HOW IT WORKS: TOYOTA HYBRID SYNERGY DRIVE

Toyota's hybrid system has been used on many different models of car, from the original Prius which debuted in 1997, through to the Hybrid Camry, Corolla, RAV4, various Lexus models and even vehicles from other manufacturers. It's the most successful (and arguably the best) vehicle hybrid system, and it's very clever. This is how it works.

by Roderick Wall

Toyota's Hybrid Synergy Drive is built around an internal combustion engine (ICE) which runs on the Atkinson cycle (rather than the Otto cycle used in most spark-ignition ICEs), two electric motor/generators and a battery pack.

The genius in this arrangement is the use of two electric motors and a 'power split device' or PSD, to control how power flows through the system.

This article describes the system used in the 2015 hybrid Camry.

The basic arrangement is shown in Fig.1. The PSD is a planetary gear system with a sun gear, planet gears, a planet gear carrier and a ring gear. The ICE is connected via the gear carrier and planet gears, while MG1 is connected via the sun gear, and the vehicle's wheels (via gears and the differential) are connected via the ring gear.

The PSD's ring gear is also connected to another planetary gear system, used as a reduction gear for the second motor/generator (MG2). Both motor/generators are three-phase permanent magnet types.

For forward motion, a combination of the ICE, MG1 and/or MG2 can provide power, while reversing is handled solely by MG2, which simply reverses its direction of rotation.

The PSD splits power from the ICE between the wheels and motor/generator 1 (MG1). How the energy is split depends on the electrical load on MG1. A greater electrical load on MG1 causes more ICE energy to go to the wheels, and less to MG1.

Thus, there is no 'gearbox' as in most other (non-electric) vehicles; not only is no reverse gear needed, as described above, but due to the way the PSD operates, there's no need to change gears as vehicle speed increases.

Electronic CVT

Toyota refers to this system as an

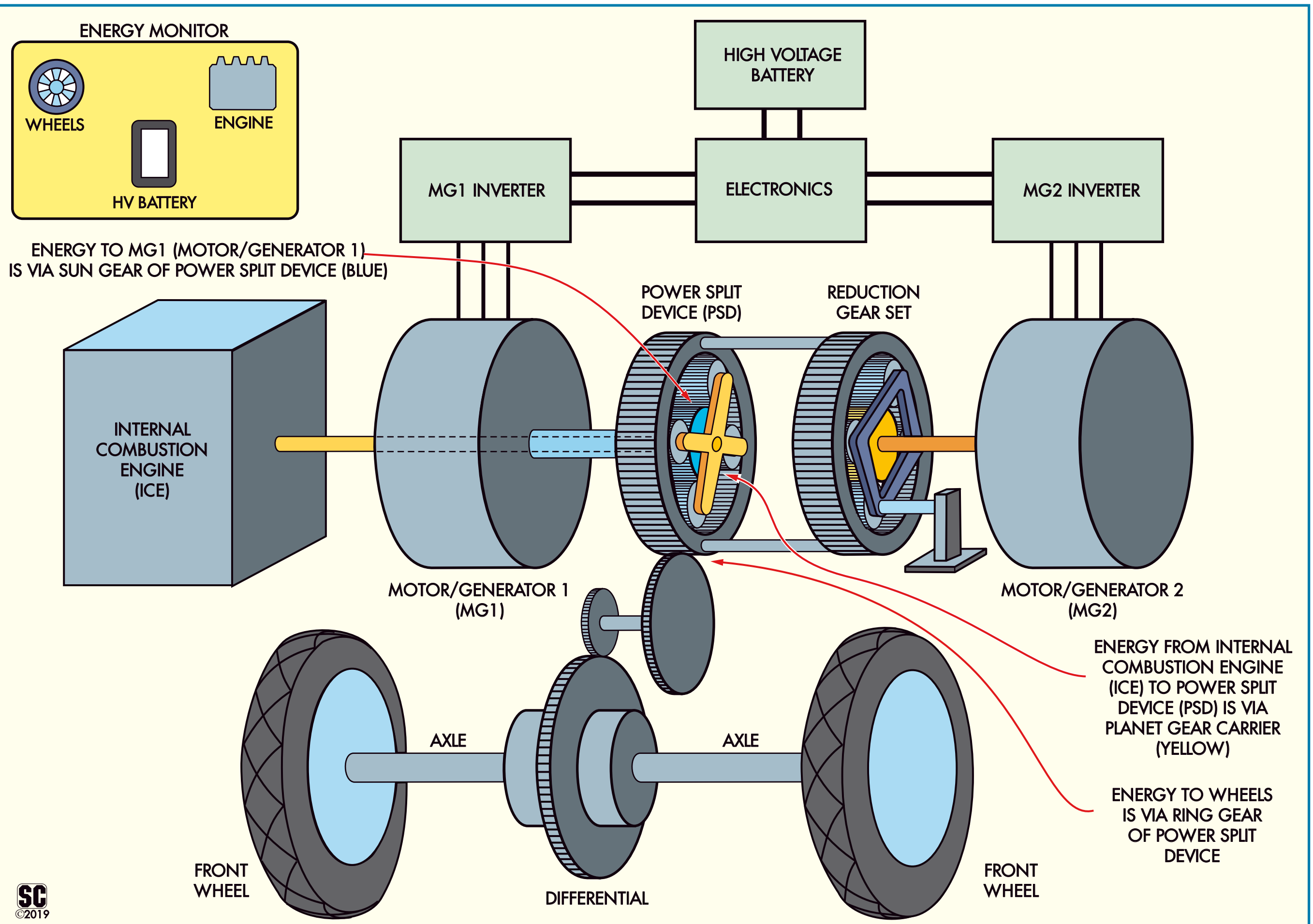


Fig.1: the Toyota Hybrid Synergy Drive provides an "e-CVT" transmission. This allows a wide range of ratios between engine (ICE) RPM and wheel RPM without needing to change any gears. The Power Split Device (PSD) connects between the ICE, motor/generator 1 and the wheels in such a way that power to or from the wheels can be apportioned to the ICE and MG1 independently, allowing the software to control the flow of energy. MG2 rotates with the wheels as it is connected through fixed gearing.

Electric Continuous Variable Transmission (e CVT), as the ratio between the engine speed and wheel speed can vary continuously and smoothly over a wide range.

Differences in the engine speed and road speed can be made up for by spinning MG1 faster or slower, as the PSD creates a fixed relationship between the three speeds.

Since MG2 is more highly geared in later hybrids, it provides more torque and can be used to move the vehicle at low speeds (even when the ICE is switched off). As the speed increases, MG1 can take over, as there is less gearing between it and the wheels.

There is also no need for a separate starter motor to start the ICE, as it can be spun up by MG1. This allows the ICE to be switched off when stopped or moving up to about 100km/h, to save fuel and reduce pollution.

It can be seamlessly stopped and started while in motion.

The ICE water cooling pump and air conditioner compressor are also powered by three-phase electric motors, rather than directly from the ICE as is the case in most vehicles.

The ICE water cooling pump can be switched off to allow the ICE to get up to temperature quickly, allowing it to run more efficiently, and also throttled as needed while driving to maintain optimal engine temperature.

The electric air conditioner compressor means that the ICE does not need to be cycled on and off to cool the cabin in hot weather.

The inverter electronics has its own separate water cooling system to keep it cool. There is also a separate DC/DC step-down converter to keep the auxiliary 12V DC battery (used to run the radio, lights etc) charged, which is powered from the HV battery/bus.

Different operating modes are used at different times, to allow the car to operate in the most efficient mode.

Atkinson cycle engine

The Atkinson cycle ICE is efficient and normally runs within a narrow RPM band at which it is most efficient.

A typical Otto cycle engine has an average efficiency of around 20%. Toyota claims a peak thermal efficiency of 38% for its latest Atkinson engines.

To achieve this, Toyota uses Variable Valve Timing intelligence (VVT-i) technology to control valve timing.

This is not new or unusual, as most manufacturers use similar technology, but in this case, it's also used to implement the Atkinson cycle.

This is done by delaying inlet valve closing during the compression stroke, making the compression stroke shorter than the expansion stroke.

A longer expansion stroke allows the engine to capture more energy

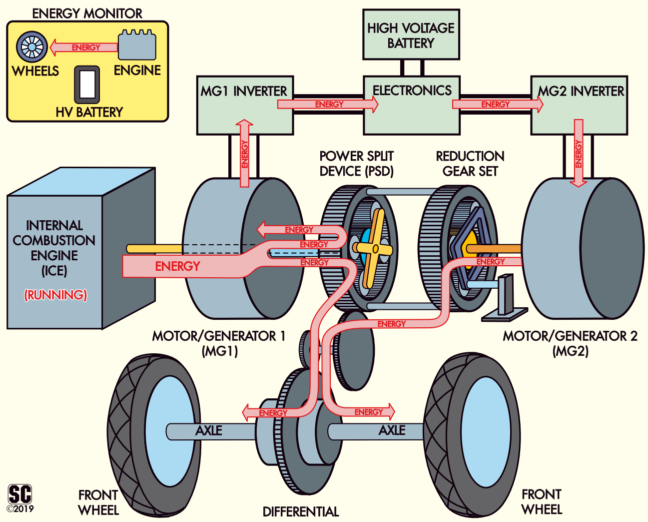


Fig.2: this shows the flow of energy in the system when only the ICE is powering the wheels, to move the vehicle forwards. The ICE spins the PSD which in turn rotates the differential to turn the wheels directly. But the PSD also spins MG1, acting as a generator, with its electrical output routed to MG2, acting as a motor. MG2 also turns the wheels, via its reduction gear set. As the PSD ring gear speed approaches the ICE speed, more of the energy goes directly to the wheels, rather than via MG1/MG2.

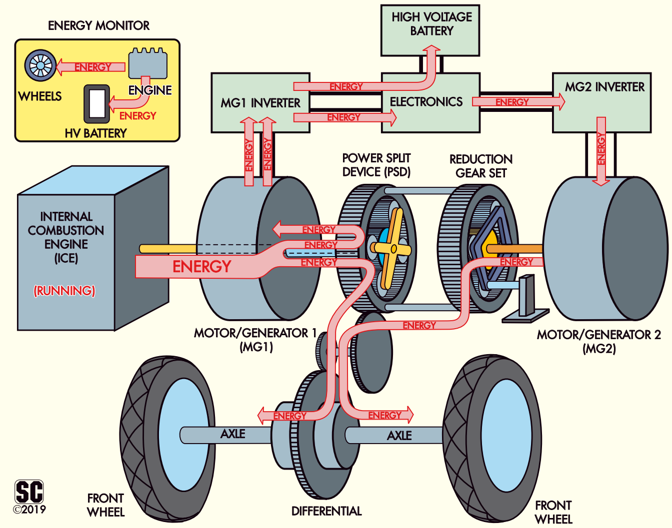


Fig.3: at the same time as powering the wheels, the ICE can also be used to charge the HV battery. This means that the ICE can run in its most efficient regime, with the excess energy not needed for acceleration or cruising stored as electrical energy, for use later. The energy flow is much the same as in Fig.2, except that some of the extra electricity that MG1 is generating is directed into the high-voltage battery pack instead of being fed to MG2 to drive the wheels.

which would otherwise be wasted as exhaust gas heat. The shorter compression stroke is necessary to prevent fuel detonation, without needing very high octane fuel (which would be very expensive).

The disadvantage of the Atkinson cycle is less overall power and poor operation over a wide range of RPM,

However, as mentioned above, the PSD and MG1 are used to keep the ICE in a narrow RPM operating range, plus the electric motors provide extra power to the wheels, negating all of these disadvantages.

By keeping the inlet valve open at the start of the compression stroke, some of the fuel/air mixture is pushed back into the inlet manifold. This mixture will be sucked back in during the next intake stroke, so as long as the engine is designed with this in mind, it isn't a problem.

If you push the accelerator pedal to the floor, the valve timing changes to produce more power from the ICE (as well as the electric motor(s) providing some assistance, assuming the battery is not depleted).

This is not as efficient as when operating in the Atkinson mode, but as hard acceleration isn't required very often, it doesn't have a big impact on overall efficiency.

The Hybrid Camry (which, until recently, was assembled in Australia) also has underbody panels to reduce wind resistance (drag), increasing efficiency. It is classified as a 'green car', which in Victoria, gives discounted road registration.

The Hybrid Camry does not use the

Recovering potential energy

When a vehicle is going up a hill at a constant speed, it requires more energy than when it is moving at that same speed on a level road. Conversely, when it is going down a hill at that same speed, less energy is required.

The extra energy from the engine when going up a hill is converted into gravitational potential energy, and that same potential energy is then 'returned' when going down a hill, hence less energy is required to maintain speed.

A vehicle's kinetic energy (in Joules) is calculated as $e(k) = m \times v^2 \div 2$ where m is the vehicle's mass in kg and v is the velocity in m/s (3.6km/h = 1m/s).

Similarly, its potential energy is calculated as $e(p) = m \times g \times h$ where m is again the mass in kg, g is the Earth's gravitational constant of about $9.8m/s^2$ and h is the height in metres.

So you can see that if the vehicle's height (h) varies, its potential energy also changes, while kinetic energy only changes if its velocity (speed) changes.

Hence, regenerative braking can recover energy either through deceleration (capturing excess kinetic energy) or going down a hill (capturing excess potential energy) or both.

Decelerating up a hill may result in excess kinetic energy if the rate of decrease in kinetic energy is faster than the rate of increase in potential energy, or it may require energy input from the engine or motors if the reverse is true. Or it may require no energy at all if the rates are identical, ie, potential energy is being converted directly into kinetic energy.

The same is true in reverse when accelerating down a hill; ie, if the rate of change in the two energies is not balanced, either energy input is required (accelerating fast), or energy may be recovered (accelerating slowly).

The balance of energy is indicated on a Toyota hybrid vehicle via its "ECO" gauge. Its power needle swings up when going up a hill, indicating more energy is being used, and it swings down when going down a hill, indicating that less energy is being used.

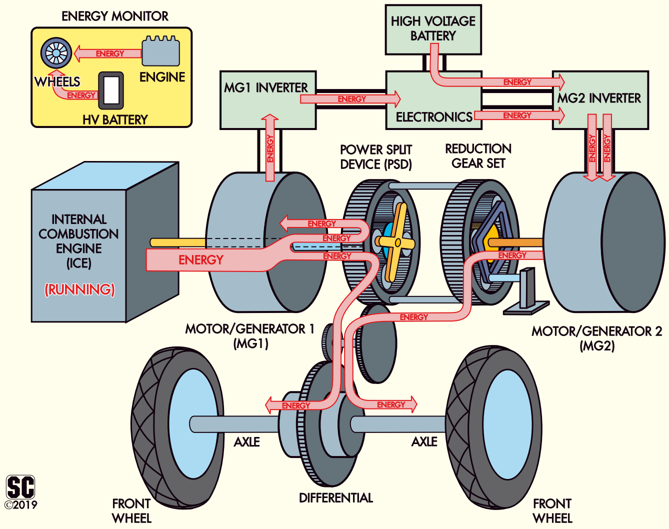


Fig.4: the wheels can be powered by the ICE and MG2 at the same time, providing more power and/or torque than the ICE can deliver. This compensates for the disadvantages of the more-efficient Atkinson-cycle combustion engine. As before, the ICE drives the wheels and MG1 acting as a generator, but this time the electricity from MG1 is supplemented with energy from the HV battery before being fed to MG2. So MG2 provides more energy to the wheels than MG1 absorbs from the ICE.

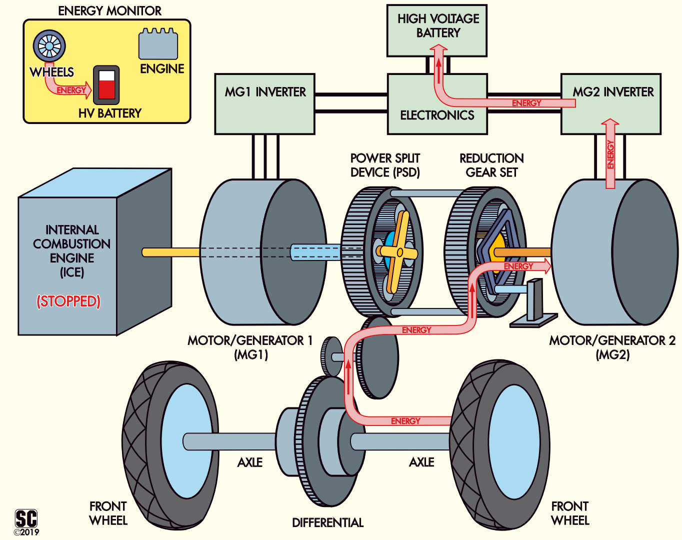


Fig.5: while coasting or decelerating, or cruising down a hill, the ICE can be shut off, and the excess kinetic/potential energy of the vehicle converted into electrical energy to charge the HV battery. This is known as regenerative braking. With the ICE stopped and MG1 spinning freely, power flows from the wheels and through the reduction gear set into MG2, which operates as a generator, supplying its inverter with energy for charging the battery.

extreme aerodynamic measures taken by the earlier Prius designs, such as enclosed rear wheels; it mostly shares its body shape with the regular Camry.

However, it still achieves impressive efficiency figures, achieving an official combined rating of 4.2l/100km (2018 model), while still having 160kW of peak power available.

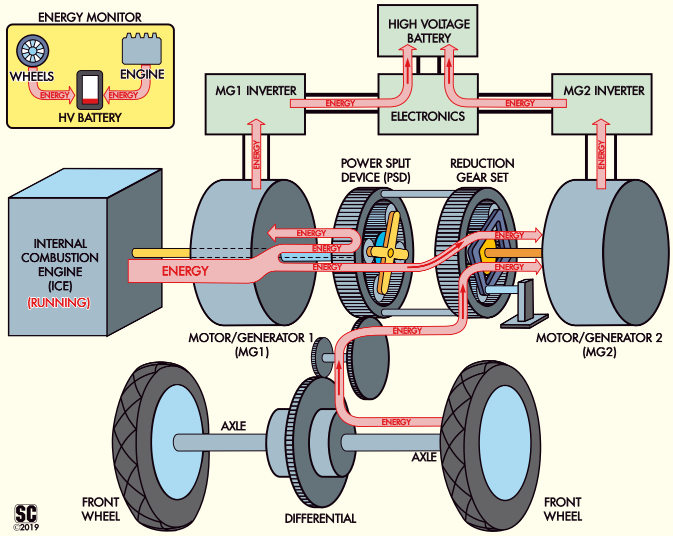


Fig.6: the battery can be charged using energy from regenerative braking at the same time as using energy produced by the ICE. The ICE turns both MG1 and MG2, both acting as generators and charging the battery simultaneously. This adds to the energy being fed to MG2 from the wheels. This would typically only occur when the HV battery charge is low, and the vehicle is also slowing down, to provide the maximum amount of energy for battery charging.

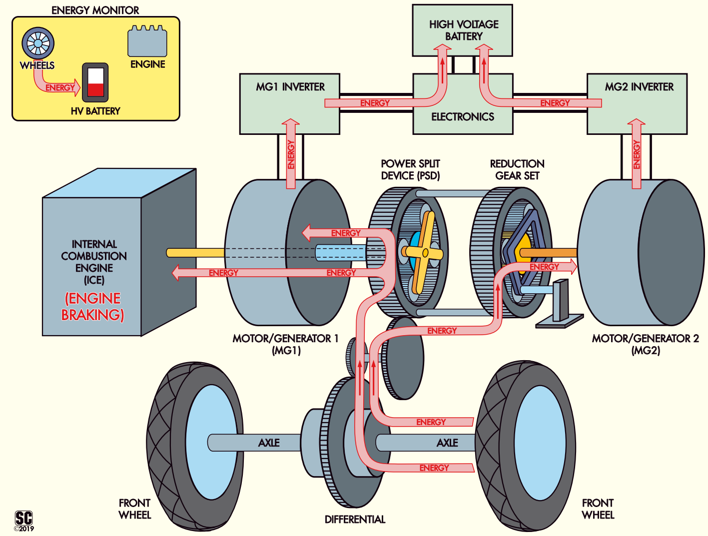


Fig.7: to minimise brake wear and heating, regenerative braking can be augmented with engine braking from the ICE. As shown here, in addition to the energy going from the wheels to MG2 to charge the battery, MG1 is also used as a generator and thus the ICE is allowed to spin. Since its fuel supply is shut off, only the energy from the wheels is available to overcome its internal friction and other losses. This provides more braking than regeneration alone, without using the disc brakes.

Operating modes

Fig.1 demonstrates that no energy is used when the car is not moving, eg, while waiting at a red traffic light. It's a similar situation if the car is rolling down a hill, and gravitational potential energy is making the car move.

Note that the Energy Monitor Display on the dashboard in Fig.1 shows no energy going to the wheels.

A steep enough hill allows energy recovery via regenerative braking, as explained above.

Fig.2 shows the scenario where only the ICE is powering the car in forward motion. The Energy Monitor display on the dashboard shows energy flowing from the engine to the wheels.

There are two paths the energy takes to get to the wheels, after being split by the Power Split Device (PSD). The most direct path is from the PSD ring gear to the differential and then the wheels. But power also flows via MG1, MG1 Inverter, MG2 Inverter, MG2 and the reduction gear set to the wheels.

In other words, MG1 is acting as a generator, producing electrical power which is then possibly converted to a different voltage before being fed to MG2, acting as a motor, to also provide power to the wheels.

The amount of energy that flows in each path determines the effective 'gear ratio' of the e-CVT system.

When the e-CVT is in 'low gear', the ICE RPM is a lot higher than the wheel RPM, causing MG1 to spin at high speed and generate more electrical energy to power MG2, and on as mechanical energy through the reduction gear set to the wheels, providing extra torque.

A high electrical load on Motor Generator 1 (MG1) causes more energy from the ICE to go to the wheels via the PSD ring gear. A lighter electrical load allows more energy to go to MG1 via the sun gear.

When the battery charge is below 80%, the ICE can charge the battery as well as providing forward motion. This situation is shown in Fig.3.

This is very similar to what is shown in Fig.2, except that the electronics redirects some of MG1's electrical output to the battery pack.

Therefore, more energy must flow from the ICE to MG1 via the PSD to maintain the same wheel speed.

This is indicated on the dashboard display by a second arrow, showing power also flowing from the engine to the HV battery.

The ICE RPM does not necessarily need to change; the throttle simply opens further to provide more torque, supplying extra power to charge the battery.

This allows the Atkinson-cycle ICE to run at a constant RPM in a narrow speed band, where it is most efficient.

A similar situation occurs during forward motion if more power is required than the ICE can provide.

It's the same situation if the battery has sufficient charge and the computer decides that some of its energy should

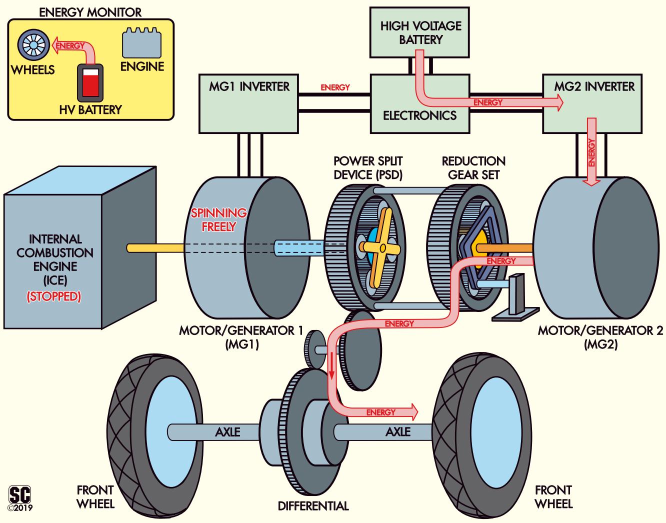
Discrepancies in e-CVT operation description

Some websites indicate that for some 'gear ratios', MG2 can operate as a generator and its output can flow to MG1, which then operates as a motor.

This is the opposite of what is shown in Fig.2. However, Toyota always describes MG1 as being the generator in this case.

We suspect that this is a simplification on Toyota's part.

It makes sense that MG1 and MG2 may swap roles as generator and motor depending on the ratio between ICE RPM and wheel RPM, as a way to control the power split through the PSD and therefore the effective 'gear ratio', as determined by the percentage of energy going to the wheels which flows through the reduction gear set.



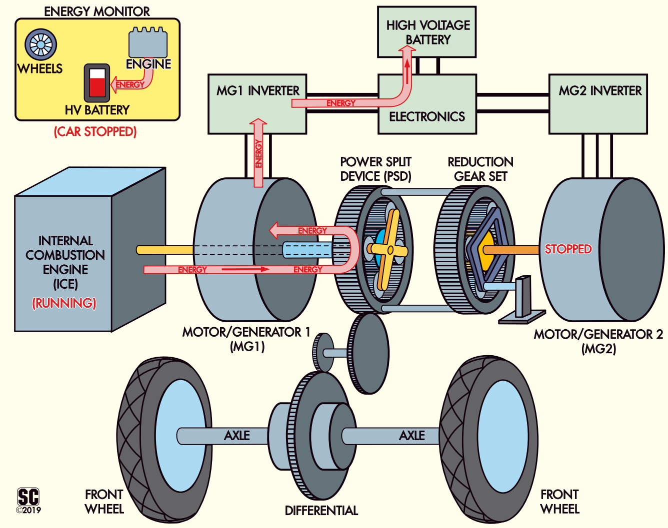


Fig.8: the vehicle can move with the ICE shut off, drawing energy only from the battery (EV mode). The ICE is stopped and MG1 is allowed to spin freely. Energy from the battery is used to rotate MG2, and as this is meshed directly to the differential, despite MG1 freewheeling, it can move the vehicle. The reduction gear set provides plenty of torque for setting off or even climbing a hill. MG2's direction of rotation determines whether the vehicle moves forwards or backwards.

Fig.9: if the HV battery is low or the ICE is cold, the vehicle can charge its battery directly from the ICE even when it is stationary. In this case, the ring gear of the PSD cannot turn, and thus MG2 can't turn either, so all of the ICE's energy goes into MG1 via the PSD. This is then converted to an appropriate voltage for battery charging by MG1's inverter.

be used to maintain forward speed, as may be the case when driving up a hill.

This is shown in Fig.4. As with Figs.2 & 3, energy is still flowing from the ICE to the wheels via the PSD and MG1/MG2.

But extra power is also flowing from the battery to the MG2 inverter, so that MG2 is delivering more power to the wheels than it is receiving from MG1.

By varying the position of the accelerator pedal while driving, the dashboard energy monitor display will change between those shown in Figs.2, 3 & 4.

Regenerative braking

Fig.5 shows what happens during regenerative braking, for example, when braking slowly to come to a stop, or when coasting or decelerating down a hill.

Kinetic energy from the wheels goes through the reduction gear set to MG2, which operates as a generator to charge the HV battery. The ICE is not running, and MG1 is allowed to spin freely.

To achieve maximum charging efficiency during regenerative braking, brake pedal pressure should be applied early and consistently to keep the "ECO gauge" power needle within the charging ("CHG") range on the dial.

Hard braking will engage the friction brakes, wasting energy (although this is not a concern in emergencies!).

But generally, it is better for the vehicle's kinetic energy to be used to charge the HV battery than to generate heat energy and to wear out the brake pads.

Note that while going downhill, it may be gravitational potential difference energy rather than kinetic energy that is being used to charge the HV battery (eg, when descending a hill at a constant speed).

Fig.6 also shows regenerative braking, but this time, the HV battery charge is low, so the ICE is also running to recharge it.

The ICE spins MG1 (acting as a generator) via the PSD, but some of its energy also passes through the reduction gear set to MG2, boosting its output as well.

Additional engine braking is available when the "gear shift" lever is placed in the "B" position. This provides the situation shown in Fig.7.

Note how the dashboard display ("Energy Monitor") now shows energy flowing from the wheels to the battery but not to the engine.

Regenerative braking is in effect, as shown previously. But now energy is also flowing from the wheels to the PSD, and into both MG1 (operating as a generator), and into the ICE, which has its fuel supply cut off.

This means that the wheels are forced to spin it, overcoming its internal friction, absorbing the excess energy.

The maximum amount of energy possible is converted into electricity to charge the HV battery, with the rest being dissipated as heat in the ICE.

This has the advantage, compared to using the disc brakes, that the engine has a large thermal mass along with a water-cooling system to better dissipate the resulting waste heat energy.

If the HV Battery is full during regenerative braking, MG1 switches from being a generator to being a motor, so that the ICE dissipates all the excess energy.

Full electric mode

Fig.8 shows the car operating in electric vehicle (EV) mode. Electrical energy is taken from the HV Battery via the MG2 inverter to motor/generator 2 (MG2).

This powers the wheels via the reduction gear set and differential. The ICE is not running, and MG1 spins freely as no energy is being used to charge the HV battery.

When the HV battery charge is low and the car is stopped, Fig.9 shows how the ICE can still charge the battery. All of the ICE energy is sent to MG1, as the PSD ring gear cannot turn, and MG1 acts

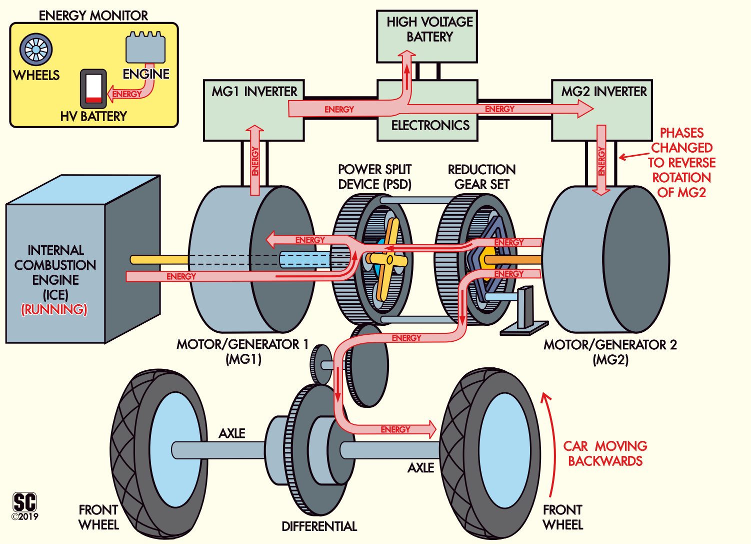


Fig.10: here is how the vehicle is reversed even when the HV battery charge is too low to power MG2. This is effectively a combination of the configurations shown in Fig.8 & Fig.9, with the ICE charging the HV battery via MG1 and then the HV battery supplying the power to run MG2. This is necessary as only MG2 can move the vehicle in reverse.

as a generator to charge the HV Battery.

This mode often occurs after the car is first started, as it allows the ICE to quickly get up to operating temperature without wasting any energy (as long as the battery is not full).

Reversing

When the vehicle is reversing using electrical energy from the HV battery, the situation is the same as shown in Fig.8.

The only difference is that MG2 rotates in the reverse direction as the drive sequencing of its three coils changes.

But if the battery is low, the car still needs to be able to reverse, and this can be achieved as shown in Fig.10.

This is effectively a combination of Fig.8 (EV mode) and Fig.9 (stationary battery charging).

The ICE is switched on to charge the HV battery via MG1, operating as a generator, and the resulting electrical energy is also used to power MG2 for moving the vehicle.

As shown, a small amount of the energy going to MG2 is also fed back to MG1 via the PSD, and that energy is recovered as electricity.

As before, MG2's direction of rotation is reversed by manipulating the sequencing of its phases.

Note that the Energy Monitor display does not show energy flowing from the engine to the wheels or from the HV battery to the wheels in this case, although that is surely the case.

But this is an unusual situation. In most circumstances, there will be enough energy in the battery to reverse, unless the car has been sitting for a long time. **SC**