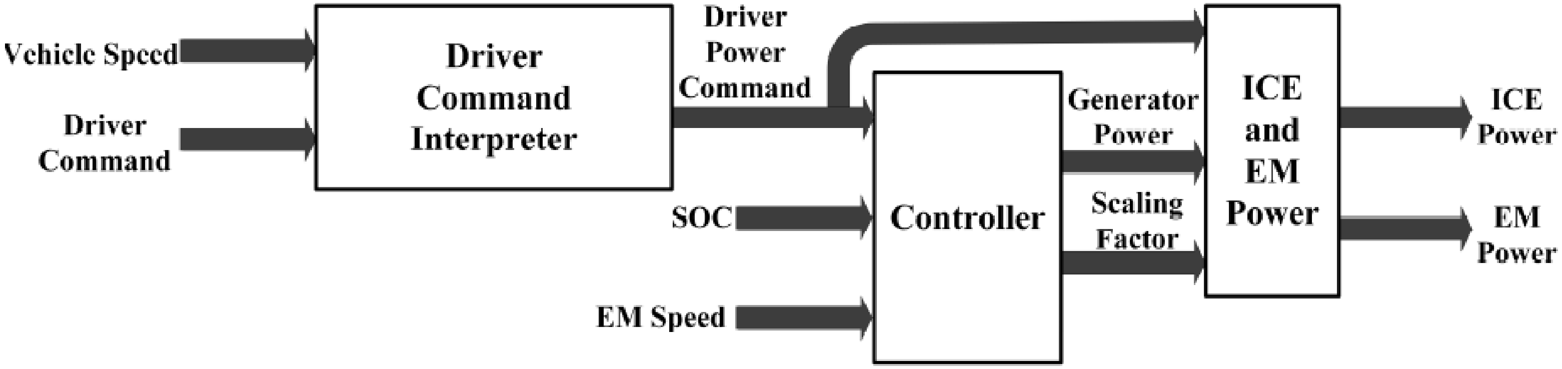


Fig. 21. An example of power management system between ICE and EM in an HEV.

- There are some patterns of operating two power trains to meet the load requirement:

1. Power train 1 alone delivers its power to the load.
2. Power train 2 alone delivers its power to the load.
3. Both power train 1 and power train 2 deliver their power to the load simultaneously.
4. Power train 2 obtains power from the load (regenerative braking).
5. Power train 2 obtains power from power train 1.
6. Power train 2 obtains power from power train 1 and the load simultaneously.
7. Power train 1 delivers power to the load and to power train 2 simultaneously.
8. Power train 1 delivers its power to power train 2, and power train 2 delivers its power to the load.
9. Power train 1 delivers its power to the load, and the load delivers the power to power train 2.

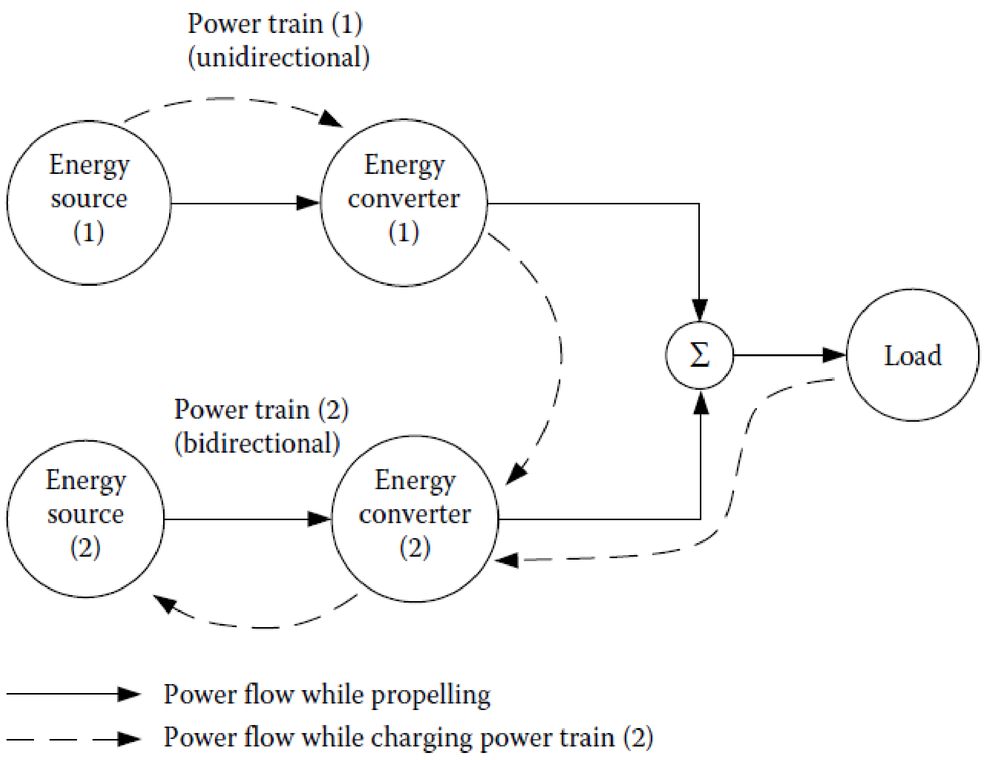


Fig. 22. Conceptual illustration of a hybrid electric drive train

- **HEVs improve the fuel economy** of the conventional fossil-fuel-powered vehicles by addressing **a number of critical factors which impact fuel economy**:

1) Fuel consumption by the engine is eliminated in vehicle idling .
2) Regenerative braking energy is recovered and stored in the battery. In an ICE vehicle, the braking energy is dissipated as heat by the braking system and lost to the vehicle.
3) The stop-start, low-speed, and low-torque nature of city driving is inefficient for the conventional vehicle, whereas the hybrid vehicle decouples the driving condition from efficient operation of the engine by storing and using battery energy when it is efficient to do so.
4) The engine size can be smaller in an HEV compared to an ICE vehicle, and can run more efficiently.
5) Significant low-speed torque can be available in HEVs due to the electric traction motor.

- The hybrid vehicle has **an additional advantage over the BEV**:

1) The battery lifetime can be extended and the battery cost reduced as shallower battery discharges can be implemented in a hybrid system compared to a battery electric car.

- Two famous HEVs are: **Toyota Camry Hybrid SE** (25.000 $ price), **Lexus NX 300h** (40.000 $ price), and **Toyota Prius** (25.000 $ price).



- HEVs are divided into **micro hybrids**, **mild hybrids**, and **power (full) hybrids** based on the relative size of the electric propulsion system with respect to the ICE and the role and functions performed by the electrical and mechanical propulsion systems.
- ✓ **Hybridization Factor (HF)**, in its simplest form, is defined as the ratio between the peak electrical propulsion power and the peak total electrical + mechanical propulsion power:

$$\mathrm{HF} = \frac{P_{EM}}{P_{EM} + P_{ICE}}$$

a) **Micro hybrids:** HF is in the range of **5%–10%** (benefit from the start/stop technology).
b) **Mild hybrids:** HF is usually in the range of **10%–25%** (only use their EM to support the engine during acceleration and cruising. The EM cannot power the car on its own).
c) **Power (full) hybrids:** have higher HFs than **25%** (cruising at speeds up to 50 km/h can be done in a limit distance. At higher speeds or when overtaking on the highway, the engine and EM work together to give a strong boost of power).

- **Note:** in some definitions, **energy hybrid** is pointed that has an ESS larger than power hybrids. Thus, **PHEVs** in Charge-Sustaining (CS) mode are also referred to as energy hybrids because of their larger ESS.
- ❖ **CS means** that the batteries onboard, in CS mode, never fall below a certain level of charge, because they are constantly recharged by regenerative braking or the use of the electric machine as a generator.

- Direction of power flow in the various driving conditions, in a typical HEV, can be categorized in five sections:

a) **Starting:** the ICE may run the motor as a generator to produce some power and store it in the battery.

b) **Stopping:** The power flow is stopped once the vehicle stops.

c) **Passing:** HEV needs a boost in speed, therefore the ICE and the EM both drives the power train.

d) **Braking:** During braking, the power train runs the motor as generator to charge the battery by regenerative braking.

e) **Cruising:** the ICE runs both the HEV and the EM as generator, which charges the battery.

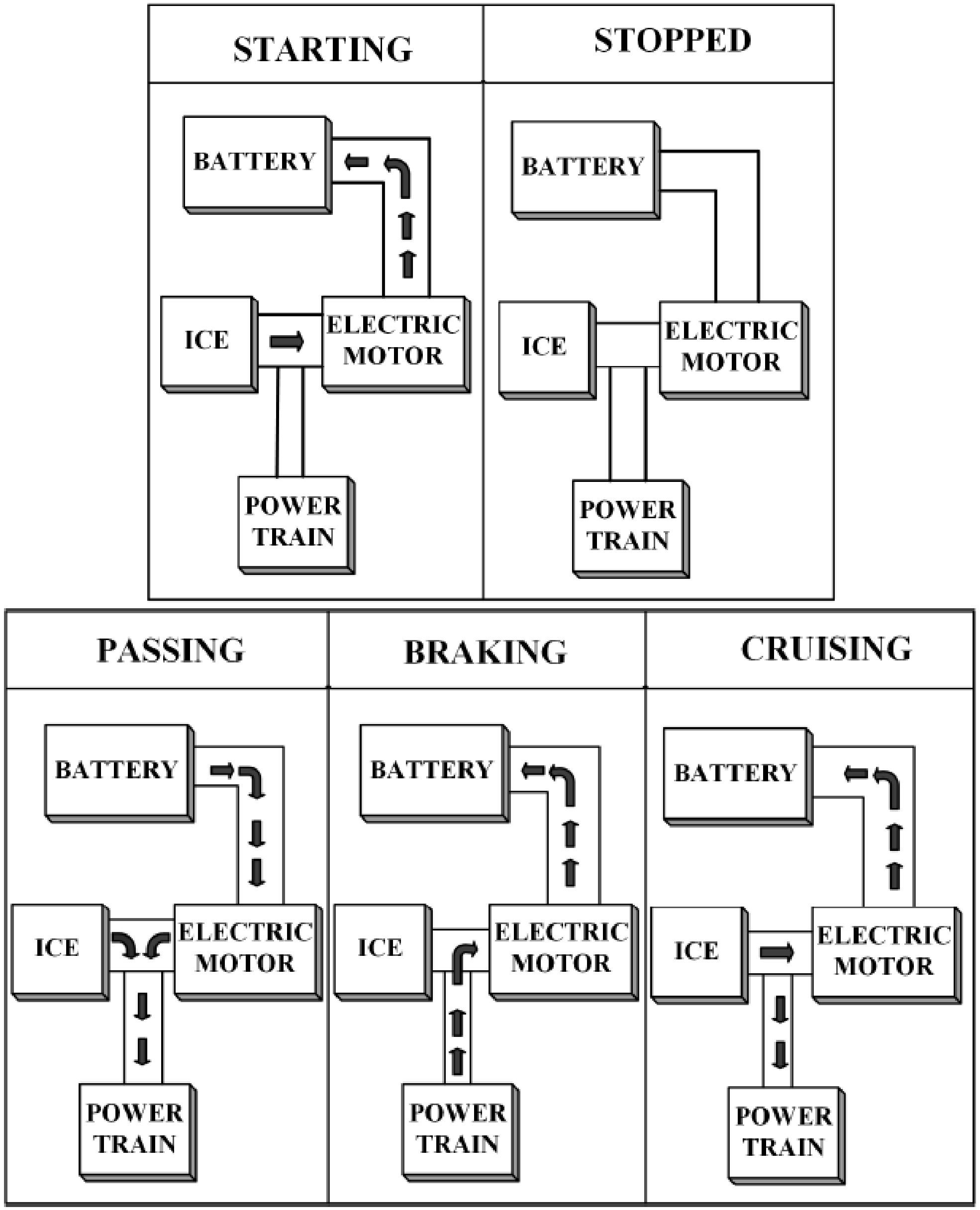


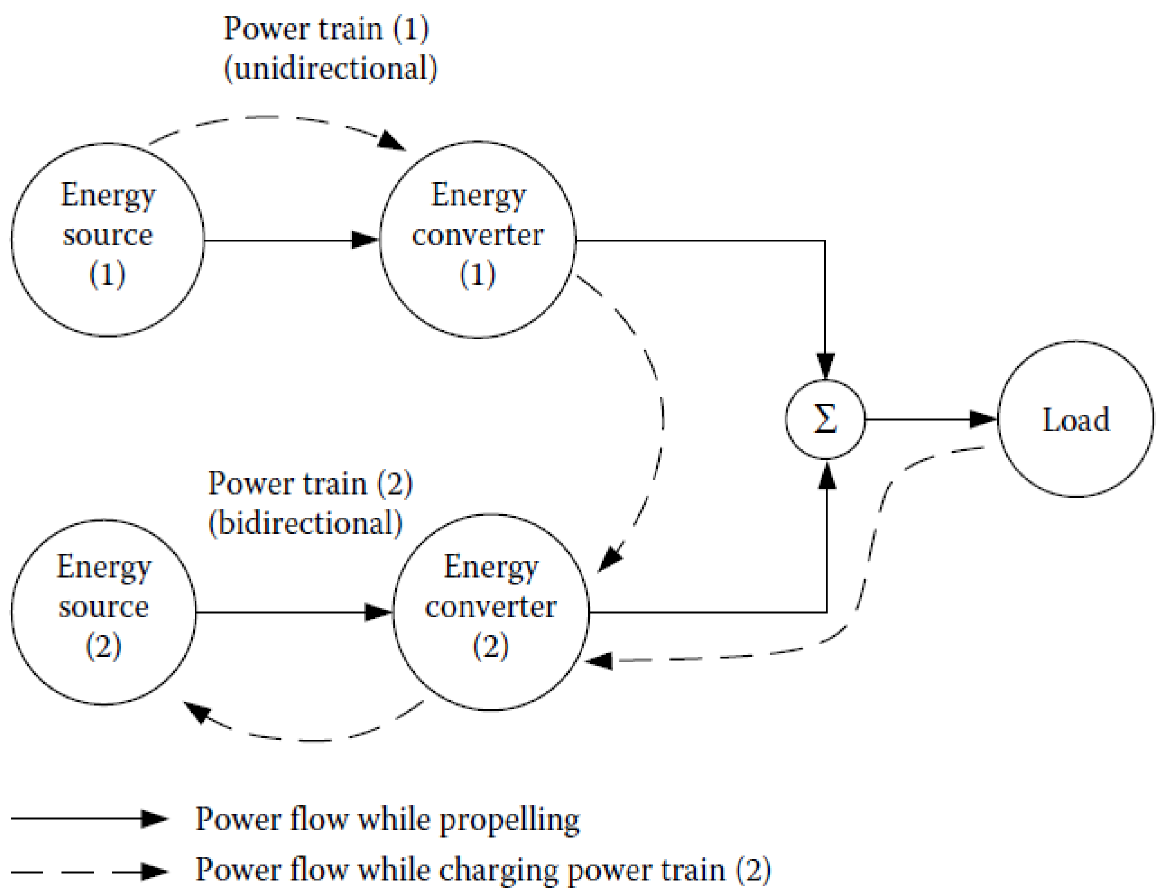
Fig. 23. Power flow among the basic building blocks of a typical HEV during various stages of a drive cycle.

- **HEVs** use both an electrical propulsion system and an ICE. Various architectures in which these two can be set up to spin the wheels and creates different powertrain configurations as:

a) **Series Hybrid;**

b) **Parallel Hybrid;**

c) **Series-Parallel (complex) Hybrid;**



a) Series Hybrid

- ✓ Only the motor is connected to the wheels;
- ✓ The engine is used to run a generator which provides the electrical power;
- ✓ It can be considered as an EV that is assisted by an ICE generator. Also named as: **Extended Range Electric Vehicle (EREV).**
- ✓ combines the best attributes of the ICE (high-energy-density fuel) and the BEV (powertrain efficiency).

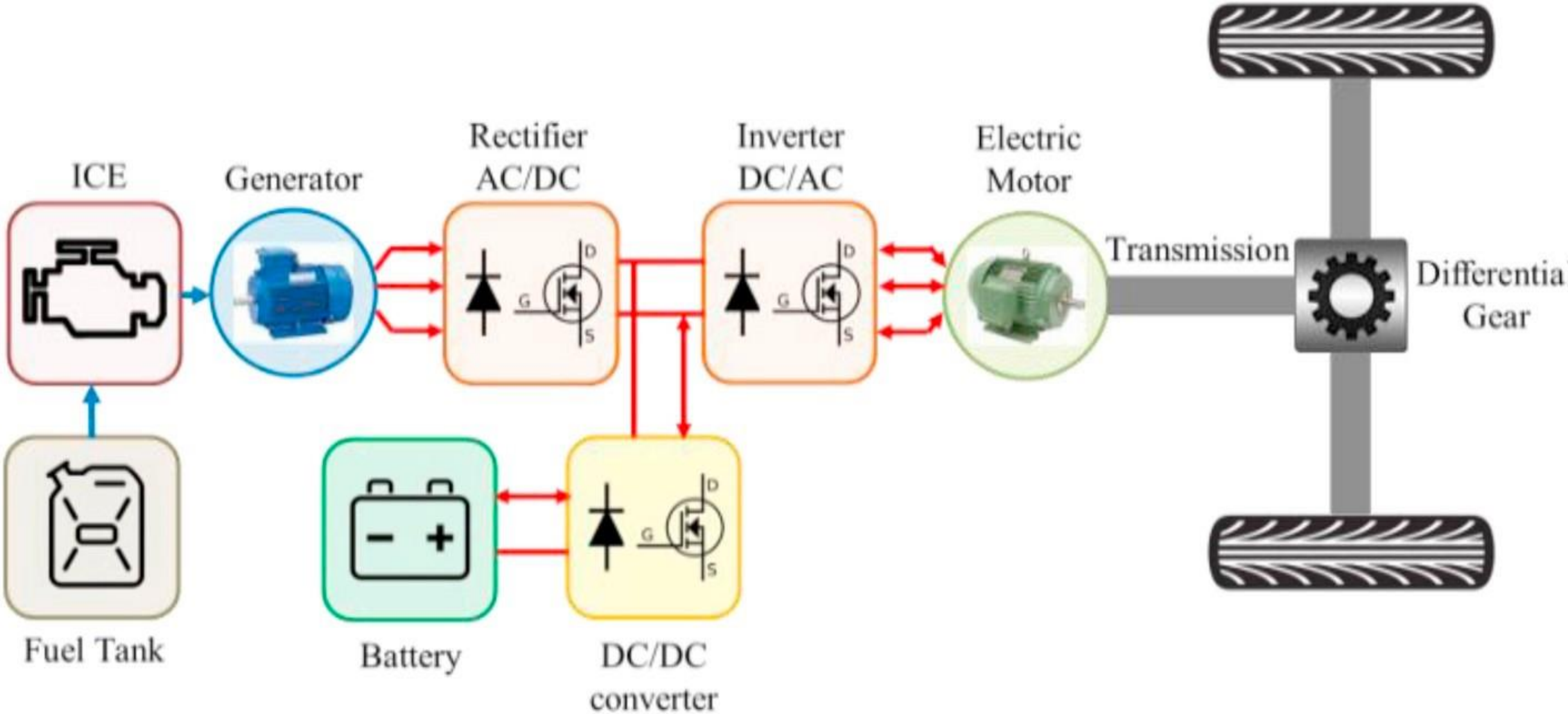


Fig. 24. Configuration of a series hybrid powertrain.

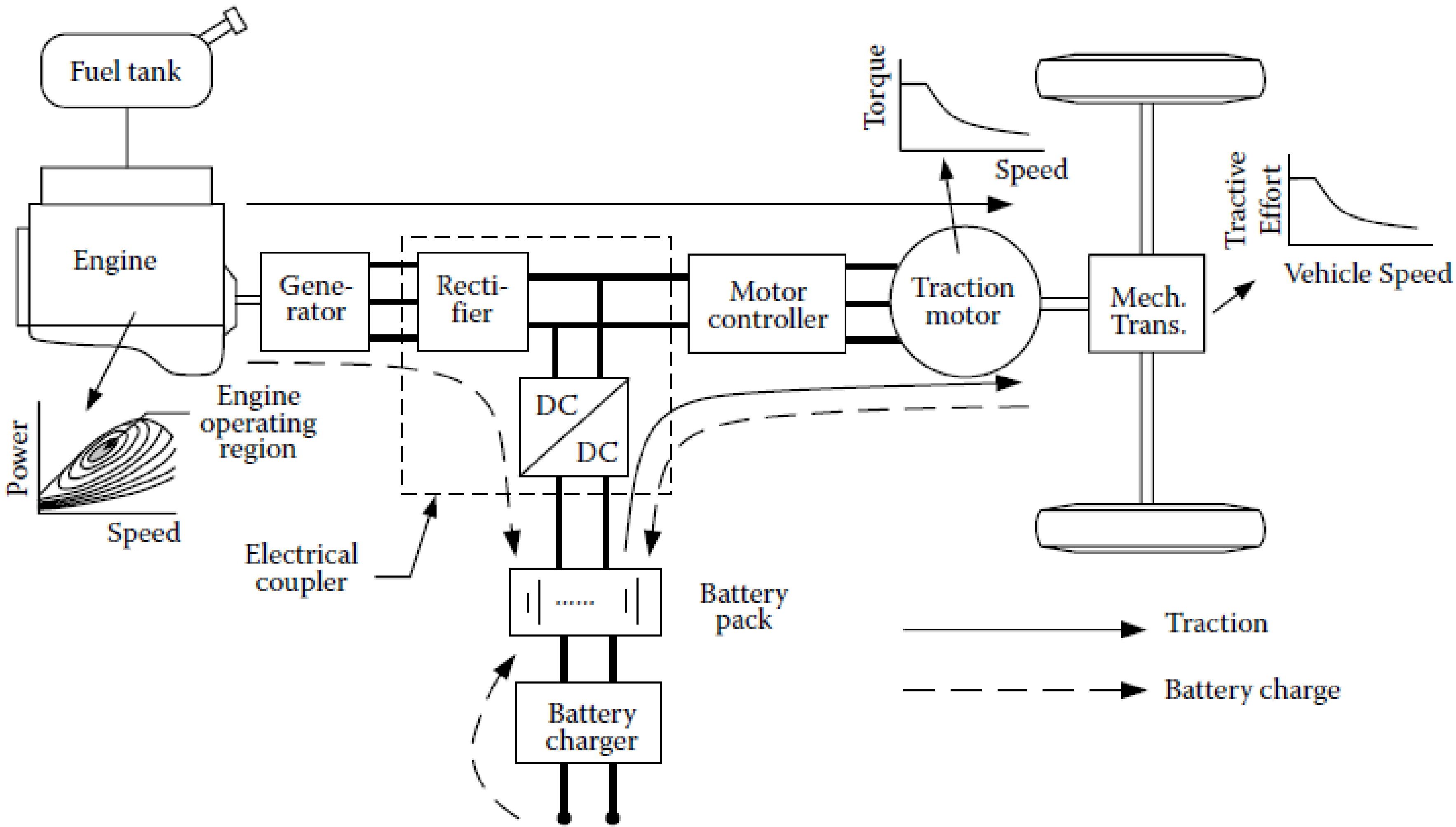


Fig. 25. Configuration of a series hybrid powertrain with powers flow directions.

$$\eta_{W-W} = \eta_{W-T} \times \eta_{eng} \times \eta_{gen} \times \eta_{B-W}$$

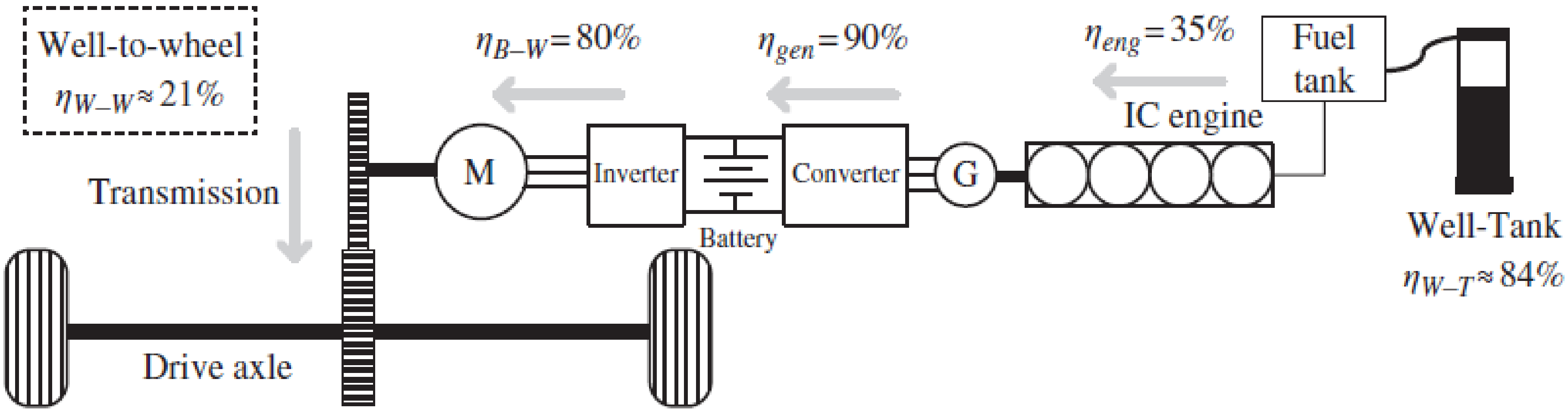


Fig. 26. Efficiency presentation of a series hybrid powertrain.

- **Main applications:** larger vehicles such as heavy-duty buses, trucks and locomotives.
- **Chevrolet Volt** (35.000 $ price), **Cadillac ELR** (45.000 $ price), and **BMW i3** (45.000 $ price) are three samples of EREVs.



Fig. 27. Operating modes of a series hybrid powertrain:
(a) EM is the only propulsive;
(b) ICE is supplying the propulsive torque/power demand;
(c) ICE and EMs are supplying the propulsive torque/power demand;
(d) regenerative braking mode of the vehicle;
(e) ICE supplies the propulsive torque/power demand of the vehicle and charge the battery;
(f) ICE charges the battery system (also, battery can receive power from regenerative braking).

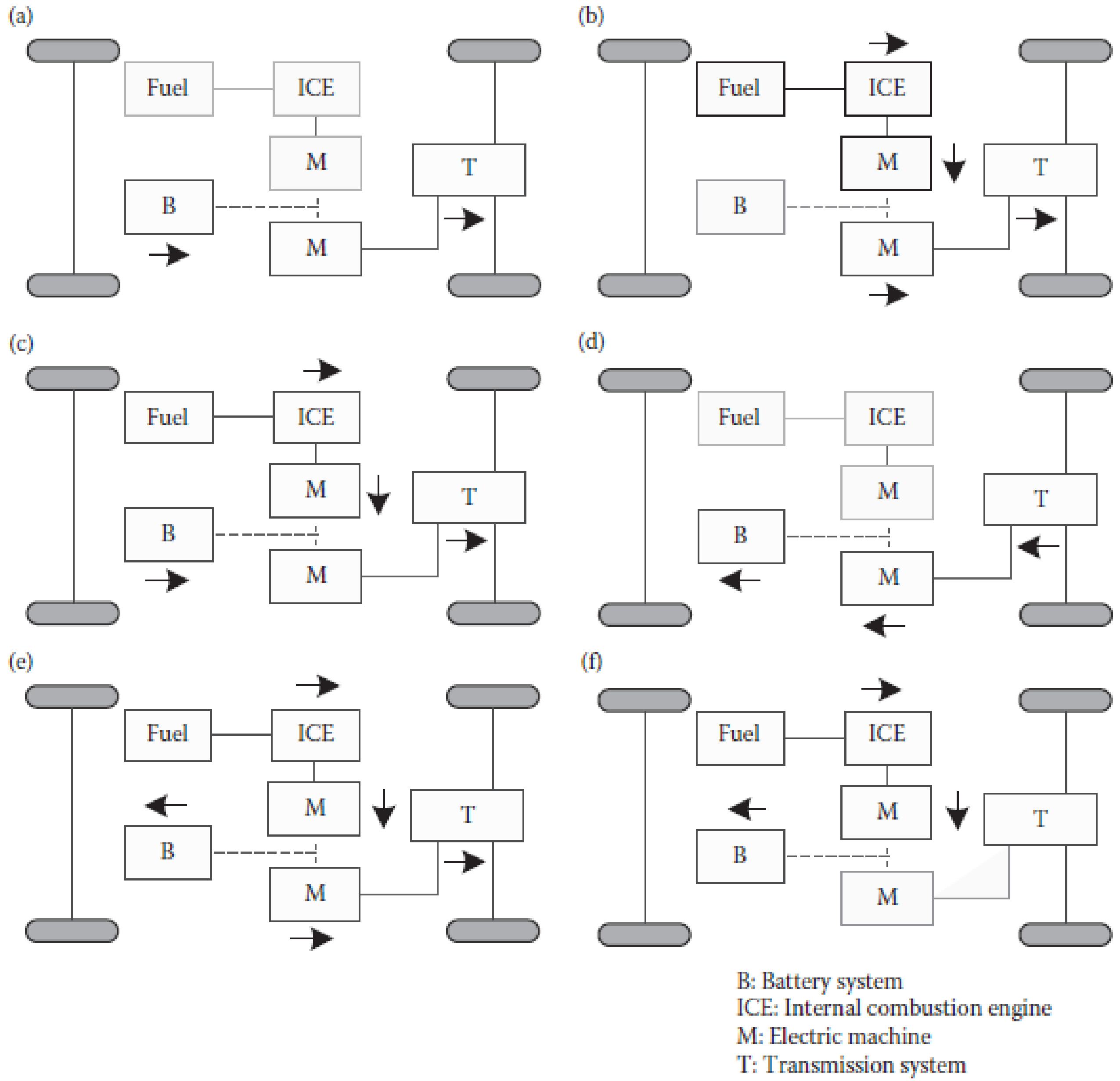
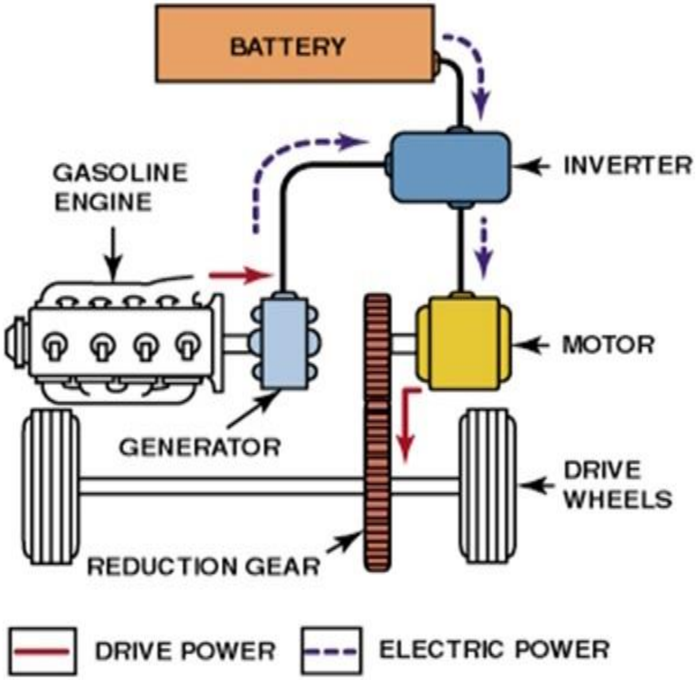


Table 2. A series hybrid powertrain merits and limitations.

Advantages	Efficient and optimized power-plant Possibilities for modular power-plant Optimized drive line Possibility of swift 'black box' service exchange Long lifetime Mature technology Fast response Capable of attaining zero emission
Limitations	Large traction drive system Requirement of proper algorithms Multiple energy conversion steps



b) Parallel Hybrid

- ✓ both the ICE and the EM are connected in parallel to the wheels and either or both of (ICE and EM) take part in delivering the power;
- ✓ Can be considered as an ICE vehicle with EM assistance;
- ✓ The energy storages can be charged by the EM by means of regenerative braking or by the ICE, when it produces more than the power required to drive the wheels.
- ✓ Has been implemented using a **Dual-Clutch Transmission** (**DCT**) on vehicles such as the **Honda Fit** and the **Hyundai Ioniq**.

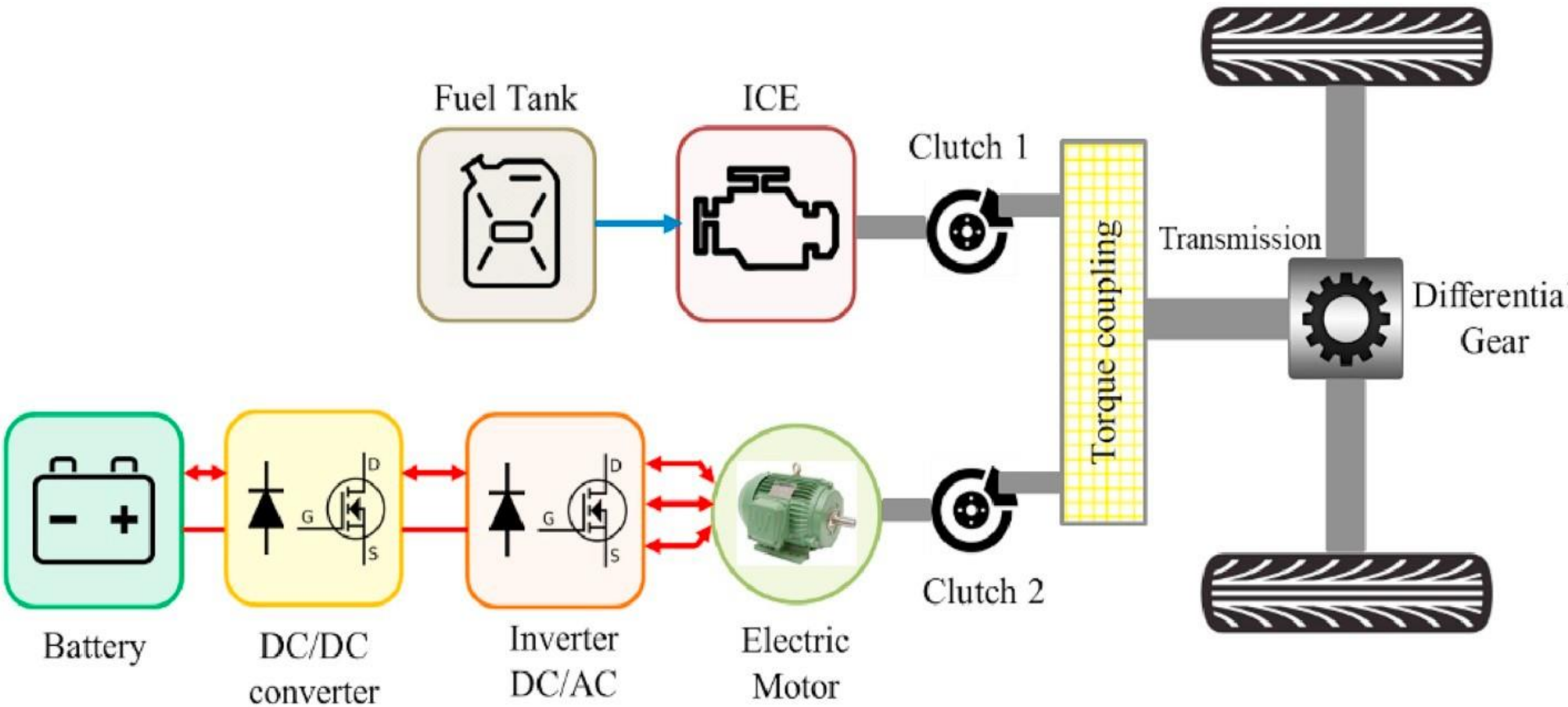


Fig. 28. Configuration of a parallel hybrid powertrain.

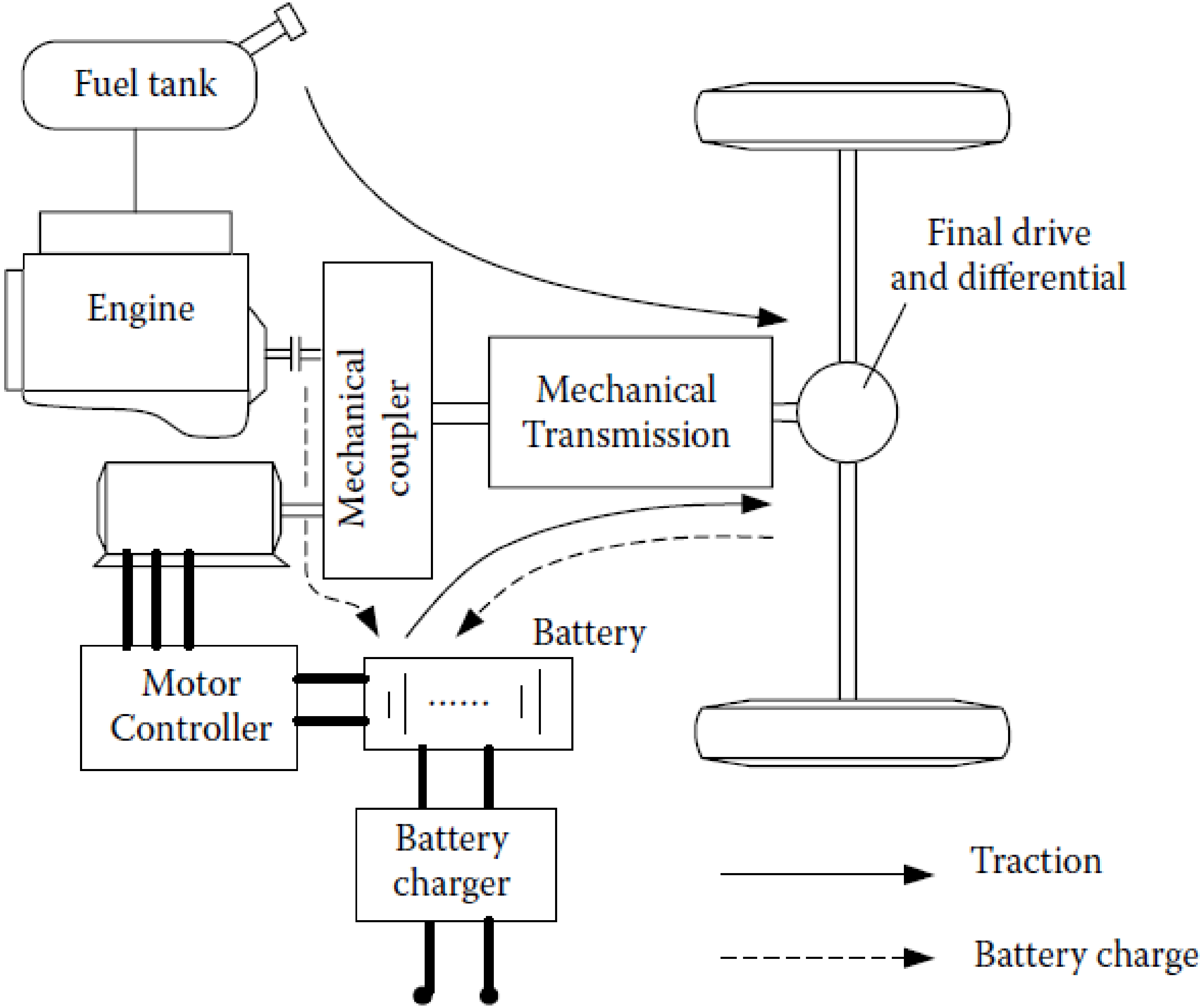


Fig. 29. Configuration of a parallel hybrid powertrain with powers flow directions.

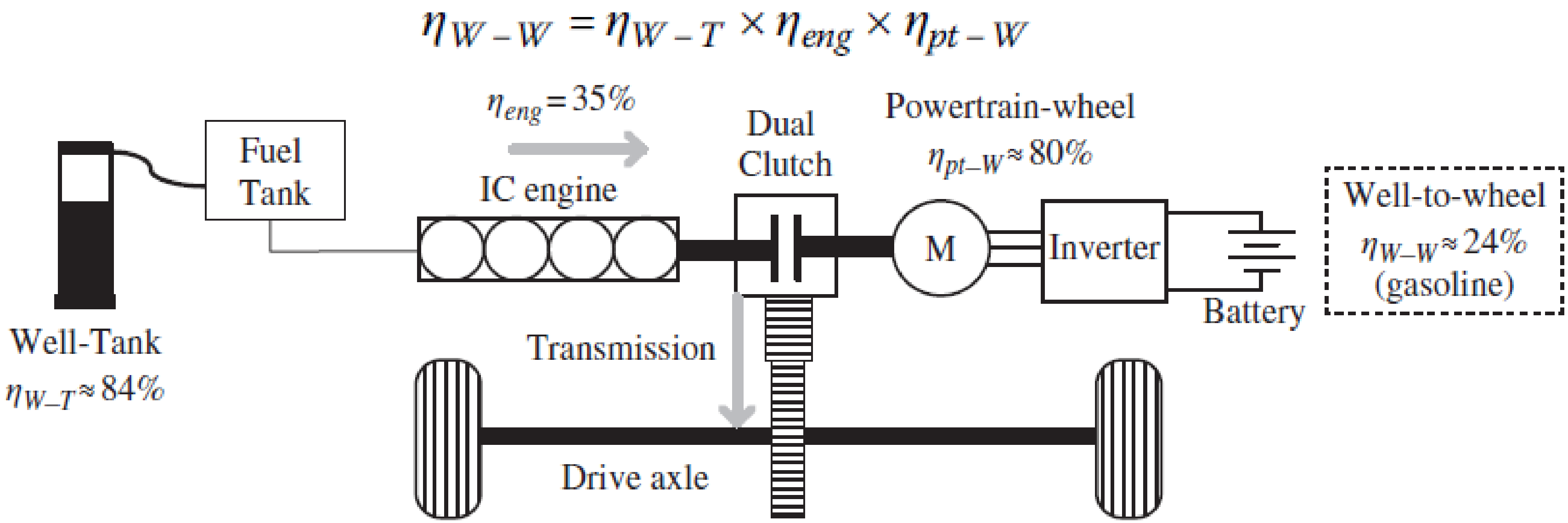


Fig. 30. Efficiency presentation of a parallel hybrid powertrain.

- ❑ **Main applications:** urban passenger cars.
- ❑ **Honda Fit** (17.000 $ price) and **Hyundai Loniq** (26.000 $ price) are two samples that use from parallel hybrid powertrain.

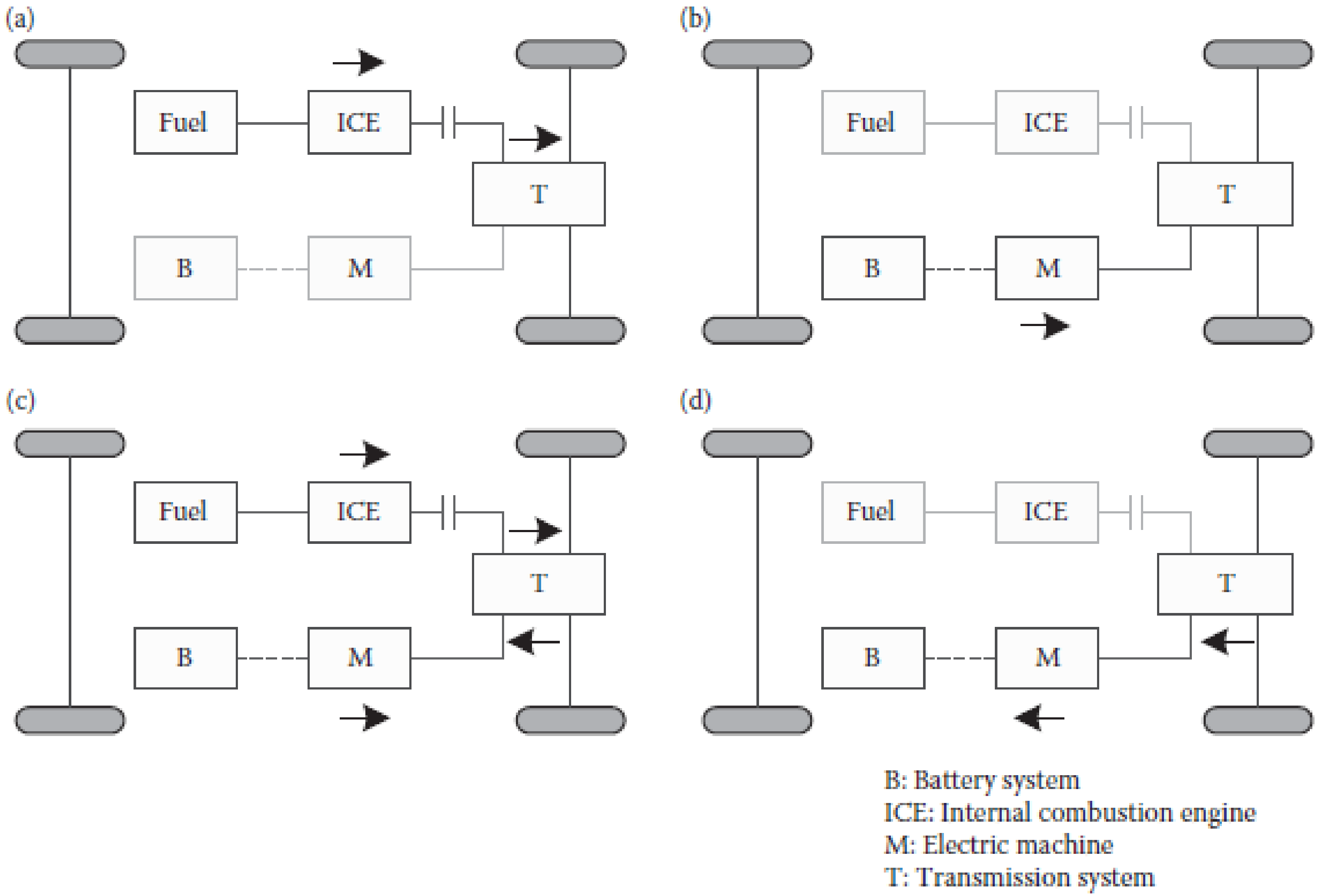


Fig. 31. Operating modes of a series hybrid powertrain:
(a) ICE supplies the propulsive torque/power demand;
(b) EM is the only propulsive medium;
(c) ICE and EMs supply the propulsive torque/power demand;
(d) regenerative braking mode of the vehicle.

Table 3. A series hybrid powertrain merits and limitations.

Advantages	Capable of attaining zero emission Economic gain More flexibility
Limitations	Expensive Complex control Requirement of proper algorithms Need of high voltage to ensure efficiency

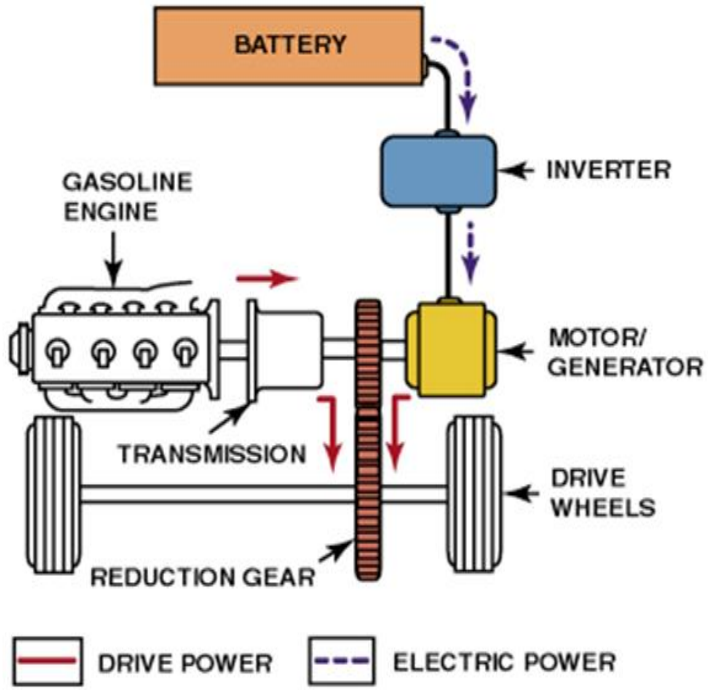


Table 4. Electrical characteristics comparison of parallel and series hybrid powertrain configurations.

Parameters	Parallel HEV	Series HEV
Voltage	14 V, 42 V, 144 V, 300 V	216 V, 274 V, 300 V, 350 V, 550 V, 900 V
Power requirement	3 KW–40 KW	>50 KW
Relative gain in fuel economy (%)	5–40	>75

c) Series-Parallel (complex) Hybrid

- ✓ Has an **additional mechanical link** compared to the **series** type, or an **extra generator and power conversion system** when compared to the **parallel** type;
- ✓ Has the advantages of both the systems but is more costly and complicated nonetheless;
- ❑ Complications in drive train are caused to some extent by the presence of a sun and planetary gear unit.

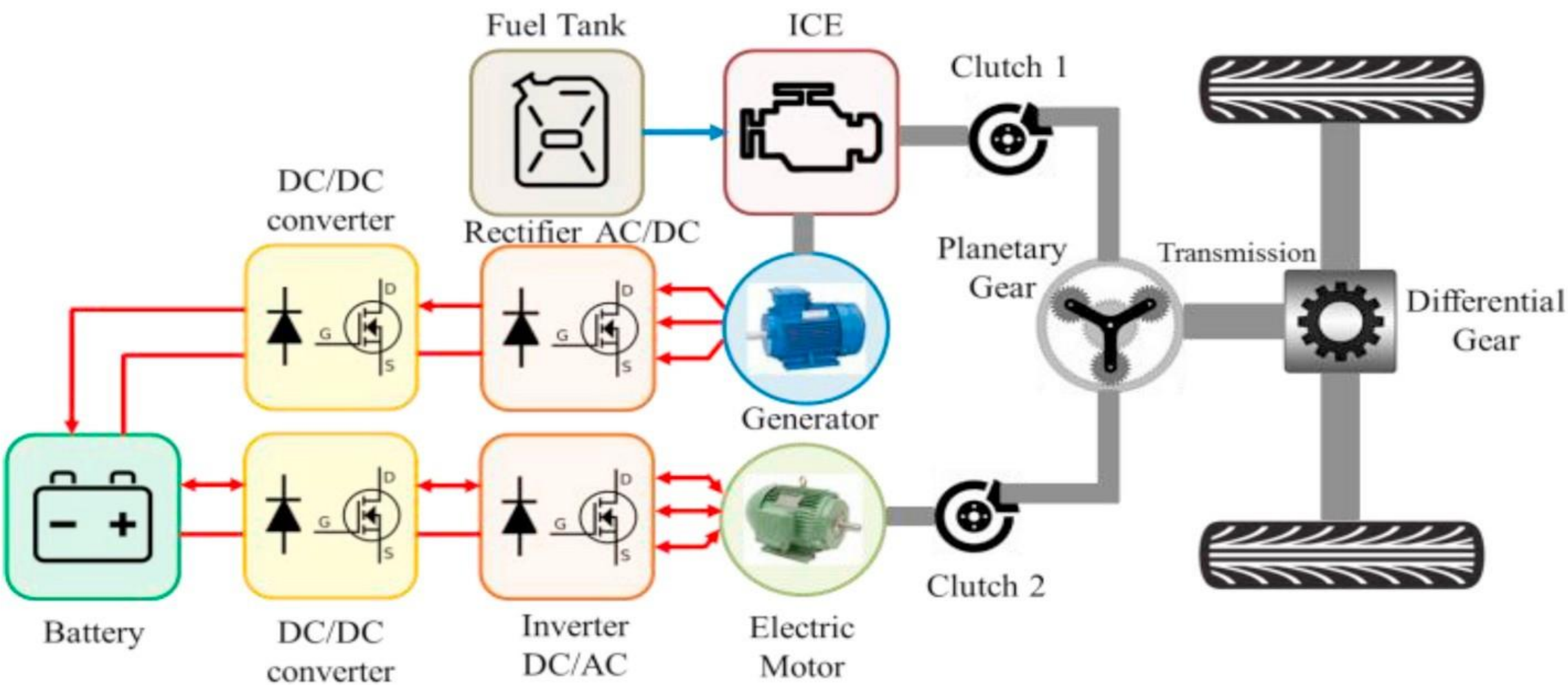


Fig. 32. Configuration of a series-parallel hybrid powertrain.

$$\eta_{W-W} = \eta_{W-T} \times \eta_{eng} \times \eta_{pt-W}$$

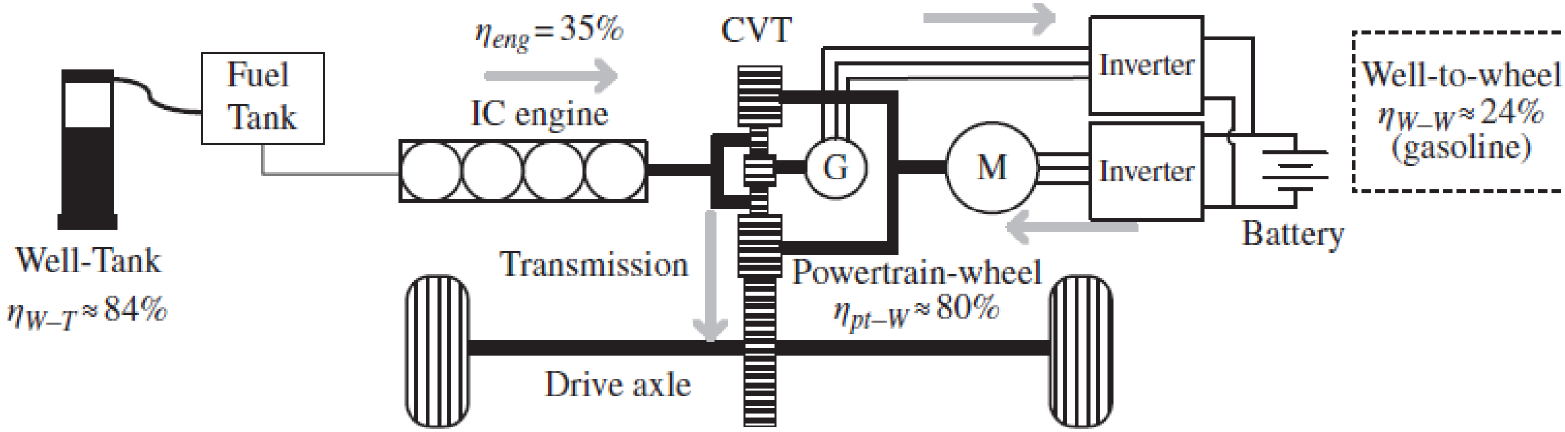


Fig. 33. Efficiency presentation of a series-parallel hybrid powertrain.

- **Main applications:** passenger cars, light duty vehicles
- **Toyota Prius** (25.000 $ price) and **Ford Escape** (36.000 $ price) are two samples that use from series-parallel hybrid powertrain.

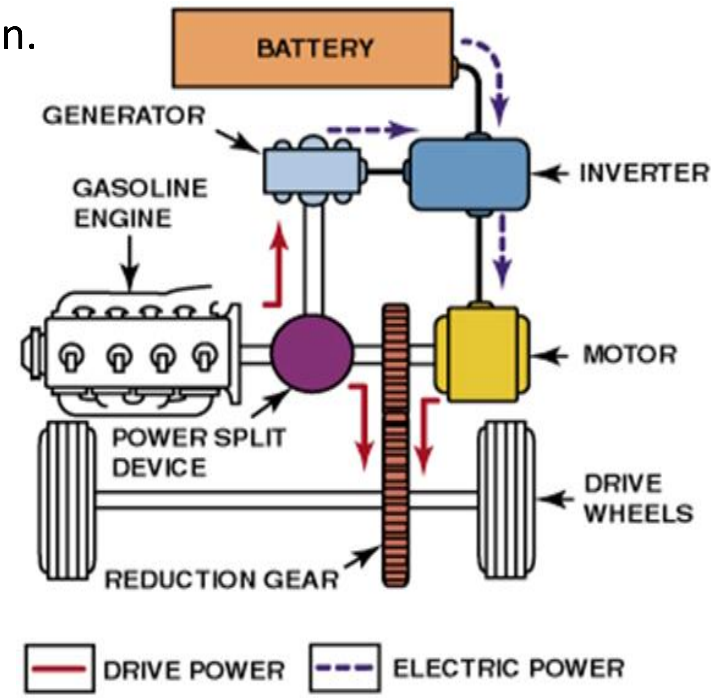
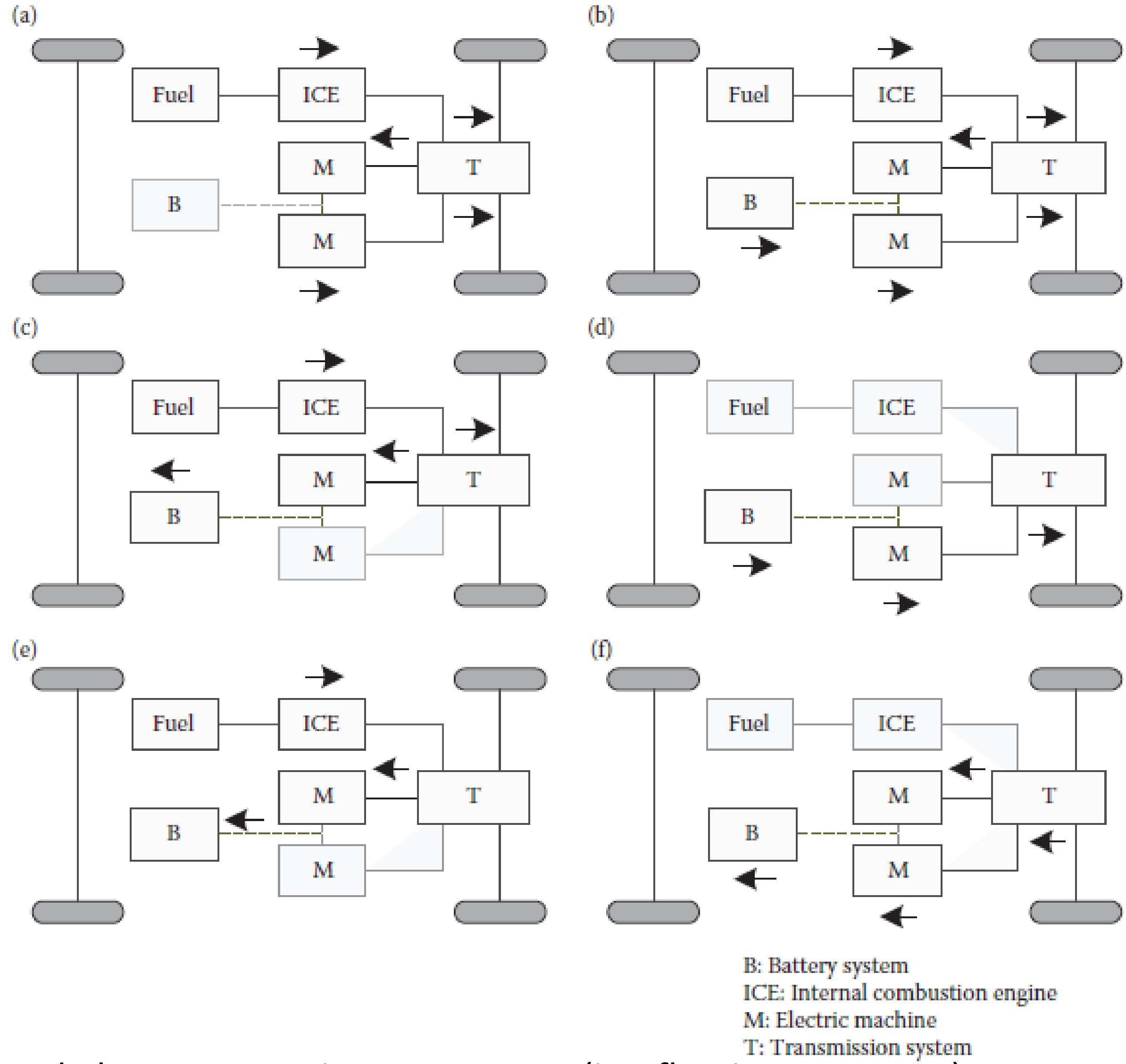


Fig. 34. Operating modes of a series-parallel hybrid powertrain:
(a) ICE is the only propulsive medium. Here part of the power produced by the ICE is converter via motor generator to the traction wheels;
(b) ICE and electric batteries are supplying the propulsive torque/power demand;
(c) ICE is supplying the propulsive torque/power demand while the battery is charging;
(d) Batteries are supplying the propulsive demand;
(e) ICE charges the battery while the vehicle is standstill;
(f) Regenerative braking of the vehicle.



- ❑ A less complex alternative for sun and planetary gear is a **transmotor** (is a floating-stator EM):
- ✓ The planetary gear system is eliminated;
- ✓ the engine is attached to the stator;
- ✓ the rotor stays connected to the drive train wheel through the gears;
- ✓ The motor speed is the relative speed between the rotor and the stator;
- ✓ controlling it adjusts the engine speed for any particular vehicle speed.

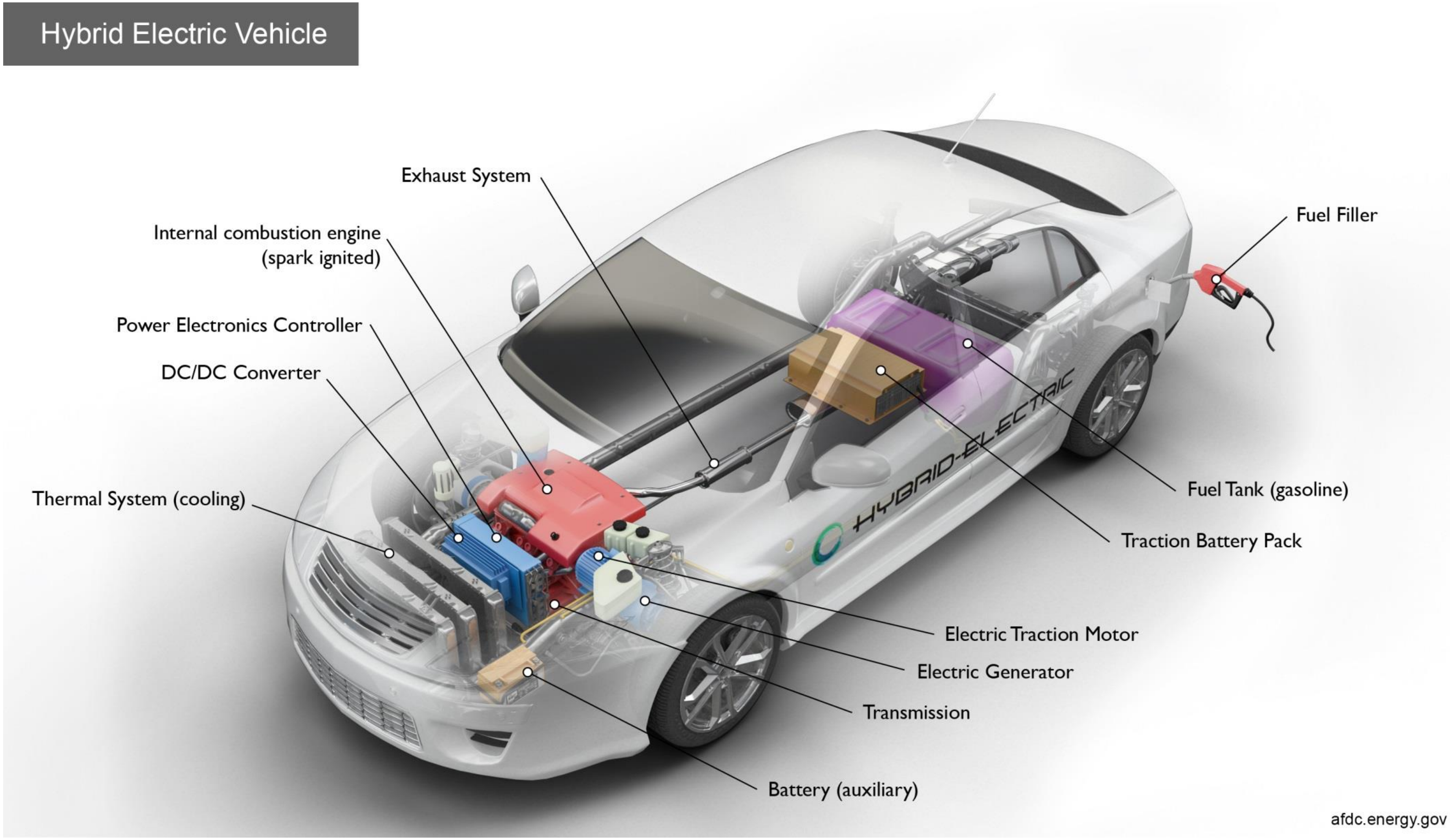


Fig. 35. Conceptual presentation of a typical HEV instruments.

1.5.3. Plug-in Hybrid Electric Vehicle (PHEV)

- ❑ The PHEV concept arose **to extend the all-electric range of HEVs**. It like an HEV, but the difference between them is that the PHEV uses **electric propulsion** as the **main driving force**, so these vehicles require **a bigger battery capacity than HEVs**.
- ✓ When the PHEV battery is low in charge, it calls on the ICE to provide a boost or to charge up the battery pack. The ICE is used here to extend the range.
- ✓ PHEVs can charge their batteries directly from the grid (which HEVs cannot) and have the facility to utilize regenerative braking.
- ✓ PHEV has ability **to run solely on electricity for most of the time**, makes its carbon footprint smaller than the HEVs. They consume **less fuel** as well and thus **reduce the associated cost**.

- ❑ A PHEV run in BEV mode for a significant distance. A PHEV running as a BEV is operating in **Charge Depleting** (**CD**) mode. A PHEV running as a HEV and maintaining the battery at an average State Of Charge (SOC) is operating in **Charge-Sustaining** (**CS**) mode.

- ❑ The vehicle market is populated with these PHEVs: **Chevrolet Volt** (35.000 $ price), **Toyota Prius Prime** (28.000 $ price)**, and Mitsubishi Outlander** (25.000 $ price).

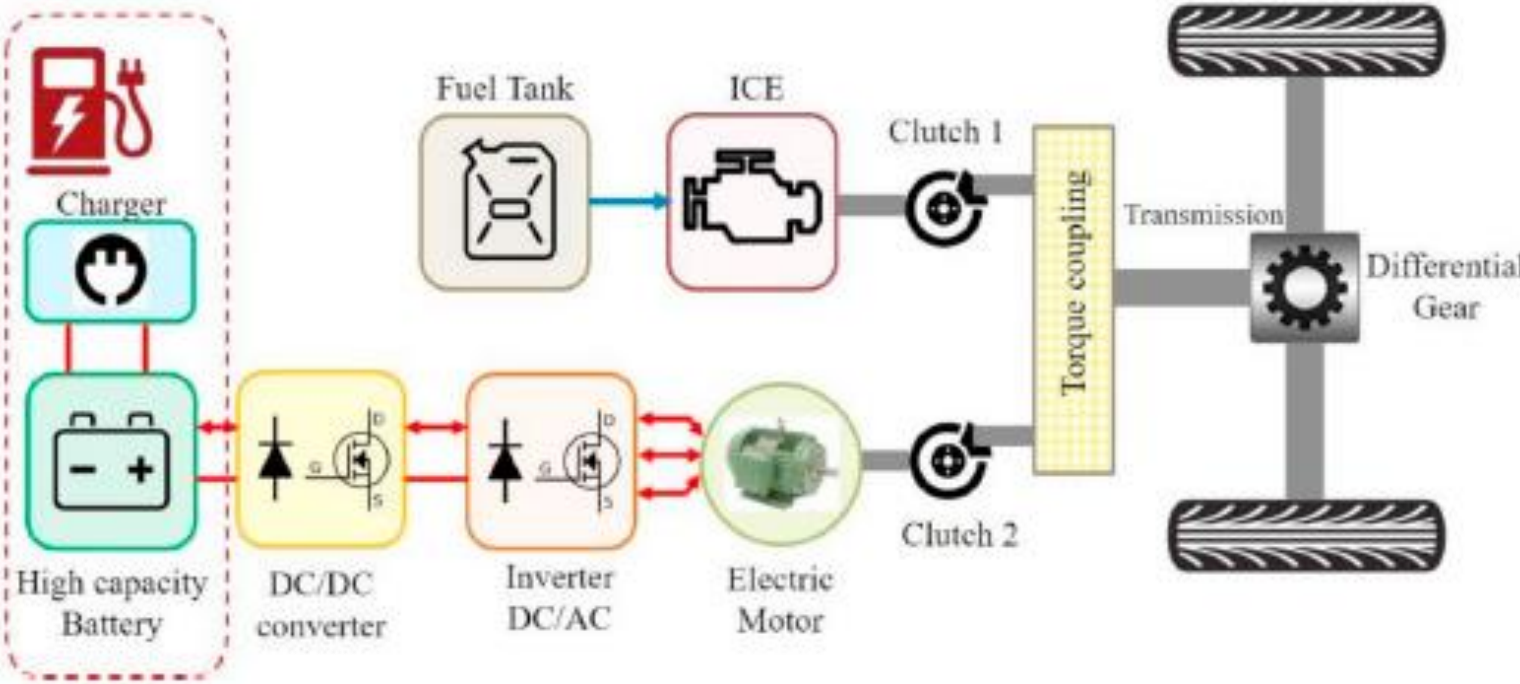


Fig. 36. Powertrain configuration of a PHEV.

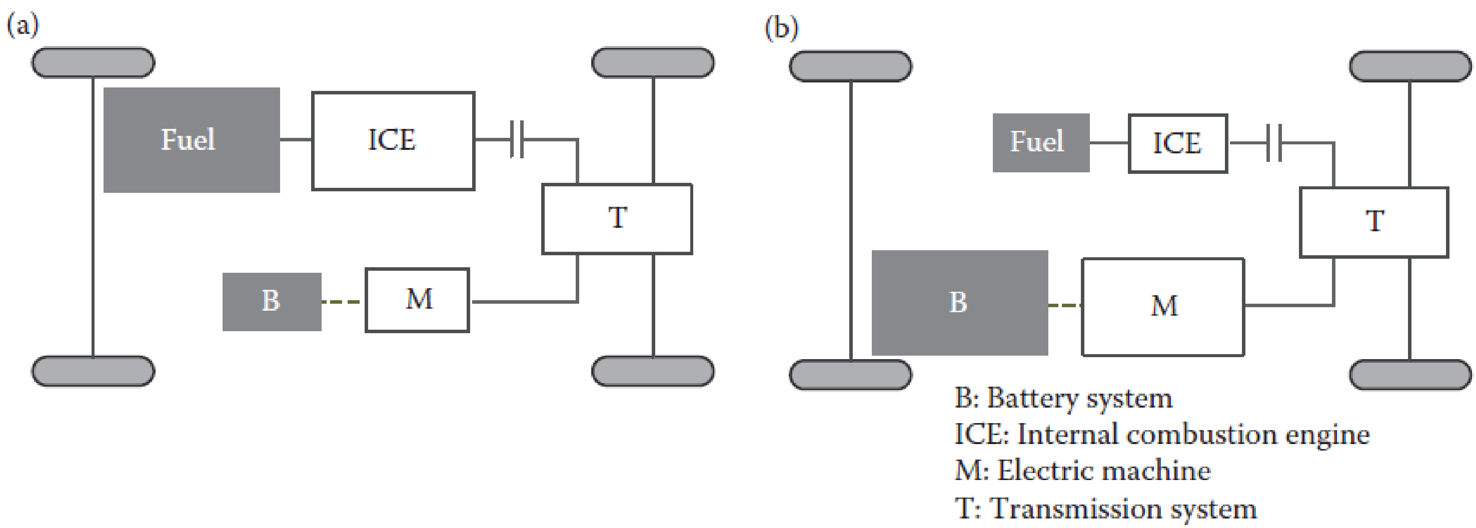


Fig. 37. ESS difference between a parallel HEV and a parallel PHEV:
(a) parallel HEV, (b) parallel PHEV.

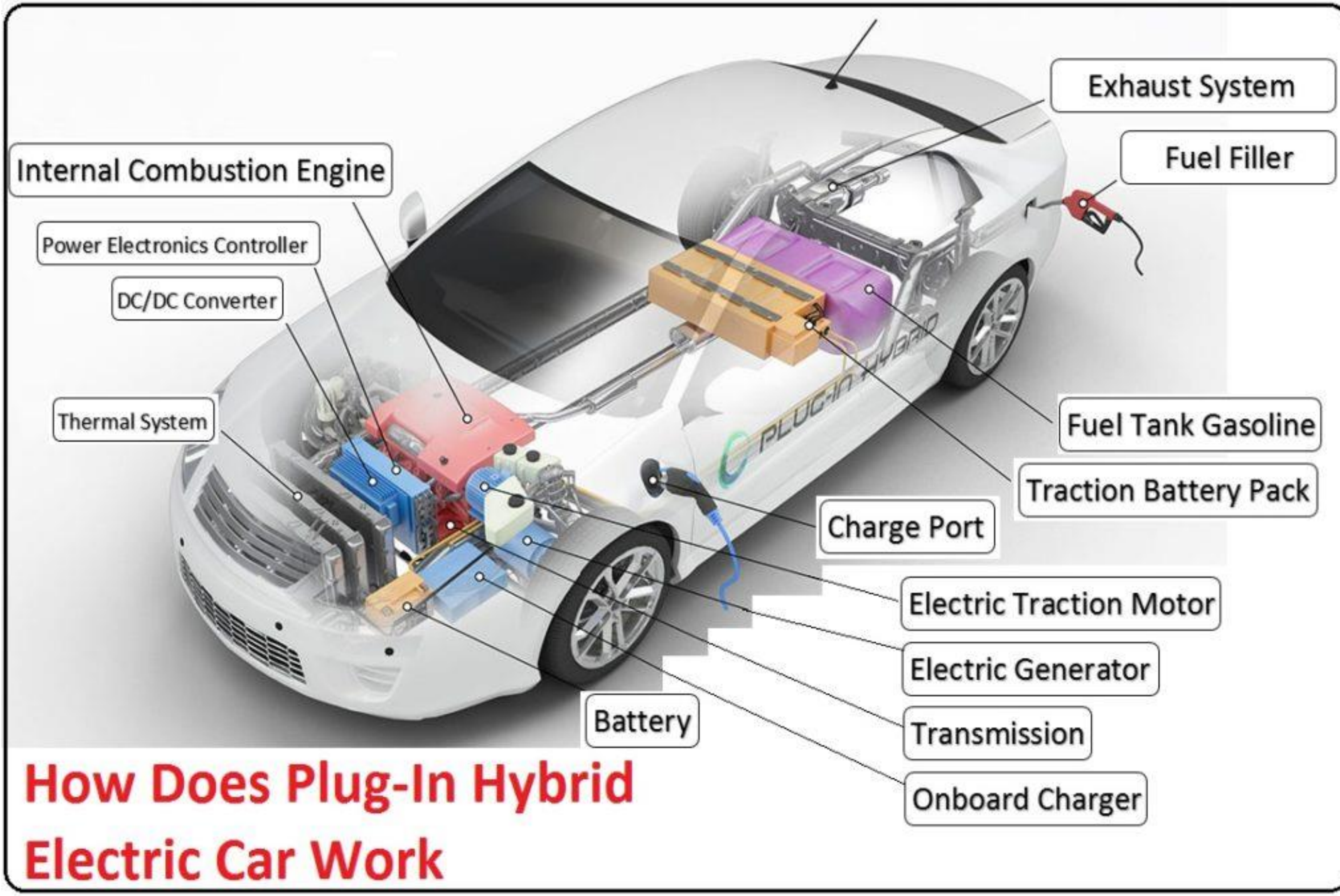


Fig. 38. Conceptual presentation of a typical PHEV instruments.

❑ **Degree of hybridization** can be classified according to some capabilities as:

The vehicle is a….

If it…	Micro Hybrid	Mild Hybrid	Full Hybrid	Plug-in Hybrid
Automatically stops/starts the engine in stop-and-go traffic	✓	✓	✓	✓
Uses regenerative braking and operates above 60 volts		✓	✓	✓
Uses an electric motor to assist a combustion engine		✓	✓	✓
Can drive at times using only the electric motor			✓	✓
Recharges batteries from a wall outlet for extended all-electric range				✓

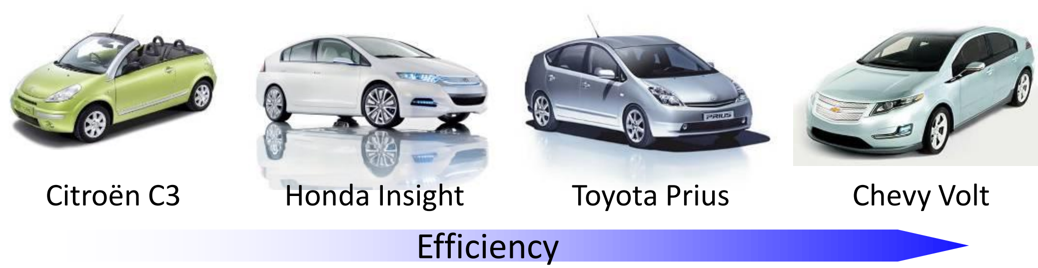


Fig. 39. EVs capability in various degrees of hybridization.

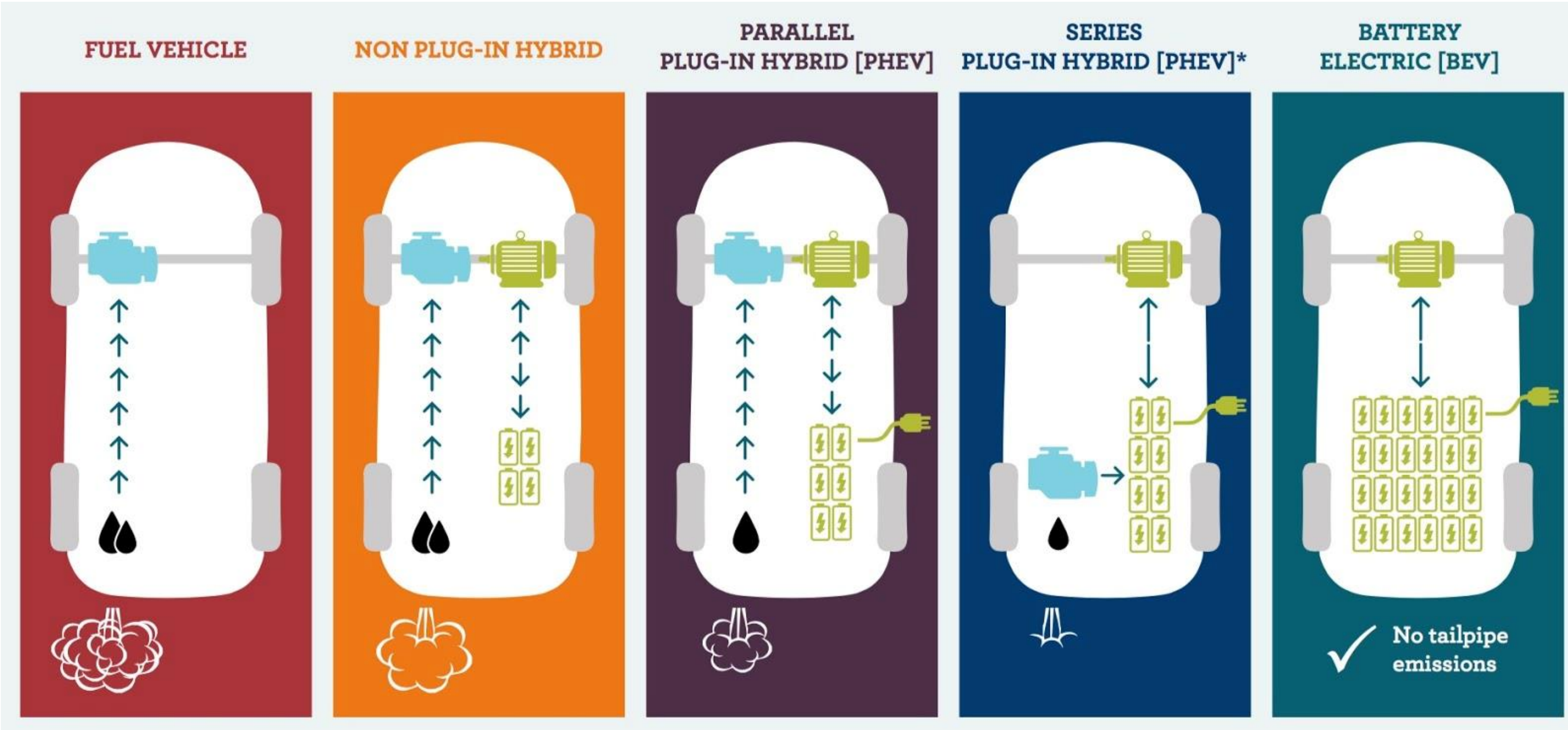


Fig. 40. Comparison of GHG emission in various types of EVs.

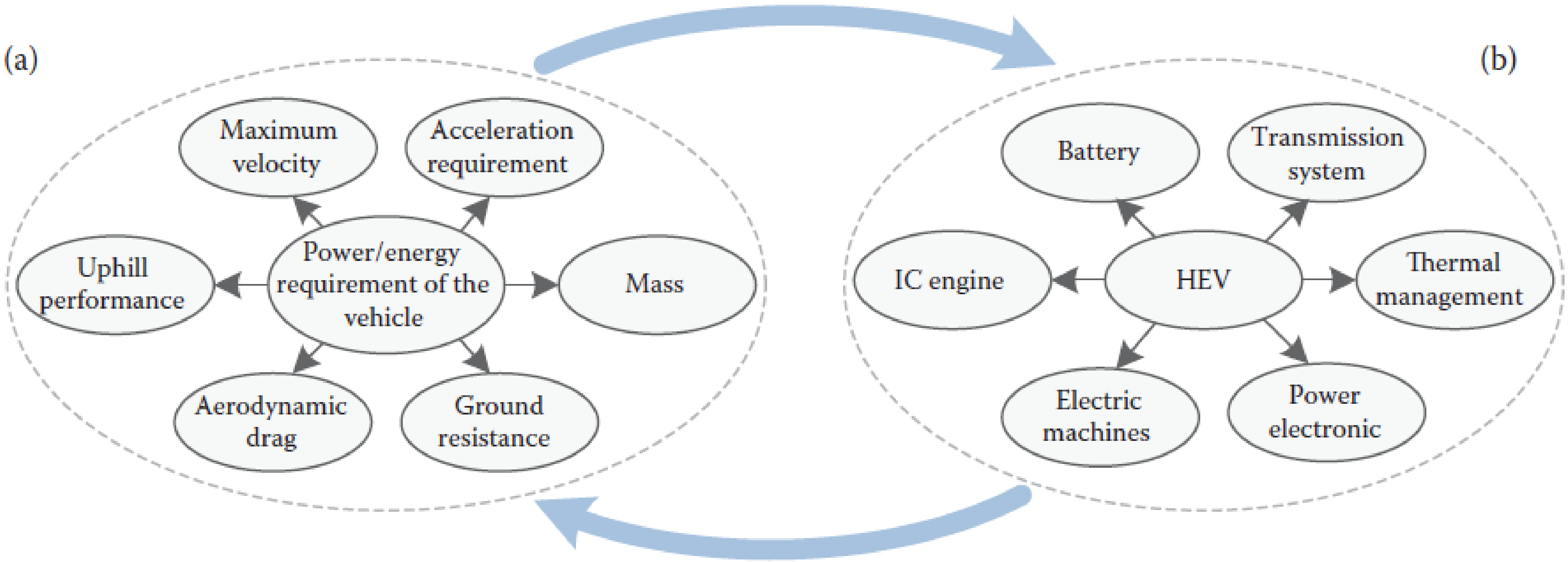


Fig. 41. Power and energy requirement of the vehicle and their effect on HEV/PHEV design. (a) Key design parameters to define the power and energy requirements of the vehicle. (b) Power and energy supplying components of the powertrain.

1.5.4. Fuel Cell Electric Vehicle (FCEV)

- **FCEVs or FCVs** got the name because the heart of such vehicles is FC that uses chemical reactions to produce electricity.
- ✓ FCEVs carry the **hydrogen** in special **high pressure tanks**. Another ingredient for the power generating process is **oxygen**, which it acquires from the air sucked in from the environment. Electricity generated from the FCs goes to an EM which drives the wheels.
- ✓ **Excess energy** is stored in storage systems like **batteries** or **UCs**.
- ✓ FCVs only produce water as a byproduct of its power generating process which is ejected out of the car through the tailpipes (produced HGH is near to zero).
- ✓ Commercially available FCEVs that use the battery are: **Toyota Mirai** (20.000 $ price), and **Honda Clarity** (17.000 $ price).

$$\eta_{W-W} = \eta_{W-T} \times \eta_{fc} \times \eta_{pt-W}$$

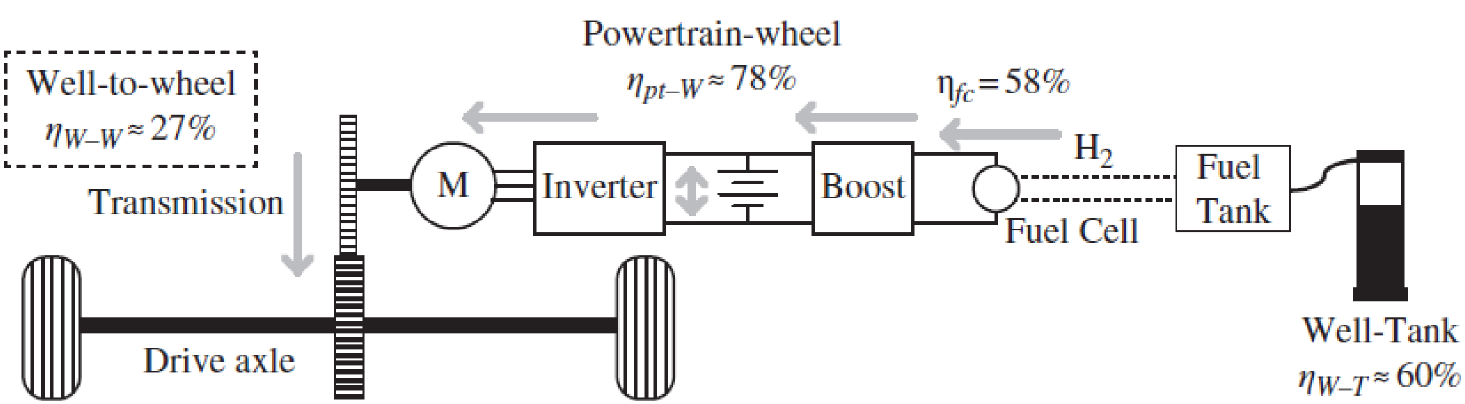


Fig. 42. An FCEV block diagram configuration.

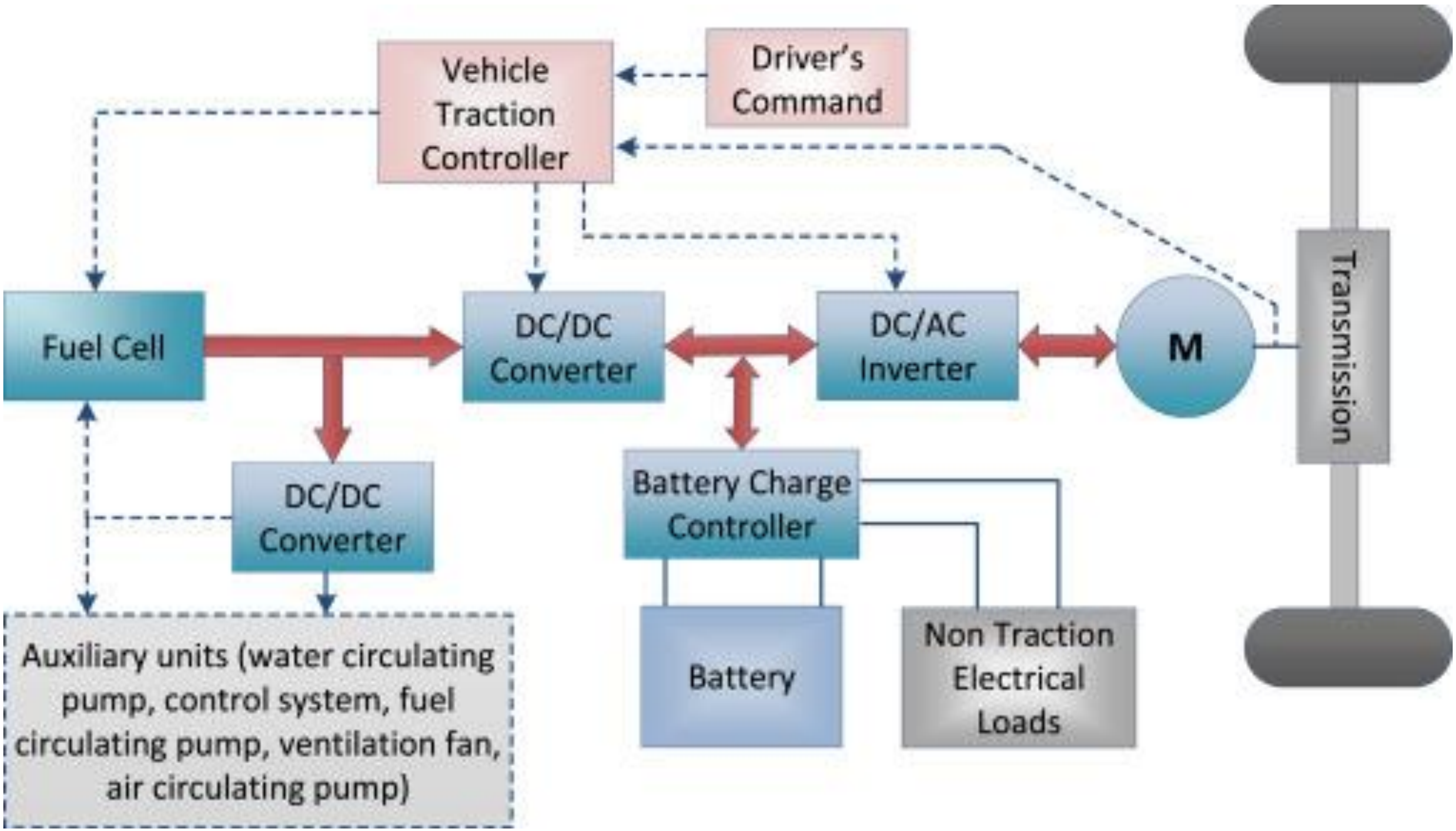


Fig. 43. Block diagram presentation of a FC-based powertrain..

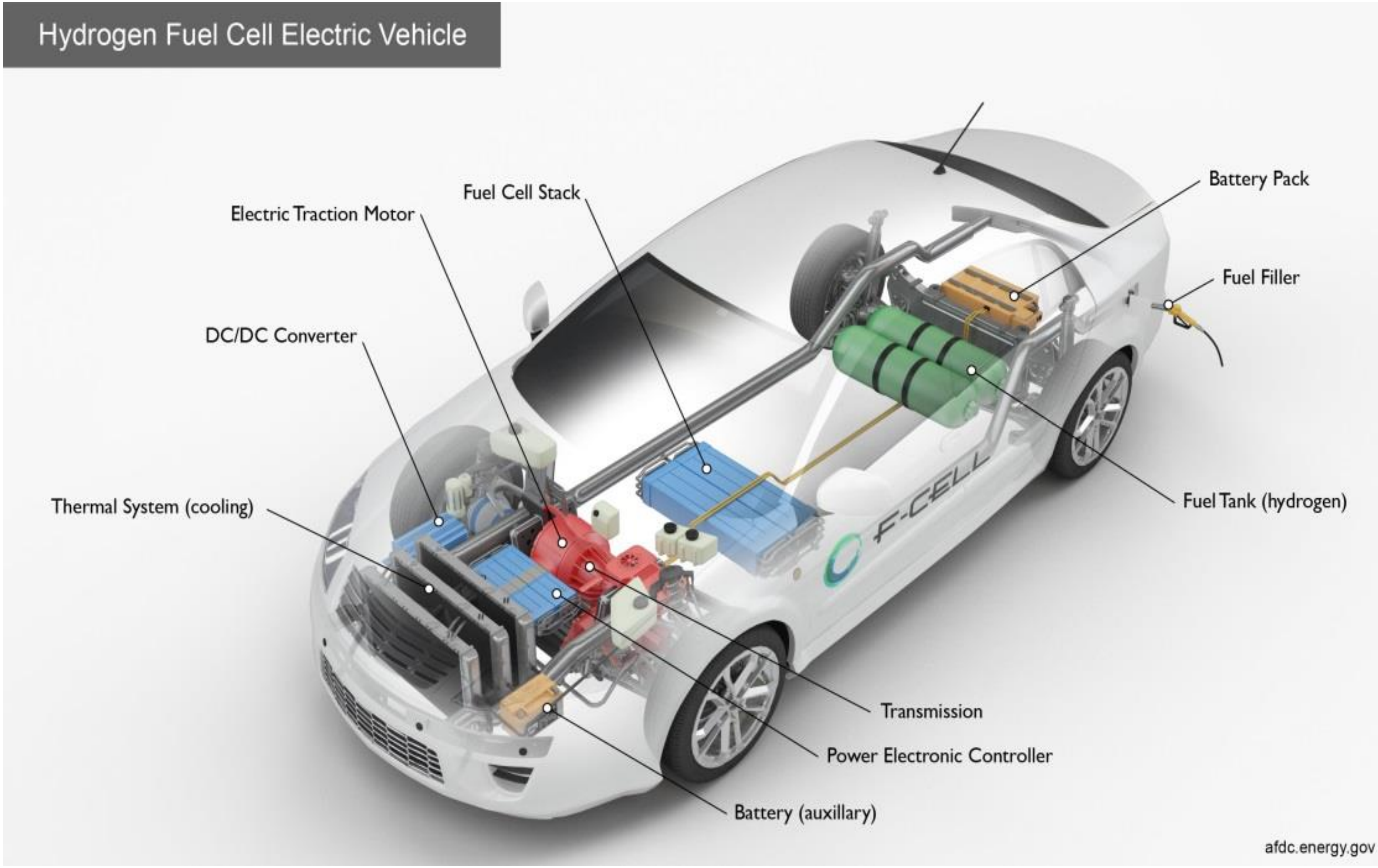


Fig. 44. Conceptual presentation of a typical FCEV instruments.

❑ FCEVs merits:

- ✓ can produce their own electricity **without carbon emission**, enabling it to reduce its carbon footprint;
- ✓ refilling FCEV **takes the same amount of time** required to fill a conventional vehicle at a **gas pump**. This makes adoption of these vehicles more like near future;

❑ FCEVs limitations:

- ✓ **scarcity of hydrogen fuel stations**, but then again, BEV or PHEV charging stations were not a common scenario even a few years back;
- ✓ **Relative slow response** in comparison with battery;
- ✓ **high cost** of FCs (more than 50$/kW), which is more greater than ICE cost;
- ✓ **concerns regarding safety** in case of flammable hydrogen leaking out of the tanks.

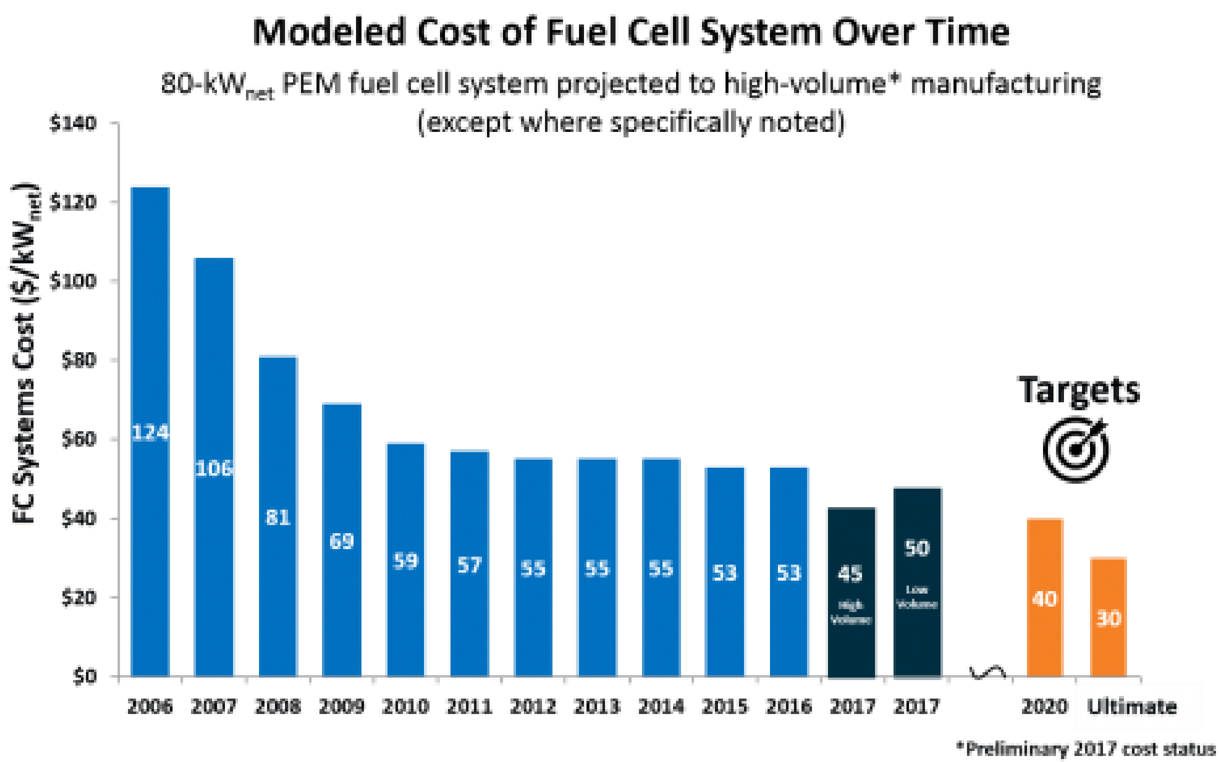


Fig. 45. Modeling of the FC cost trend.

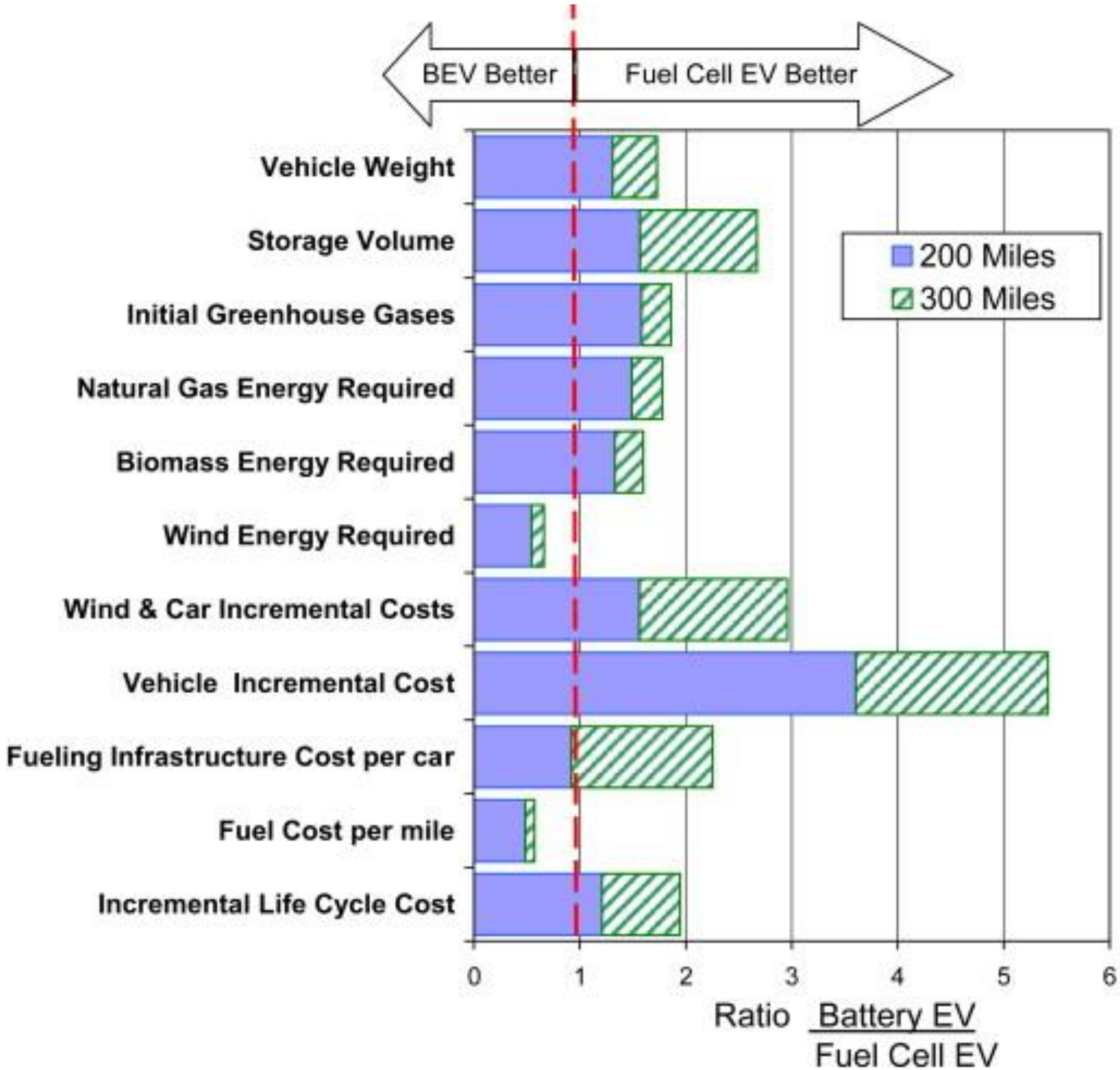


Fig. 46. FCEVs and BEVs comparison in different aspects for 320 km (colored blue) and 480 km (colored green) ranges. All hydrogen made from natural gas.

- In plug-in FCEVs (PFCEVs), with a **larger battery and smaller FC (battery-dominant car)**, if hydrogen can be made from the renewable sources, to run the FC, and the energy to charge the battery come from green sources, this PFCEV will be the vehicle future.

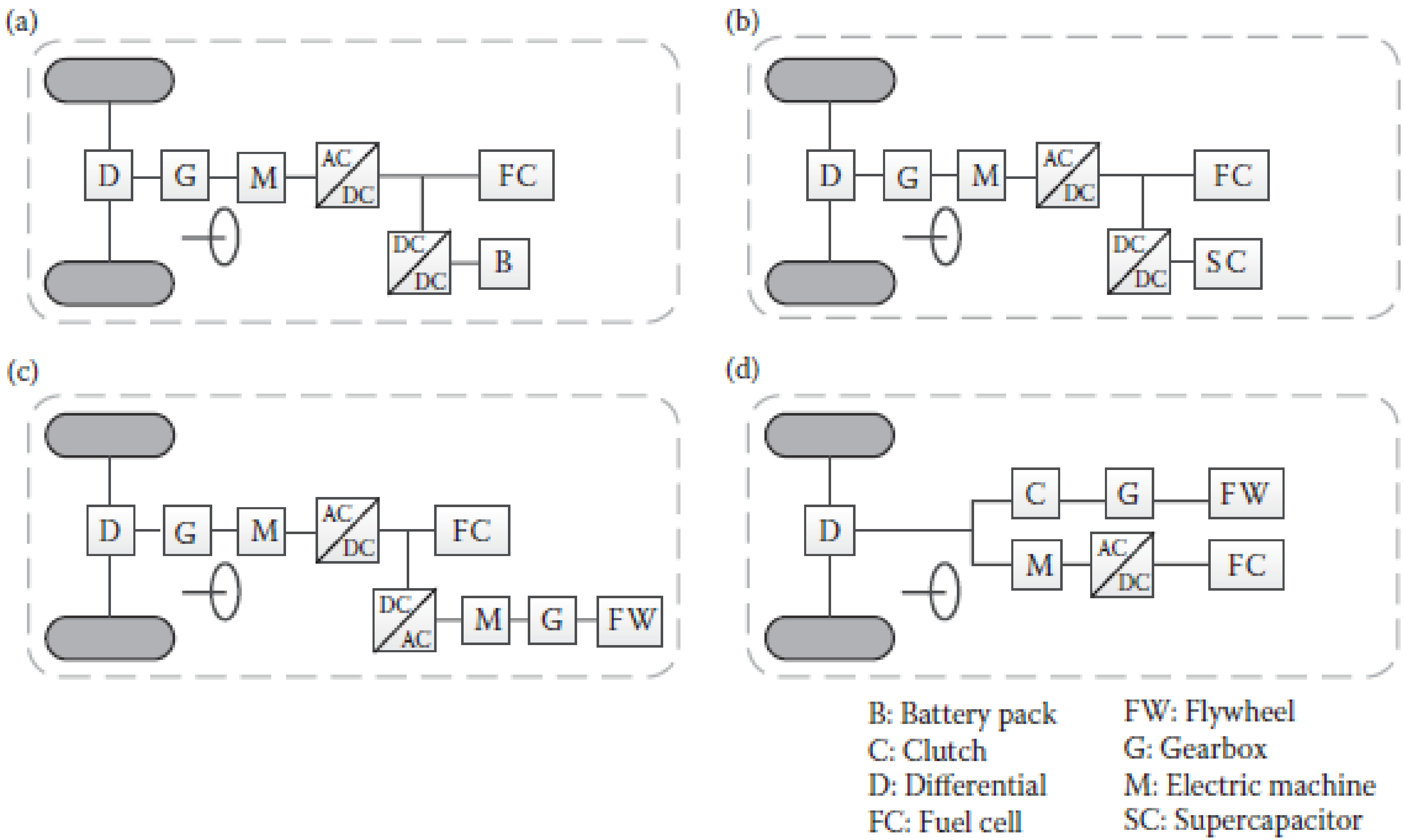


Fig. 47. FCs combined with other energy sources: (a) FC and a battery pack, (b) FC and a UC, (c) FC and a flywheel, and (d) another type of combination of FC and flywheel, in which flywheel can provide mechanical energy directly and propel the vehicle through mechanical transmission.

Table 5. Comparison of various EV types in terms of driving component.

EV Type	Driving Component	Energy Source	Features	Problems
BEV	• Electric motor	• Battery • Ultracapacitor	• No emission • Not dependent on oil • Range depends largely on the type of battery used • Available commercially	• Battery price and capacity • Range • Charging time • Availability of charging stations • High price
HEV	• Electric motor • ICE	• Battery • Ultracapacitor • ICE	• Very little emission • Long range • Can get power from both electric supply and fuel • Complex structure having both electrical and mechanical drivetrains • Available commercially	• Management of the energy sources • Battery and engine size optimization
FCEV	• Electric motor	• Fuel cell	• Very little or no emission • High efficiency • Not dependent on supply of electricity • High price • Available commercially	• Cost of fuel cell • Feasible way to produce fuel • Availability of fueling facilities

$$\text{mpge} = \frac{33.705 \frac{\text{kWh}}{\text{gal}}}{FC}$$

- mpge: miles per gallon of gasoline-equivalent;
- FC: Fuel Consumption (kWh/mile);
- SI: Spark Ignition;
- CI: Compression Ignition.

Table 6. Powertrain efficiency comparison by various ESS types.

Fuel	Powertrain efficiency (%)	Well-to-wheel efficiency (%)
Gasoline SI	17	14
Diesel CI	20	17
BEV	80	27
Gasoline Series HEV	25	21
Gasoline Parallel HEV	28	24
Hydrogen FCEV	45	27

*EPA: Environmental Protection Agency

Table 7. Various aspects of powertrain comparison by various ESS types (by EPA).

	Fuel	Storage	η_{pt} (%)	FC_{in} (Wh/km)	(L/100 km)	mpge (US) (mpg)	CO_2 (gCO_2/km)	Range (km)
SI	Gasoline	40 L	20.4	512	5.78	40.7	134	692
CI	Diesel	40 L	24.1	434	4.32	54.4	115	926
BEV	Electricity	60 kWh	84.6	146		144	73/1.5	485
Series HEV	Gasoline	40 L	26.4	396	4.47	52.7	103	895
Series-Parallel HEV	Gasoline	40 L	32.7	320	3.6	65.2	84	1108
FCEV	Hydrogen	5 kg	47.1	222		94	69	750

1.6. Wheels drive configuration

- Motor, mechanical transmission, and wheel configuration in an EV has different types as:

a) front-wheel drive with just an ICE replaced by an EM. The wheels rotate at different speeds by differential.

b) a clutch omitted configuration. It has a FG in place of the GB which removes the chance of getting the desired torque-speed characteristics (reducing weight and size).

c) the motor, gear and differential as a single unit that drives both the wheels. (Nissan Leaf, and the Chevrolet Spark).

d) obtaining differential action by two EMs for two wheels.

e) mechanical interaction is further reduced by placing the motors inside the wheels (in-wheel drive). A planetary gear system is employed because advantages like high speed reduction ratio and inline arrangement of input and output shafts.

f) System is gearless by mounting a low-speed motor with an outer rotor configuration on the wheel rim. Controlling the motor speed thus controls the wheel speed and the vehicle speed.

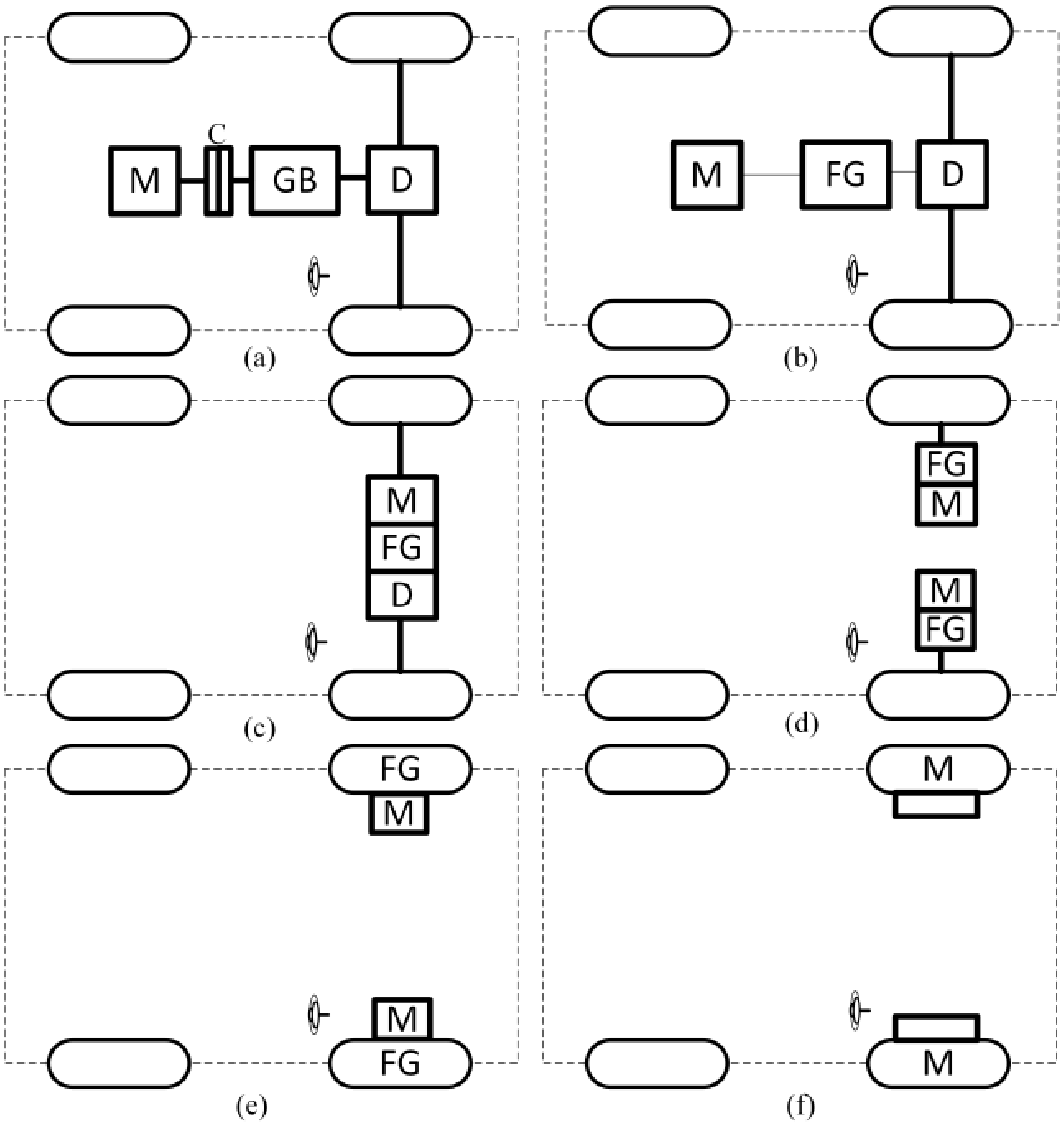


Fig. 48. Different front wheel drive EV configurations.

❑ Motor, mechanical transmission, and wheel configuration in an EV can be mounted on the **rear wheels as well**, such as:

✓ Single motor version of **Tesla Model S** (rear wheel drive)

✓ in-wheel motor (**Nissan Blade glider**) (rear wheel drive)

❑ The use of **in-wheel motors** enables it to apply different amount of torques at each of the two rear wheels to allow better cornering.

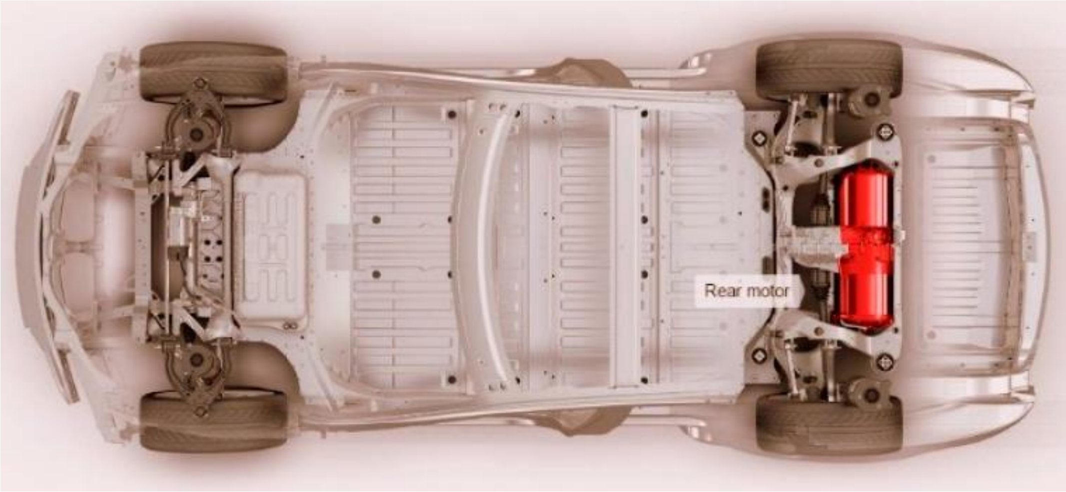
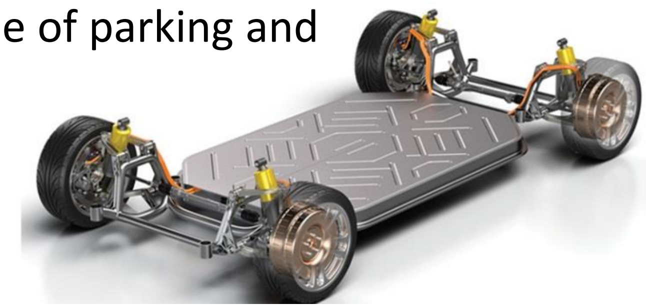


Fig. 49. Two real wheel drive vehicles: motor, gear, and differential as a single unit (Tesla Model S (left); in-wheel type (Nissan Blade Glider (right)).

- ❑ **All-Wheel Drive** (**AWD**) can be applied by increasing cost, weight, and complexity for:
- ✓ more control and power;
- ✓ providing better traction in slippery conditions;
- ✓ using torque vectoring for better cornering performance and handling.

- ❑ **AWD** configuration can also be realized for **in-wheel motor** systems:
- ✓ It is useful for city cars like the **Hiriko Fold** that has steering actuator, suspension, brakes and a motor all integrated in each wheel. (cause efficient all wheel driving, all wheel steering along with ease of parking and cornering).



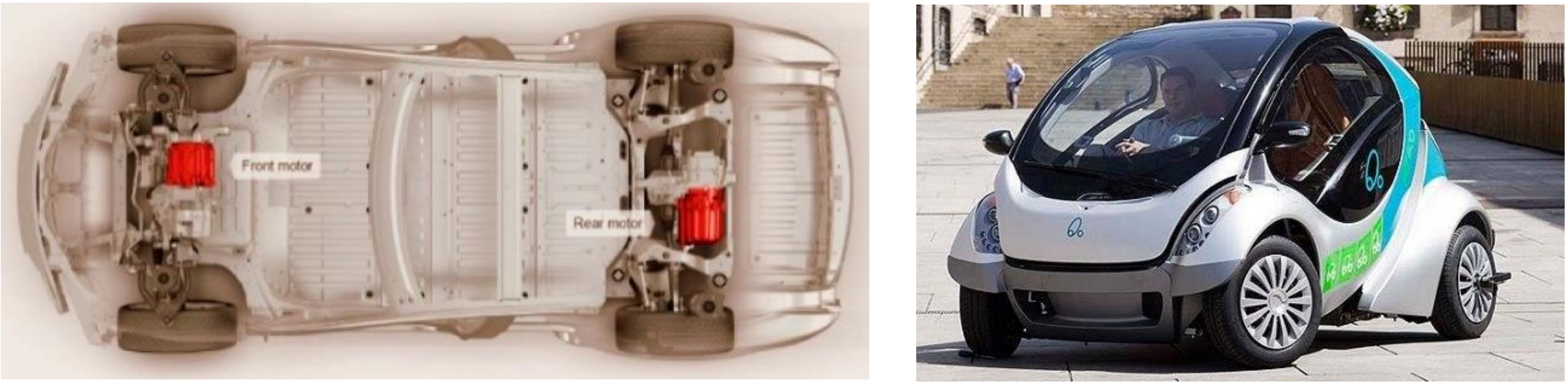


Fig. 50. Two AWD-based vehicles: motor, gear, and differential as a single unit (Tesla Model S (left)); in-wheel type (Hiriko Fold (right)).

❑ In-wheel drive merits:

- ✓ Reduce the weight of the drive train by removing the central motor, related transmission, differential, universal joint, and drive shaft;
- ✓ More controllability;
- ✓ Better turning capability;
- ✓ More space for battery, FC, or cargo.

❑ In-wheel drive limitations:

- ✓ Motor is connected to the power and control system through wire that can damage because of harsh environment, vibration, and acceleration;
- ✓ Relatively high cost.

Fig. 51. Mounting of various part in a wheel for in-wheel drive.

❖ A solution for this problem: **Wireless In-Wheel Motor (W-IWM)** system, which wires are replaced by two coils, which are able to transfer power in-between them.

❑ Because of vibrations, the motor and the vehicle can be **misaligned** and the secondary voltage can be varied. The proposed solutions are:

✓ magnetic resonance coupling (efficiency can be reduced due to more three stage power conversion);

✓ use of a hysteresis comparator and applying the secondary power inverter to a controller to counter the change in secondary voltage.

❑ W-IWM **is compliant with the regenerative braking** as well.

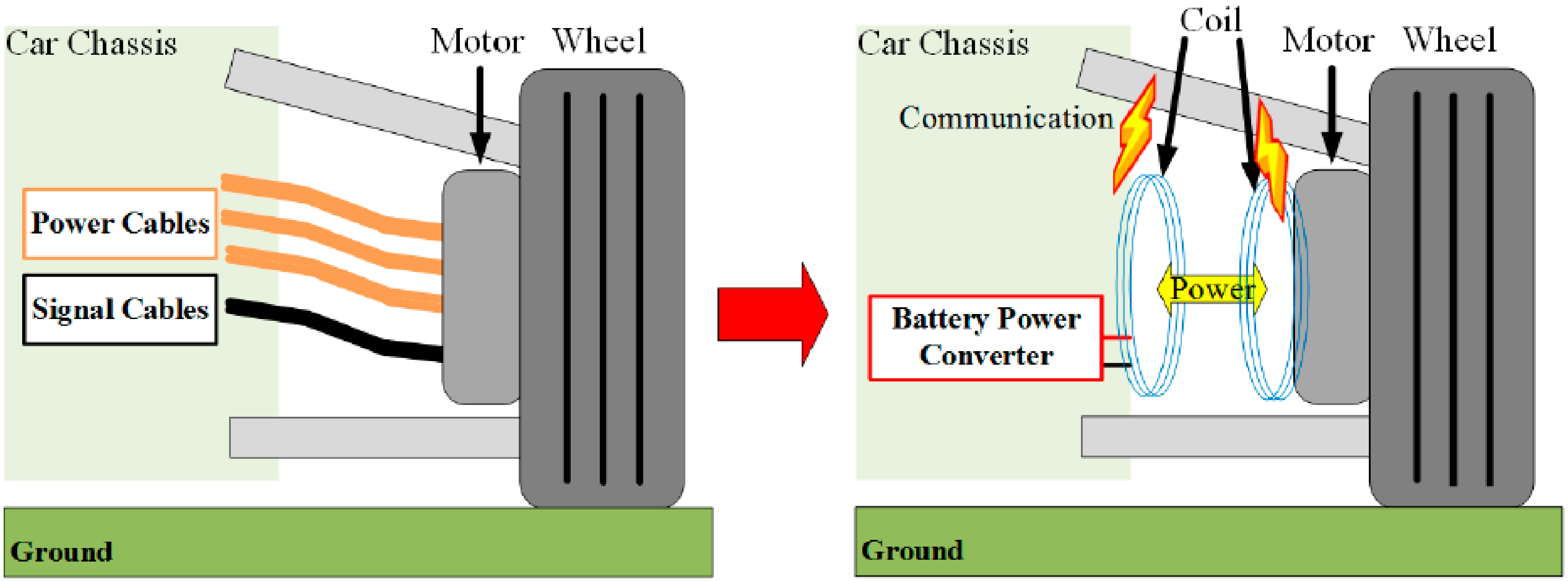


Fig. 52. In-wheel drive structures in conventional (wired) and W-IWM structures.

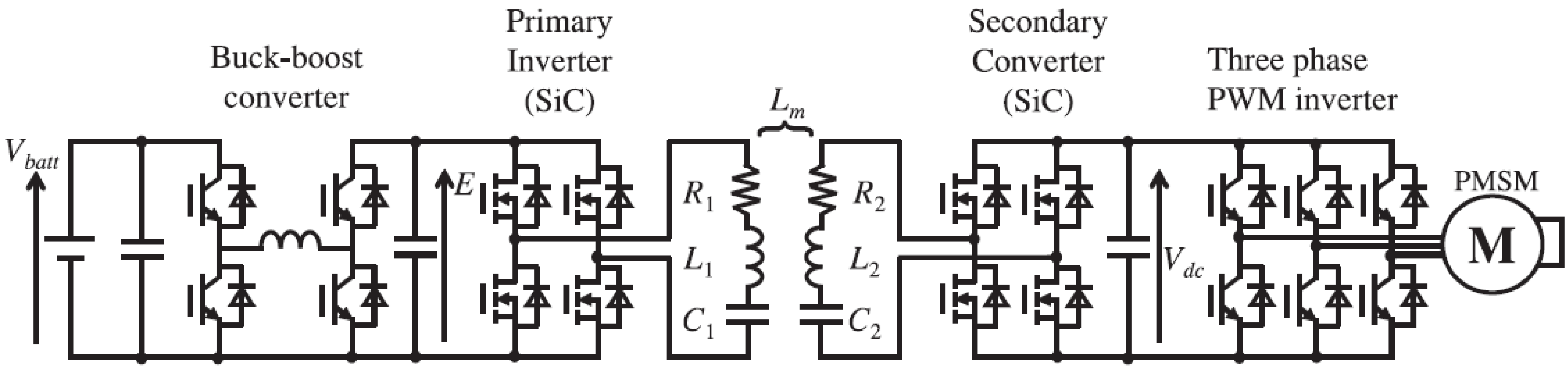


Fig. 53. W-IWM multi-stage power converter topology using magnetic resonance coupling.

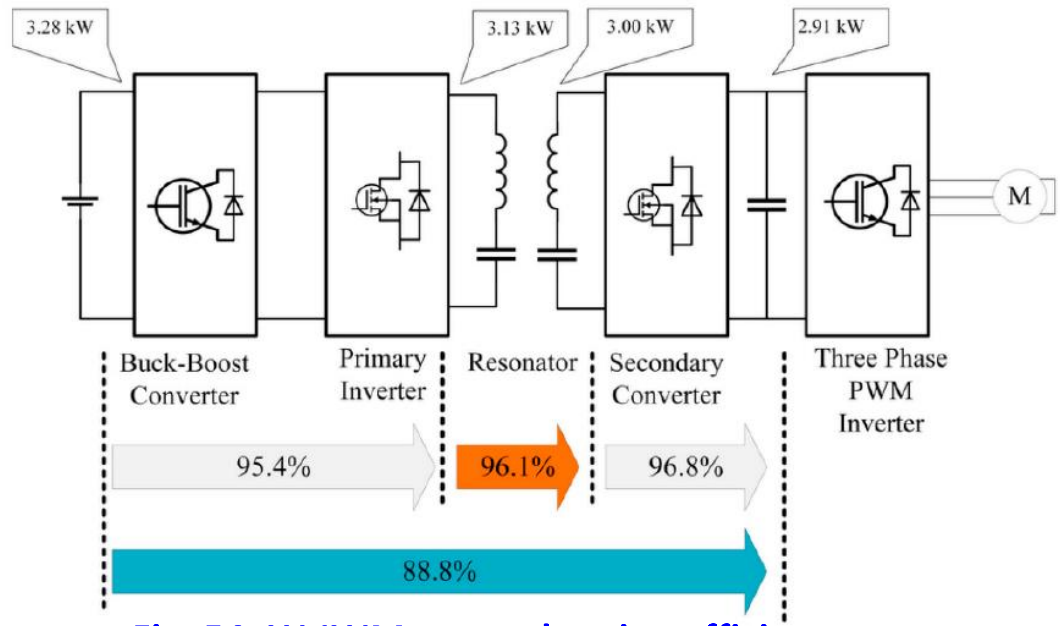


Fig. 54. W-IWM setup showing efficiency at 100% torque reference.

Table 8. Some of Famous EVs specifications.

INSIDEEVs

Plug-In Hybrid (PHEV & EREV) Car Comparisons - US

Estimated/Unofficial

Updated 2020-08-15

Brand	Model		Base Price (MSRP)	Dest. Charge	Tax Credit	Price After Tax Credit	Battery Size (kWh)	EPA EV Range (mi)	Total Range (mi)	0-60 mph (sec)	Top Speed (mph)	Peak System Output Total (kW)	EV (kW)	ICE (kW)	Weight (lbs)
Audi	A7 55 TFSI e quattro (2021)	AWD	$ 74 900	$ 995	$ 6 712	$ 69 183	14.1			5.7		270	105	185	
Audi	A8 L 60 TFSI e quattro (2020)	AWD	$ 94 000	$ 995	$ 6 712	$ 88 283	14.1	17	420	4.9	130	330	100	250	5 335
Audi	A8 L 60 TFSI e quattro (2021)	AWD	$ 95 900	$ 995	$ 6 712	$ 90 183	14.1	17	420	4.9	130	330	100	250	5 335
Audi	Q5 55 TFSI e quattro (2020)	AWD	$ 52 900	$ 995	$ 6 712	$ 47 183	14.1	20	390	5.0	130	270	105	185	4 685
Bentley	Bentayga Hybrid (2020)	AWD			$ 7 500		17.3	18	390	5.2	158	330	94	250	
BMW	330e (2021)	RWD	$ 44 550	$ 995	$ 5 836	$ 39 709	12.0	22	320	5.6	130	215	83	135	4 039
BMW	330e xDrive (2021)	AWD	$ 46 550	$ 995	$ 5 836	$ 41 709	12.0	20	290	5.7	130	215	83	135	4 138
BMW	530e (2021)	RWD	$ 57 200	$ 995	$ 5 836	$ 52 359	12.0	20	350	5.9	146	185	83	135	4 264
BMW	530e xDrive (2021)	AWD	$ 59 500	$ 995	$ 5 836	$ 54 659	12.0	18	330	5.9	146	185	83	135	4 396
BMW	745e xDrive (2021)	AWD	$ 95 900	$ 995	$ 5 836	$ 91 059	12.0	16	290	4.9	155	290	83	210	4 600
BMW	i3 REx (2020)	RWD	$ 48 300	$ 995	$ 7 500	$ 41 795	42.2	126	200	8.0	93	125	125	34	3 269
BMW	i3s REx (2020)	RWD	$ 51 500	$ 995	$ 7 500	$ 44 995	42.2	126	200	7.6	100	135	135	34	3 302
BMW	X3 xDrive30e (2021)	AWD	$ 49 600	$ 995	$ 5 836	$ 44 759	12.0	17	340	5.9	130	215	80	135	4 400
BMW	X5 xDrive45e (2021)	AWD	$ 65 400	$ 995	$ 7 500	$ 58 895	21.6	31	400	5.3	146	290	83	210	5 672
Chrysler	Pacifica Hybrid (2020)	FWD	$ 39 995	$1 495	$ 7 500	$ 33 990	16.0	32	520			194	89		4 987
Ford	Escape PHEV (2020)	FWD	$ 33 040	$1 245	$ 6 843	$ 27 442	14.4	37	530			165	88		
Ford	Fusion Energi - Titanium (2020)	FWD	$ 35 000	$1 195	$ 4 609	$ 31 586	9.0	26	610			143	35	103	3 986
Honda	Clarity Plug-in Hybrid (2020)	FWD	$ 33 400	$ 955	$ 7 500	$ 26 855	17.0	47	340			156	135	76	4 052
Hyundai	IONIQ Plug-in Hybrid (2020)	FWD	$ 26 500	$ 975	$ 4 543	$ 22 932	8.9	29	630			102	45	76	3 318
Hyundai	Sonata PHEV (2019)	FWD	$ 33 400	$ 955	$ 4 919	$ 29 436	9.8	28	600		75	148	50	113	3 787
Karma	Revero GT (2020)	RWD	$144 800	$1 800	$ 7 500	$ 139 100	28.0	61	330	4.5	125	400	400	125	5 050
Kia	Niro PHEV (2020)	FWD	$ 29 490	$1 120	$ 4 543	$ 26 067	8.9	26	560				45	76	3 391
Kia	Optima PHEV (2020)	FWD	$ 36 090	$ 925	$ 4 919	$ 32 096	9.8	28	630	9.1	74	148	50	113	3 799
Land Rover	Range Rover P400e (2020)	AWD	$ 95 950	$1 295	$ 6 295	$ 90 950	13.1	19	480	6.4	137	297	105	221	5 532
Land Rover	Range Rover Sport P400e (2020)	AWD	$ 79 000	$1 295	$ 6 295	$ 74 000	13.1	19	480	6.3	137	297	105	221	5 448
Lincoln	Aviator Grand Touring (2020)	AWD	$ 68 800	$1 095	$ 6 534	$ 63 361	13.6	21	460			363	75	294	
Mercedes	GLC 350e 4MATIC (2020)	AWD	$ 51 900	$ 995	$ 6 462	$ 46 433	13.5	22	360	5.6		232	90	153	4 555
Mercedes	S 560e Sedan (2020)	RWD	$109 750	$ 995	$ 6 462	$ 104 283	13.5	18	510	4.9	155	345	90	266	5 115
MINI	Cooper S E Countryman ALL4 (2020)	AWD	$ 37 900	$ 850	$ 5 002	$ 33 748	10.0	17	300	6.7	78	165	65	100	
Mitsubishi	Outlander PHEV (2020)	AWD	$ 36 510	$1 195	$ 5 836	$ 31 869	12.0	22	310				120	86	4 222
Polestar	1 (2020)	AWD	$155 000		$ 7 500	$ 147 500	34.0	52	470	4.0		440	194	240	5 180
Porsche	Cayenne E-Hybrid (2020)	AWD	$ 81 800	$1 350	$ 6 712	$ 76 438	14.1	14	420	4.7	157	339	100	264	5 164
Porsche	Cayenne E-Hybrid Coupe (2020)	AWD	$ 87 600	$1 350	$ 6 712	$ 82 238	14.1	14	420	4.8	157	339	100	264	5 265
Porsche	Cayenne Turbo S E-Hybrid (2020)	AWD	$163 200	$1 350	$ 6 712	$ 157 838	14.1	12	360	3.6	183	500	100	403	5 265
Porsche	Cayenne Turbo S E-Hybrid Coupe ('20)	AWD	$166 200	$1 350	$ 6 712	$ 160 838	14.1	12	360	3.6	183	500	100	403	5 265
Porsche	Panamera 4 E-Hybrid (2020)	AWD	$103 800	$1 350	$ 6 712	$ 98 438	14.1	14	490	4.4	172	340	100	246	4 945
Porsche	Panamera Turbo S E-Hybrid (2020)	AWD	$187 700	$1 350	$ 6 712	$ 182 338	14.1	14	450	3.2	192	504	100	410	5 238
Subaru	Crosstrek Hybrid (2020)	AWD	$ 35 145	$1 010	$ 4 502	$ 31 653	8.8	17	480				86	100	3 726
Toyota	Prius Prime (2020)	FWD	$ 27 900	$ 955	$ 4 502	$ 24 353	8.8	25	640			90	68	71	3 365
Toyota	RAV4 Prime (2021)	AWD	$ 38 100	$1 120	$ 7 500	$ 31 720	18.1	42	600	5.7		225	174	130	
Volvo	S60 T8 Twin Engine (2020)	AWD	$ 55 400	$ 995	$ 5 419	$ 50 976	11.6	22	510	4.3		294	64	230	4 474
Volvo	S90 T8 Twin Engine (2020)	AWD	$ 63 200	$ 995	$ 5 419	$ 58 776	11.6	21	490	4.8		294	64	230	4 589
Volvo	V60 T8 Twin Engine Polestar (2020)	AWD	$ 67 300	$ 995	$ 5 419	$ 62 876	11.6	22	510	4.3		305	64	230	4 521
Volvo	XC60 T8 Twin Engine (2020)	AWD	$ 53 950	$ 995	$ 5 419	$ 49 526	11.6	18	520			294	64	230	4 704
Volvo	XC90 T8 Twin Engine (2020)	AWD	$ 67 000	$ 995	$ 5 419	$ 62 576	11.6	18	520			294	64	230	5 053

Table 8. Some of Famous EVs specifications (continues).

INSIDEEVs

All-Electric Car Comparisons - US

Estimated/Unofficial

Updated 2020-08-12

Brand	Model		Base Price (MSRP)	Dest. Charge	Tax Credit	Price After Tax Credit	Battery Size (kWh)	EPA EV Range (mi)	0-60 mph (sec)	Top Speed (mph)	Peak Power (kW)	EPA Energy consumption combined (Wh/mi)	city	highway	Weight (lbs)
Audi	e-tron (2021)	AWD	$ 65 900	$1 095	$ 7 500	$ 59 495	95	222	5.5	124	300	432	432	432	
Audi	e-tron Sportback (2021)	AWD	$ 69 100	$1 095	$ 7 500	$ 62 695	95	218	5.5	124	300	438	443	432	
BMW	i3 (2020)	RWD	$ 44 450	$ 995	$ 7 500	$ 37 945	42.2	153	7.2	93	125	298	272	330	2 965
BMW	i3s (2020)	RWD	$ 47 650	$ 995	$ 7 500	$ 41 145	42.2	153	6.8	100	135	298	272	330	3 034
Chevrolet	Bolt EV (2020)	FWD	$ 36 620	$ 875	N/A	$ 37 495	66	259	6.5	90	150	286	265	312	3 563
Fiat	500e (2019)	FWD	$ 33 460	$1 495	$ 7 500	$ 27 455	24	84	8.9	85	83	301	279	327	2 980
Hyundai	IONIQ Electric (2020)	FWD	$ 33 045	$ 975	$ 7 500	$ 26 520	38.3	170	10,0	102	100	253	232	279	3 371
Hyundai	Kona Electric (2020)	FWD	$ 37 190	$1 140	$ 7 500	$ 30 830	64	258	7.6	104	150	281	255	312	3 715
Jaguar	I-PACE (2020)	AWD	$ 69 850	$1 025	$ 7 500	$ 63 375	90	234	4.5	124	294	443	421	468	4 784
Kia	Niro EV (e-Niro) (2020)	FWD	$ 39 090	$1 120	$ 7 500	$ 32 710	64	239	7.5	104	150	301	274	330	3 854
MINI	Cooper SE	FWD	$ 29 900	$ 850	$ 7 500	$ 23 250	32.6	110	6.9	93	135	312	293	337	
Nissan	LEAF (40 kWh) (2020)	FWD	$ 31 600	$ 925	$ 7 500	$ 25 025	40	149	7.4	90	110	304	274	340	3 433
Nissan	LEAF e+ S (62 kWh) (2020)	FWD	$ 38 200	$ 925	$ 7 500	$ 31 625	62	226	6.5		160	312	286	347	3 780
Nissan	LEAF e+ SV/SL (62 kWh) (2020)	FWD	$ 39 750	$ 925	$ 7 500	$ 33 175	62	215	6.5		160	324	296	359	3 811
Polestar	2 (2020)	AWD	$ 59 900	$1 300	$ 7 500	$ 53 700	78	275	4.7		300				
Porsche	Taycan 4S Perf Battery Plus (2020)	AWD	$112 990	$1 350	$ 7 500	$ 106 840	93.4	203	3.8	155	420	488	496	475	4 953
Porsche	Taycan Turbo (2020)	AWD	$153 510	$1 350	$ 7 500	$ 147 360	93.4	201	3.0	161	500	488	496	475	5 132
Porsche	Taycan Turbo S (2020)	AWD	$187 610	$1 350	$ 7 500	$ 181 460	93.4	192	2.6	161	560	496	503	496	5 121
Tesla	Model 3 Standard Range Plus (2020)	RWD	$ 37 990	$1 200	N/A	$ 39 190	59.5	250	5.3	140		239	228	255	3 627
Tesla	Model 3 Long Range AWD (2020)	AWD	$ 46 990	$1 200	N/A	$ 48 190	80.5	322	4.4	145		279	272	291	4 072
Tesla	Model 3 Perf. LR AWD (2020) 20"	AWD	$ 54 990	$1 200	N/A	$ 56 190	80.5	299	3.2	162		298	286	315	4 072
Tesla	Model S Long Range Plus (2020)	AWD	$ 74 990	$1 200	N/A	$ 76 190	100	402	3.7	155		288	279	301	4 883
Tesla	Model S Performance LM (2020) 19"	AWD	$ 94 990	$1 200	N/A	$ 96 190	100	348	2.3	163		324	324	324	4 941
Tesla	Model X Long Range Plus (2020)	AWD	$ 79 990	$1 200	N/A	$ 81 190	100	351	4.4	155		351	340	362	5 421
Tesla	Model X Performance LM (2020) 20"	AWD	$ 99 990	$1 200	N/A	$ 101 190	100	305	2.6	163		374	374	379	5 531
Tesla	Model Y Long Range AWD (2020) 19"	AWD	$ 49 990	$1 200	N/A	$ 51 190	80.5	316	4.8	135		279	265	296	4 416
Tesla	Model Y Perf. LR AWD (2020) 21"	AWD	$ 59 990	$1 200	N/A	$ 61 190	80.5	291	3.5	155		304	291	318	4 416