

48 Volt High Power – Much More than a Mild Hybrid

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Summary

It is widely accepted that hybrid electric vehicles will be an important tool, besides pure electric vehicles, to lower the CO₂ emissions of passenger cars in the coming decade and beyond. Up to now, high cost and system impact on existing drivetrains prevented the introduction of these systems on a large scale. By increasing the peak power to 30kW, the highly compact 48 Volt High Power electric drive by Vitesco Technologies now facilitates a full hybrid based on 48 V technology. This means highest fuel efficiency and low CO₂ emissions known from HV hybrids as well as a 'hybrid feeling' by pure electric driving and all this at an attractive price. The 48 V hybrid system is rounded off by the 'Advanced Energy Storage' (AES), a space-saving single power supply unit for both 12 V and 48 V. The use of Li-ion technology and the removal of the 12 V lead acid battery leads to a high charge / discharge cycle count number, high power density and a significant weight reduction. Finally, a 48 V plug-in hybrid variant is proposed as attractive fuel saving concept.

1 View on Hybrid Market

A snapshot of today's German hybrid market is given by Fig. 1. The diagram is based on publicly available data and shows the correlation between CO₂ emissions (as certified), the car price and the hybrid type (mild, full and plug-in hybrid). Although the diagram does not differentiate between vehicle segments and is not complete, it reveals the following:

- Plug-in hybrids (PHEV) cover a wide car price span and enable low certified CO₂ values. The CO₂ emission stays below the thresholds given by subsidies in place in Europe (such as 50 g/km) for the majority of vehicles
- No offers for PHEVs below 30,000 € and A- and B-segment are not covered. However, in total, PHEVs represent the vast majority of hybridized models
- Mild hybrids (MHEV) cover a wide span of applications, prices and resulting vehicle CO₂ emissions
- The number of full hybrids (FHEV) is significantly lower and they populate the price range of 20,000 € to 40,000 €
- As general trend, FHEVs show lower CO₂ emissions than MHEVs (average ~25 g/km) and a lower car price than PHEVs (by ~10,000 € in average)

Obviously, full hybrids are a good compromise between low CO₂ emissions and affordable prices, which are both decisive criteria for mass market segments and their high volumes. The attractiveness of FHEVs can be further improved by reducing system cost, opening the door for the electrification of smaller cars, and additionally supporting a good drivability, which is important for higher vehicle segments.

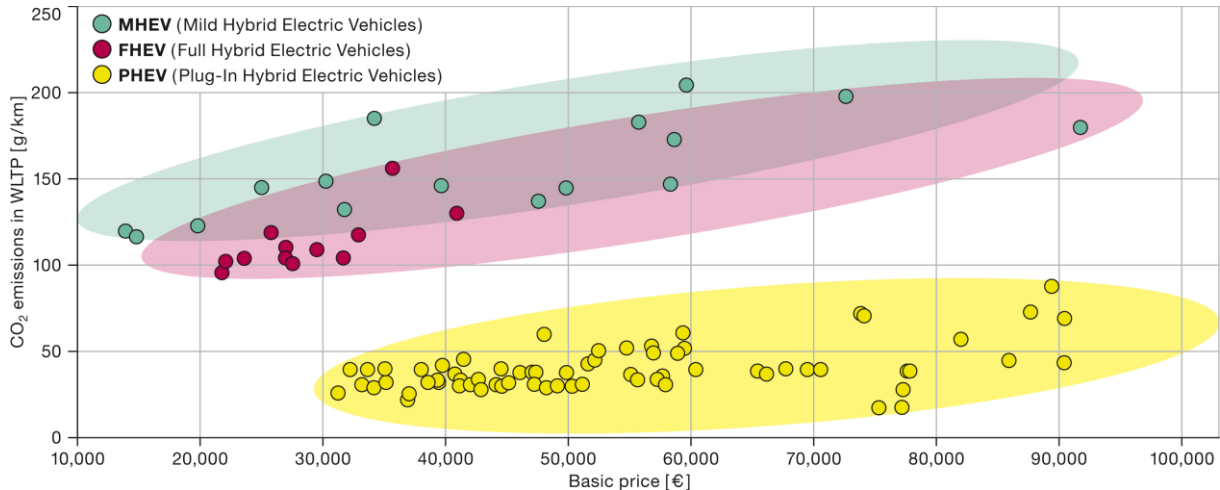


Fig. 1 Overview of German hybrid market consisting of mild, full and plug-in hybrids. CO₂ emissions are weighted CO₂ emissions according to the European type approval procedure (EU 2017/1151) and the given price is the publicly available base price for cars offered in Germany (incl. 19% VAT).

Both aspects, reducing costs and improving drivability, are satisfied by the '48 V High Power' system, which allows the realization of a full hybrid based on 48 V technology and which is described in detail within this paper. Centre point of this technology is a 48 V electric drive with 30 kW peak power and it is supplemented by an optimized 12 V / 48 V power supply system, the Advanced Energy Storage (AES).

Another subject arising from Fig. 1 are the CO₂ and price gap between FHEVs and PHEVs. Is it possible to further reduce the CO₂ emissions of FHEVs or can more cost-efficient PHEVs be realized, even if they show higher CO₂ emissions? Looking at cost, not just the car price is important but rather the total cost of ownership over several years. All these aspects are discussed in the following by looking at the fuel efficiency of FHEVs, proposing a fuel saving PHEV concept and by comparing the total cost of ownership of different 48 V and HV hybrid systems.

2 Requirements defining a Full Hybrid

Looking at the question 'what are the requirements, which define a full hybrid', two main features come into the game: A good fuel efficiency along with low CO₂ emissions, which will be further discussed in chapter 4, and the ability to drive purely electrically.

The second feature of electric driving is expected by car drivers, if the vehicle shall be perceived as a hybrid, even if it is available only at limited speeds, such as in city areas,

and the distance is limited. For mild hybrids not able to drive electrically, the perception of electrification is reduced to marginal effects, such as an improved start-stop behaviour or the engine-off coasting feature [1].

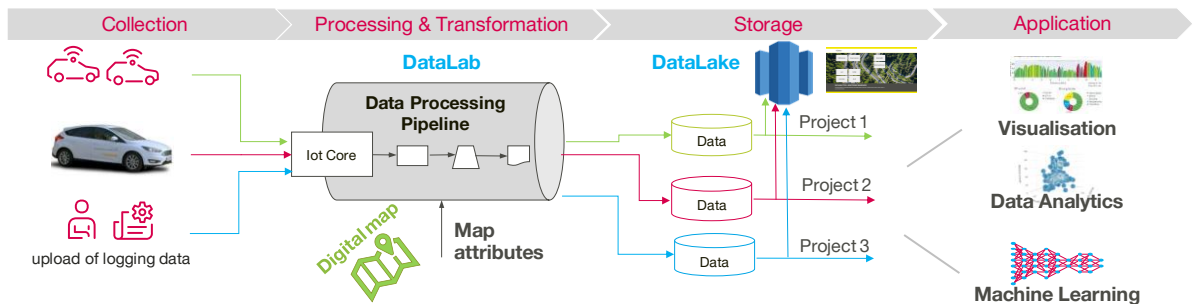


Fig. 2 Cloud-based vehicle monitoring at Vitesco Technologies

In order to decide which power of the electric drive is expected by car users so that their hybrid electric vehicle is accepted as full hybrid, Vitesco Technologies has chosen a 'big data' approach. Several demonstrator and benchmark vehicles are permanently connected to the Vitesco Technologies cloud and all essential vehicle data are continuously sent to the respective DataLab (Fig. 2). Here the data are automatically processed and map data are added, before being permanently stored in the subsequent DataLake. With this setup, questions arising can quickly be investigated by applying suitable analysis tools.

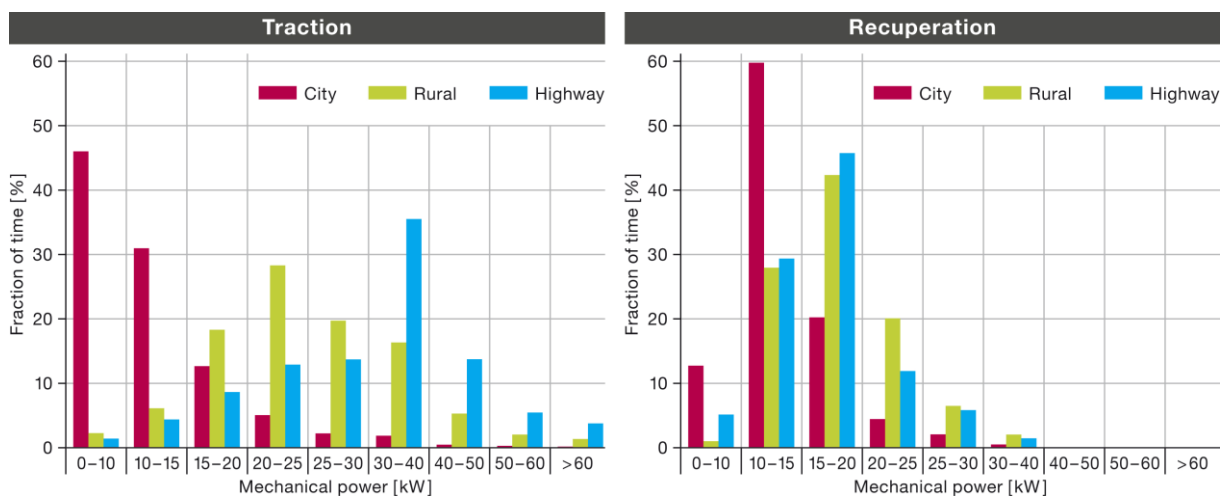


Fig. 3 Mechanical power distribution for a C-segment vehicle in different driving situations (20 s average). The data were recorded using a battery electric vehicle (e-Golf).

Applying this setup, it was analysed which (mechanical) power is requested by drivers for traction and braking during driving under different road conditions. In order to limit the impact of the specific engine and transmission characteristics, a C-segment battery electric vehicle (VW e-Golf) was chosen for these investigations. The car was driven by various drivers in various situations and at various locations. Rides over a total distance of 4887 km and a total driving time of 87.4 h were analysed.

Fig. 3 shows the resulting power distributions split into traction and braking / recuperation for city areas, rural roads and highways. The chosen 20 s-average correlates well to the power requirements during acceleration and recuperation. The data indicate that in city areas almost all situations are covered by a power of 30 kW (averaged over 20 s), whereas significantly higher values are needed on rural roads and highways. The power spectrum of recuperation events is rather similar on the different road types. Again, a power of 30 kW is capable to cover most brake events and harvest as much energy as possible by recuperation.

As a conclusion, an electric drive power in the range of 30 kW, in particular when supplied by 48 V technology, is well suited to realize a full hybrid. Pure electric driving is feasible in most city areas as well as on extended sections of other roads, and applying electric recuperation during most brake events is the key to a good on-road fuel efficiency.

3 48 V High Power Electric Drive and utilized Powertrain / Vehicle System

In line with the above-mentioned requirements on hybrid electric vehicles, Vitesco Technologies has developed a '48 V High Power' electric drive system with a peak performance of 30 kW and an excellent efficiency as centrepiece to realize a full hybrid based on 48 V technology. Its compact design with a very high-power density flexibly allows the realization of different hybrid configurations, such as the integration into a P2-hybrid module or a gearbox (P2.5, P3), as well as the realization of an electric axle drive (P4) and, thereby, enable a four-wheel drive capability.

The two main sub-components of the electric drive are:

- An electric permanent magnet synchronous motor (PSM) applying I-Pin stator winding technology (Vitesco Technologies patent) capable of reaching a maximum shaft speed of 20,000 rpm. To achieve the high power and power density of the e-machine, the combined contribution of the magnetization provided by rare-earth magnets and an optimized reluctance effect is necessary.
- 6-phase inverter based on 'Embedded PCB technology' (Vitesco Technologies patent), which includes up to 3 MOSFETs per phase to increase the current. The inverter PCB technology is an enabler for a compact design and, thereby, a high-power density of 25 kW for 0.79 litre/1.51 kg.

In terms of cooling, a joint cooling concept has been designed between inverter and electric machine. The inverter is liquid cooled as the electric machine's design benefits from a water jacket.

The key figures of the 48 V High Power electric drive are summarized in Fig. 4. The performance data, marked by solid points, have been measured on an electric drive test bench with a water cooling temperature below 85°C and a cooling flow of 3 l/min. Efficiency is already high with ~ 90 % in motor mode (measured at 14.5 Nm, 10 kW,

36 V, 6600 rpm) for the very first prototype samples and simulations indicate that there is further potential to improve this value.

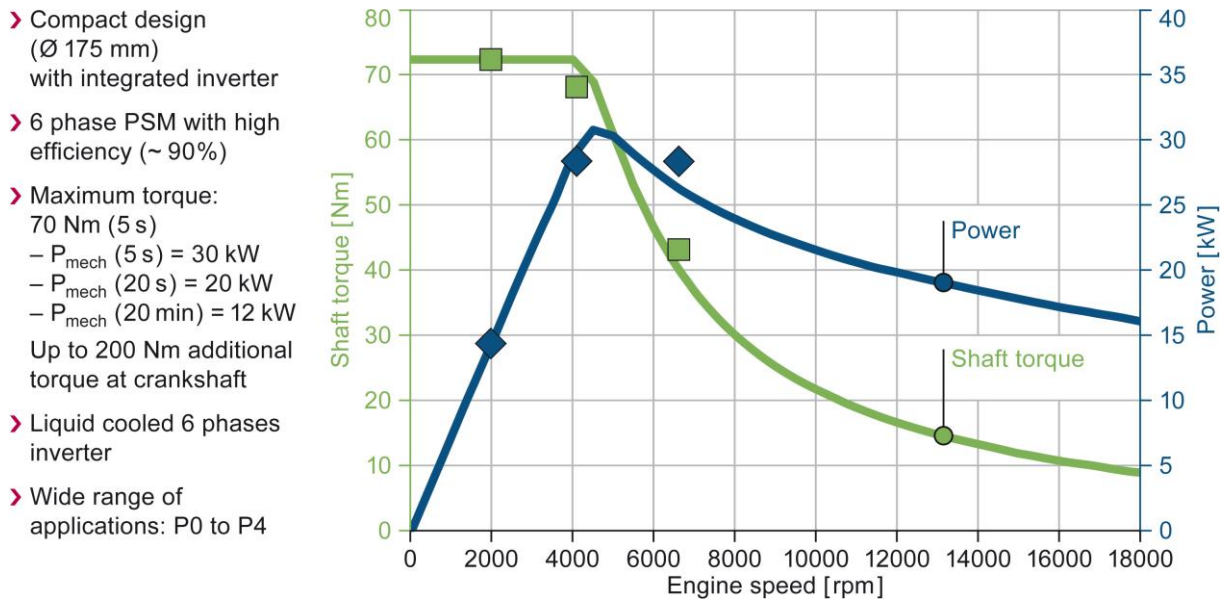


Fig. 4 Torque and power characteristics of the 48 V High Power electric drive

For a hybrid vehicle, this means that one can benefit from a theoretical additional crankshaft torque of up to 140 to 210 Nm provided by the '48 V High Power' electric drive to boost the already available torque from the internal combustion engine (the 70 Nm maximum torque of the electric drive are usually multiplied by a gear ratio of 2 to 3). Thereby, the low-end engine behaviour is significantly improved, which, when combined with highly charged, power-dense gasoline engines, offers much more dynamic acceleration and drivability (see chapter 5).

The next step for Vitesco Technologies was to integrate and to assess the performance of the '48 V High Power' electric drive in a real use case in a demonstrator car. The choice has been made to re-use as a basis the P2 hybrid architecture already developed by Vitesco Technologies and partners [2], and then to replace the previous generation of 48 V electric drive motor by the new '48 V High Power' electric drive (Fig. 5). As 48 V battery two variants are available: To realize a full hybrid vehicle the so-called advanced energy storage (AES, see chapter 6) is the suitable solution, whereas a dedicated 48 V 5.5 kWh battery (nominal) makes it possible to explore the potential of a 48 V plug-in hybrid.

This so-called P2 hybrid architecture shows the electric traction machine and the additional K0 clutch being installed between the internal combustion engine and the e-machine. Hence pumping and friction losses of the engine are eliminated in hybrid states such as recuperation, coasting (rolling with open powertrain), sailing (driving electrically at constant speed) and pure electric driving. The combustion engine is the Ford 1.0l EcoBoost 3-cylinder gasoline engine (model year 2015). It is enhanced by a matching turbocharger, a 200 bar fuel pressure direct injection system and a 48 V 4 kW electrically heated catalyst (EMICAT®). By moving the mechanical A/C compressor to the P2 hybrid module and replacing the mechanical water pump by an electric one, a

classical 'beltless engine' is realized. As required for a P2 hybrid vehicle, a small electrical water pump enables electric machine operation when the combustion engine is shut off.

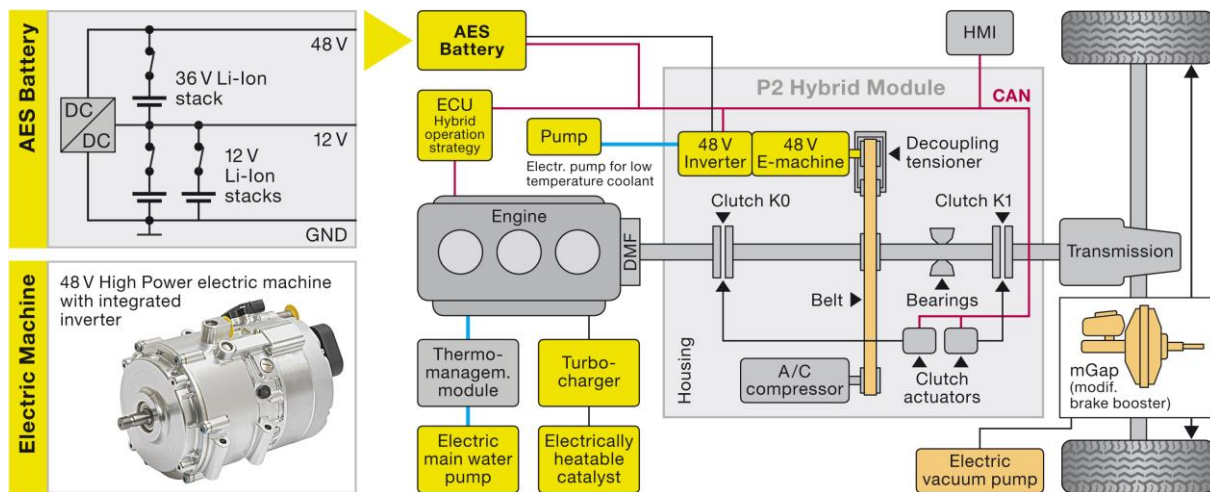


Fig. 5 Prototype system overview "48 V High Power" with Advanced Energy Storage (AES)

Another key subsystem is the high level 'hybrid operation strategy' executed by the engine control unit. It is implemented in a model-based manner and controls the entire hybrid powertrain.

All in all, the impact on the existing base powertrain is minimal and demonstrates the high integration capability and affinity to existing engines and transmissions. All following chapters refer to this vehicle and powertrain architecture.

4 Fuel Efficiency of 48 V High Power

Thanks to the utilization of the 48 V High Power system, a FHEV can now be also realized on a 48 V basis. Simulations results already showed that a reduction of 19% in CO₂ emission would be possible on WLTP thanks to the increase of available electrical power and system efficiency compared to the mild hybrid solution [3]. This marks a significant improvement of 4% in comparison to former results based on mild hybrid technology with same powertrain base [2].

The low fuel consumption level achieved on WLTP with the Vitesco Technologies demonstrator car is mainly achieved thanks to the high amount of electrical energy which can be recuperated. Due to the high efficiency of the 48 V High Power electric drive, in fact, a very high amount of electrical energy can be recuperated and the advantage of a P2 architecture is fully exploited. Second, thanks to smart reusage of this energy, the overall system efficiency can then be improved for example in high speed phases when only low power is requested, the vehicle can now drive electrically thus avoiding the operation of the combustion engine with low efficiency. Additionally, especially during acceleration phases, the electric motor reduces the inefficient transient utilization of the combustion engine. Thanks to the high torque available at low rotational speeds

and the quick response, in fact, the EM can take over vehicle acceleration phases or at least mitigate the load on the combustion engine. Thanks to the 48 V High Power system, on the one hand, eDrive feeling is significantly improved, and on the other hand the overall powertrain efficiency can be increased, differentiating from a state-of-the-art 48 V mild hybrid solution.

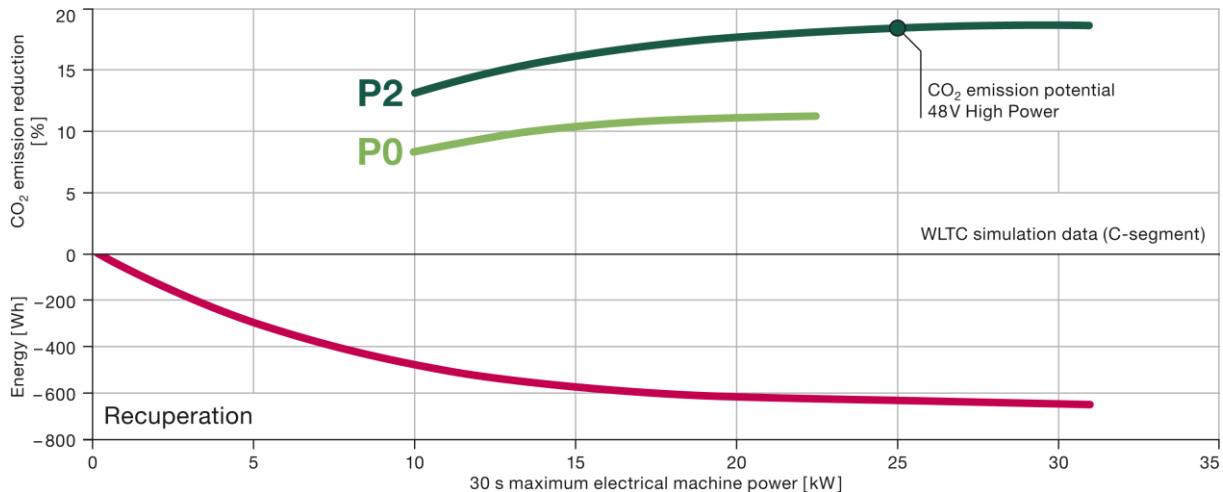


Fig. 6 CO₂ emission saving on WLTP due to 48 V High Power

High efficiency of 48 V High Power and low weight compared to other FHEVs and, in particular, to PHEVs make the 48 V High Power FHEV even superior in terms of fuel saving under real driving conditions at charge sustaining mode. In both urban and extra urban driving, these two factors allow to achieve real performances comparable to best-in-class high voltage systems already in an early development phase with an average fuel consumption of 4.76 l/100km using a production gasoline engine in an urban cycle. This means, that the 48 V High Power solution from Vitesco Technologies helps to reduce the real world energy consumption significantly, which becomes more important with the introduction of On-Board Fuel Consumption Monitoring (OBFCEM) from January 2020 on as well as in respect to total cost of ownership.

5 Benefit by Improved Drivability and the eDrive Feature

The 48 V High Power system is capable, besides reducing CO₂ emissions, of also improving vehicle drivability and it allows a purely electric driving ('eDrive') feeling, especially in urban areas. Thanks to the high and quick torque availability from the electric drive (quasi-zero time to torque), vehicle performances can be improved in terms of elasticity and an increase of the available torque at low combustion engine speeds through the so-called eBoosting. In Fig. 7 an example of an elasticity test from 20 km/h to 60 km/h in 3rd gear is shown. In this test, the time to torque due to the turbo-lag is reduced from about 4.5 s to about 200 ms thanks to the eBoosting. Additionally, by combining combustion engine and e-machine torque, the overall torque at gearbox input can be increased by more than 50 Nm even when the airpath system of the combustion engine is under nominal conditions. These manoeuvres disclose a reduction of the time to reach 60 km/h by 4.7 s, namely from 10.7 s to 6.0 s. It should also be

mentioned that the full torque potential could not be applied yet due to gearbox protection limits.

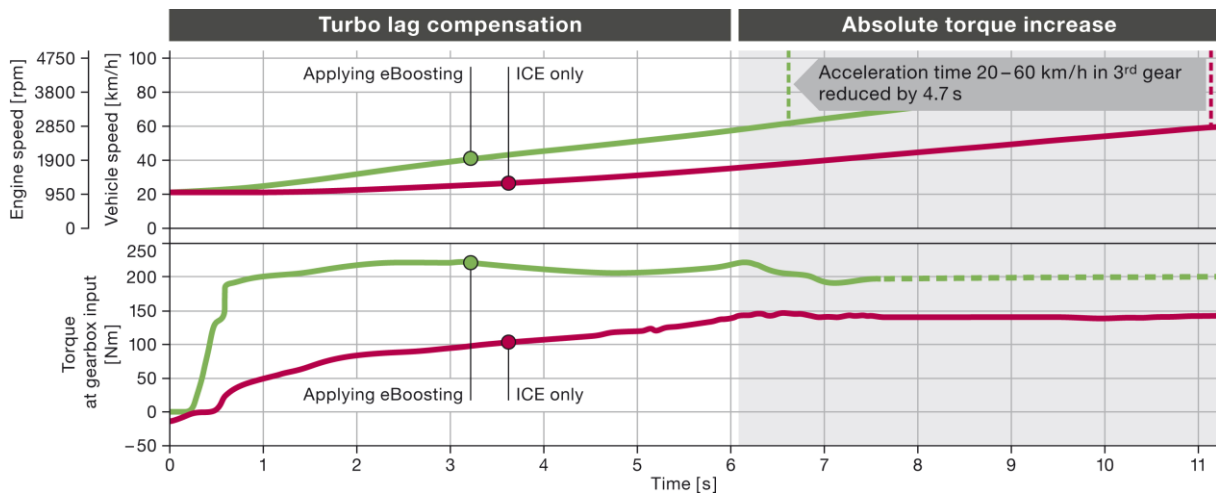


Fig. 7 Time to torque by eBoosting (compared to internal combustion engine (ICE) only)

The quick and precise availability of torque is essential to improving the overall system drivability in particular situations where a fine control of the vehicle speed is desired. In case of a parking garage, for example, the 48 V High Power system can offer a BEV-like driving feeling enabling precise and responsive control of the vehicle. The electric driving feeling can also be delivered during normal driving, especially in urban areas, thanks to the small increase in mass respect to a corresponding combustion engine driven vehicle. The peak power of 30 kW allows one to accelerate and drive electrically also under normal traffic conditions.

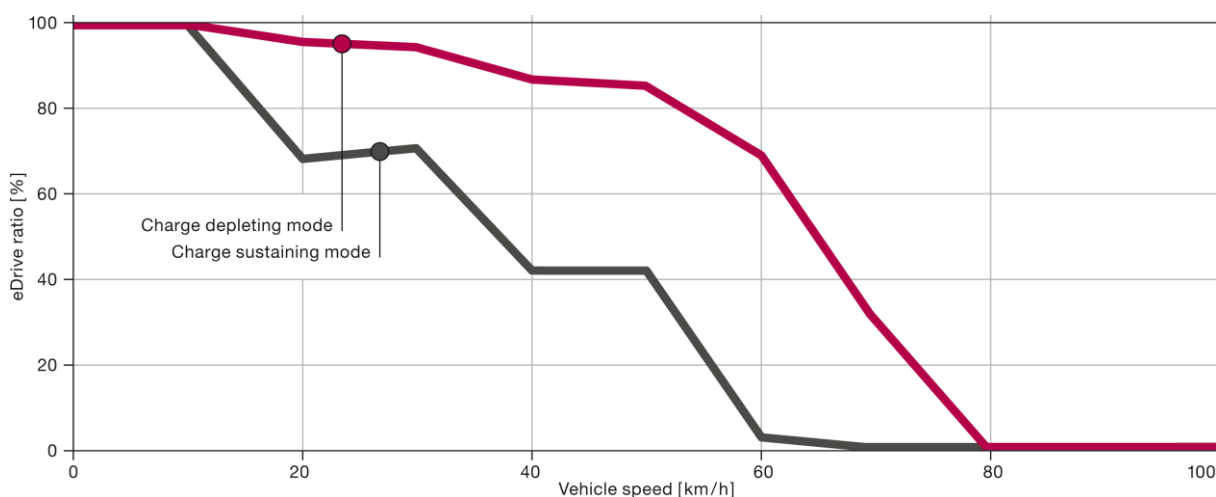


Fig. 8 The eDrive ratio (over distance) as function of vehicle speed for a city cycle

In Fig. 8, the percentage of distance driven electrically is shown as average of several urban drives carried out in the Regensburg city applying both charge sustaining and charge depleting mode. As it can be noted, more than 50% of the driven distance up to 50 km/h could be covered electrically while still fulfilling the task of balancing the battery state of charge thanks to the already mentioned high efficiency of the electrical

system. The share of electric driving in this speed range can be even increased to more than 80% (and also to 30% at 70 km/h) in case of depletion of the battery.

Using the overall capabilities of the 48 V High Power System from Vitesco Technologies could then even make it possible to drive in Zero Emission Zones if combined to a properly sized vehicle weight and battery capacity.

6 Optimized Power Supply System - Advanced Energy Storage (AES)

The complexity of power supply systems in hybrid electric vehicles can be significantly reduced by the introduction of a combined, integrated power supply system. The so-called 'Advanced Energy Storage' system (AES) acts as intelligent energy supply and management system for both 12 V and 48 V power nets. Fig. 9 shows the general setup of the AES, consisting of separate 12 V and 36 V stacks on Li-ion basis, which are interlinked with an internal DC/DC-converter. This concept was already presented as early prototype a few years ago [4]. The current sample step presented here is a completely new development with focus on fulfilling all essential requirements of both the 12 V and the 48 V power net. The main design parameters are summarized in Tab. 1. The AES setup enables the bi-directional transfer of electrical energy between the two cell stacks as well as the transfer of additional electric power if needed ('boost functionality'). Dividing the 12 V stack into two separate sub-stacks, each equipped with a dedicated relay, generates a double redundancy – the 12 V can, in case of a cell failure, be supplied by the remaining 12 V stack or by the 36 V stack via the DC/DC converter.

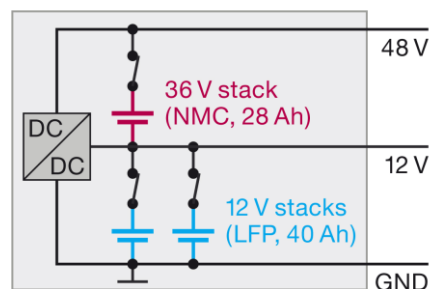


Fig. 9 Setup of the AES battery

For the current prototype, cells with different chemistry were chosen. The battery management system (BMS) can handle this configuration without major difficulties, because, from cell supervision point of view, the AES consists of two independent sub-batteries, which are monitored separately. Lithium Iron Phosphate (LFP) cells with their characteristic small increase of the open circuit voltage versus the state of charge (SOC) allow the full use of the SOC range on 12 V side without violating the narrow voltage limits of the 12 V power net. The Lithium Nickel Manganese Cobalt Oxide (NMC) cells of the 36 V stack were selected due to their advantage in power density.

The key features of this power supply system in comparison to a conventional solution using standalone components are:

- Single power supply component during vehicle integration
- Replaces standalone 12 V and 48 V batteries as well as DCDC converter
- Reduced weight
- High capacity of ~1.4 kWh (nominal)
- Supports future generations of 48 V electric drives (electric power up to 40 kW)
- Active air cooling or optional liquid cooling
- Autonomous operation (distribution of energy and power as well as cooling)
- Full system monitoring and balancing capability
- Redundant 12 V supply
- Sleep mode for long term parking ($I \approx 20$ mA, 6 weeks)
- Compliance with automotive environmental conditions (48 V and 12 V, -30°C to 55°C)

A single component energy supply system for both the 12 V and the 48 V power net of a hybrid electric vehicle is realized, which can be mounted as fully tested unit at one packaging location in the vehicle manufacturing plant. The removal of the heavy 12 V lead acid battery saves weight and complies with potential, future environmental protection rules.

Total nominal capacity	1450 Wh
Cell stack 12 V	Lithium Iron Phosphate (LFP), 2 * 20 Ah in parallel
Cell stack 36 V	Lithium Nickel Manganese Cobalt Oxide (NMC), 28 Ah
DC/DC converter power	3 kW (continuous)
Operating temperature range	$-30^{\circ}\text{C} - 55^{\circ}\text{C}$
Dimensions (prototype)	390 x 300 x 180 mm
Weight (prototype)	34 kg

Tab. 1 AES design parameters

The performance of the battery system regarding capacity and electric power exceeds the requirements of 48 V mild hybrid systems seen currently on the market (Tab. 2). It is designed to the needs of the 48 V High Power electric drive presented in this paper. The 40 kW electric peak power output of the AES fits well to the 30 kW mechanical peak power of the described next generation electric drive.

In Fig. 10, the AES concept battery is shown with opened top cover. Although the prototype character of the design is perceptible, the component already reflects a high degree of functional integration. The displayed main compartment of the battery housing (Fig. 10 left) also contains the battery cell stacks. It is enclosed by a sealed cover (here removed), thus forming a gas-tight chamber which allows for easy and safe ventilation of potential hazardous gases outside of the vehicle.

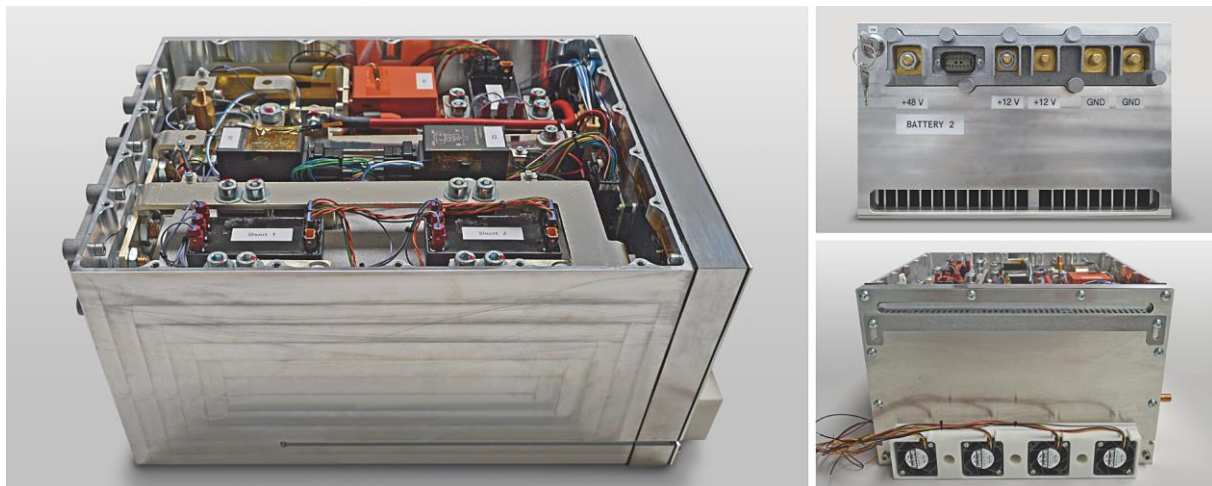


Fig. 10 Pictures of the AES prototype. Top view with internal wiring, busbars and safety components (left), front view with terminals and air inlet (right top) and rear view with suction cooling fans (right bottom).

The performance of the battery was validated on dedicated battery test benches. Tab. 2 gives an overview of the measured values. The above-mentioned target of 40 kW peak output power could be confirmed, thus showing full compatibility with future 48 V drives. The maximum charge power is 30 kW for 5 s (50 V) and fits well to the characteristics of the 48 V High Power electric drive (Fig. 4) as well as to the requirement of being able to maximize recuperation in on-road situations (Fig. 3).

48 V terminal	
Nominal voltage	46 V
Peak power (discharge)	40 kW
Current ratings (discharge)	900 A (5 s)
	700 A (20 s)
	150 A (continuous)
Current ratings (charge)	600 A (5 s)
	400 A (20 s)
	100 A (continuous)
12 V terminal	
Nominal voltage	13 V
Current ratings (discharge)	1300 A (200 ms)
	400 A (10 s)
	100 A (continuous)

Tab. 2 Validated electrical performance of the AES.

The functional validation tests in a 48 V hybrid car confirm that the AES is suited as single power supply system for such a vehicle. The power and current flows for three typical use cases are displayed in Fig. 11. The diagrams on the left show the transition from engine-off coasting (open driveline) to hybrid drive (both e-motor and combustion engine active) with the necessary re-start procedure of the combustion engine. In the

middle, a recuperation event is depicted, which leads to a charging of both the 12 V and the 36 V stack. In the case of a parking vehicle, only 12 V consumers are active. Therefore, a so-called stack balancing is performed to fill up the 12 V stack with energy out of 36 V stack using the internal DC/DC-converter. The standard requirement of the 12 V power net to supply the key-off loads of the vehicle for typically 6 weeks followed by a subsequent engine start can be fulfilled by combining the capacities of the 12 V and the 36 V stacks. Thus, by applying stack balancing, an unnecessary oversizing of the 12 V battery stack is avoided.

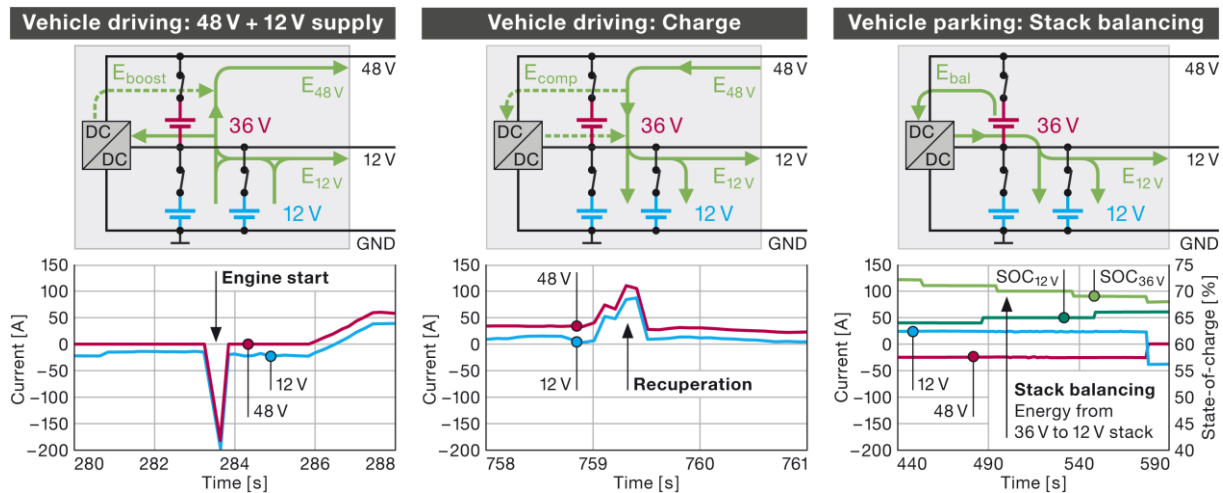


Fig. 11 Validation of battery in vehicle showing the functionality in three different operating modes. The currents labelled as '12 V' and '48V' are measured as current through the 12 V and the 36 V stack, respectively.

7 A 48 V Plug-in Hybrid - a New Fuel Saving Concept

Based on the system configuration described in chapter 3, a 48 V High Power plug-in variant with an extended battery capacity has been investigated. Simulation results show that with a C-segment car a weighted CO₂ emission of less than 50 g/km can be reached (EU Type approval 2017/1151). This means a classification as low-emission vehicle, which opens the door to various funding programmes, such as the German purchase bonus of 4500 € (2020 status). In contrast to existing PHEVs on the market, a WLTC is driven by combining the combustion engine and the electric drive system in an efficient way [3].

Beyond the homologation value, the real fuel consumption is of particular interest for vehicle owners. In this chapter, 48 V plug-in hybrids are proposed as novel fuel saving concept with the potential to be an alternative to diesel vehicles. Here, PHEVs depend in high degree on the user behaviour, especially depending on the charging frequency. This is noticed by governments in respect to further subsidies [5]. Fig. 12 shows the fuel and electric power consumption of a 48 V PHEV with a fully charged battery (SOC 80%) when driving subsequent WLTCs. Since the bigger part of the WLTC is driven purely electrically as long as enough energy is stored in the assumed 8.6 kWh battery,

the real fuel consumption over 50 km (two WLTCs as shown in Fig. 12) is in average at 1.6 l/100km.

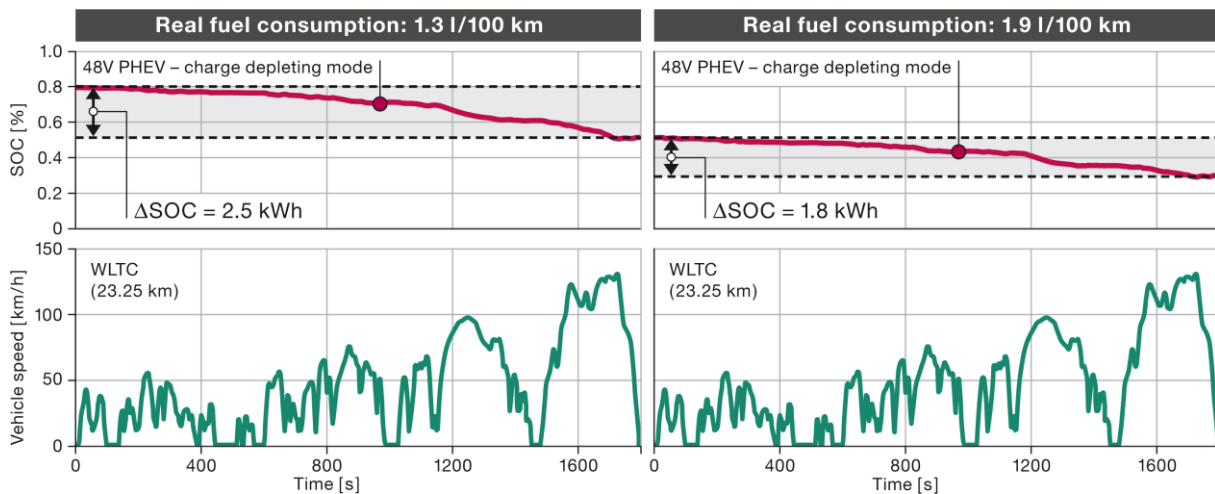


Fig. 12 Real fuel efficiency of a 48 V plug-in hybrid in charge depleting mode. The given fuel efficiencies are the actually measured values, not the calculated weighted value as applied during homologation.

It is well known and has been publicly discussed that the real fuel consumption of a PHEV is strongly dependent on the applied charging frequency. Tab. 3 summarizes the consumption for charging intervals between 50 km and 100 km. Obviously, the fuel efficiency stays always on a very attractive value far below 4 l/100km. The financial benefit of this fuel saving is discussed and compared to other hybrid and non-hybrid vehicles in chapter 8.2.

Charging interval	Fuel consumption (average over charging interval)	Electric consumption (average over charging interval)
50 km	1.6 l/100km	9.2 kWh/100km
75 km	2.3 l/100km	7.4 kWh/100km
100 km	2.9 l/100km	5.2 kWh/100km

Tab. 3 Consumption of a 48 V plug-in hybrid (C-segment vehicle) as function of the charging interval. The battery has a nominal capacity of 8.6 kWh (180 Ah).

8 48 V High Power - a Cost Efficient Approach

The main driver to apply 48 V technology in hybrid electric vehicles (passenger cars) is production cost and price. The interest of car manufacturers is to achieve low system cost for electrification and, thereby, limit the add-on price compared to non-hybrid cars to a minimum when selling these vehicles. The actual interest of car owners is cost of ownership, which means, besides the purchase price, considering also the cost for maintaining the vehicle. The impact of 48 V technology on both aspects will be described in the following.

8.1 System Market Pricing

Nowadays, cost efficient 48 V technology is well established for mild hybrids. For these systems it is the technology of choice, because high-voltage (HV) systems in the required power range are today hardly an alternative. Looking at the power range of 30 kW, both solutions applying 48 V and HV are technically feasible so that a detailed analysis of the respective system market price becomes essential.

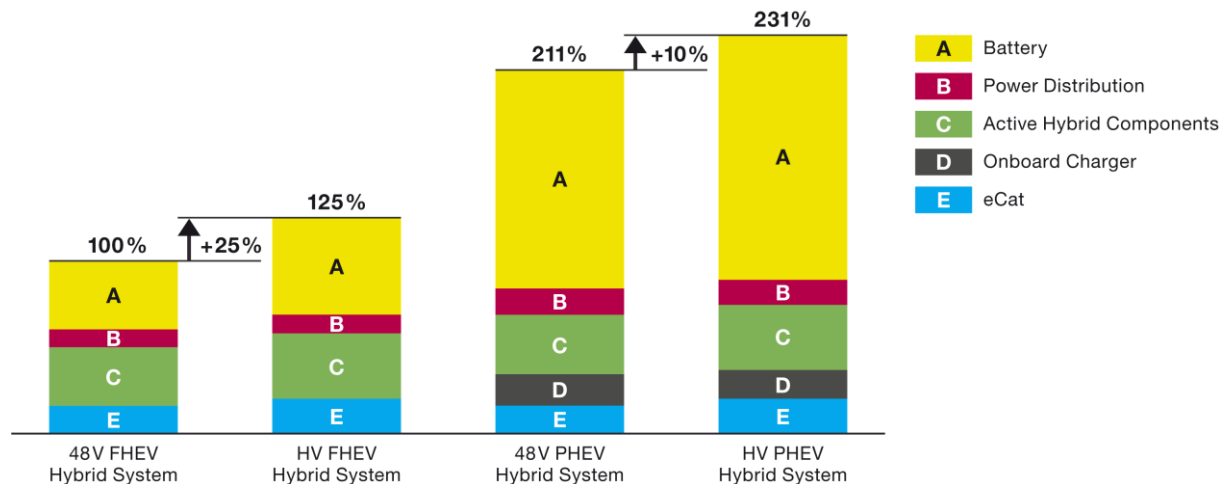


Fig. 13 Cost benefit of 48 V compared to HV hybrid systems. Both full (FHEV) as well as plug-in (PHEV) hybrids are shown. All systems have the identical e-motor power of 30 kW. Under 'Active Hybrid Components', the electric machine and the DC/DC converter are summarized.

Fig. 13 shows a market price comparison of the electrification system needed to convert a combustion engine only vehicle into a hybrid. Technically equivalent systems have been assumed to highlight the commercial benefit due to the voltage level only. A 30 kW 48 V full hybrid is compared to a HV system of the same power. The same is done for two 30 kW PHEVs. For all systems, an electrically heatable catalyst (EMICAT®) has been assumed to be compliant to future emission regulations.

This direct comparison confirms the market pricing benefit of electrification based on 48 V. For full hybrids, the price of the HV system is 25% higher than the 48 V one, for PHEVs, the relative cost adder is still 10%. Taking a closer look at the details of this comparison, it becomes clear that the biggest contribution to the observed differences comes from the battery sub-system and, in particular, from additional electronic components required for the HV battery system. These are mainly the isolation guard, which is not needed for 48 V systems, and the higher number of cell supervision chips (CSCs) which are needed due to the high number of cells mounted in series for HV batteries.

8.2 Total Cost of Ownership

For car owners the purchase price of a hybrid is only one side of the coin. Fuel saving concepts, such as full or plug-in hybrids, but also diesel vehicles have a higher purchase price than pure gasoline engine driven vehicles (Fig. 14 left). This price add-on

will be reduced and at the end compensated by the lower maintenance cost of the fuel saving vehicles. Fig. 14 (right) shows the calculated distance after which the price adder for FHEVs, PHEVs or diesel vehicles will amortise. For the PHEV, two charging intervals of either 50 km or 100 km have been assumed, which should be practicable for most drivers and which, thereby, justify public funding. A battery lifetime friendly SOC window of 20% to 80% has been assumed so that degradation of the battery is minimized from that point of view.

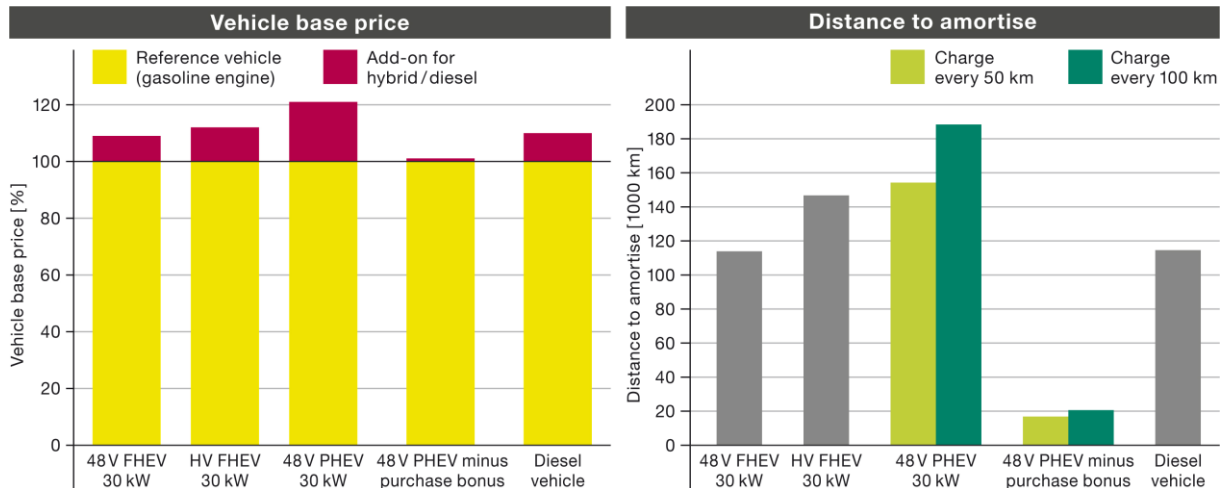


Fig. 14 Cost of ownership of 48 V full and plug-in hybrids for a C-segment vehicle compared to a HV FHEV and a diesel car. The left diagram shows the purchase price as add-on on top of a gasoline engine car. The right diagram indicates the distance after which the price add-on has been amortised. Thereby, the German purchase bonus for PHEVs (status 2020) has been assumed.

The calculation assumes an average mileage of 20,000 km per year, a consumption based on WLTP, average fuel prices from the last 10 years, a pricing for electricity averaged between private and public charging, German vehicle taxes (year 2020) and the German purchase bonus for PHEVs with a weighted CO₂ emission below 50 g/km or an equivalent all electric range of 60 km. The same representative C-segment vehicle has been assumed for all shown systems. The results are not inflation and interest adjusted. Neither included are service costs, which are relevant, but studies indicate a non-uniform picture [6]. Conversely, it is important that hybrids are designed in a way that their service costs do not exceed those of conventional vehicles to stay competitive with regard to their total cost of ownership.

According to Fig. 14, the cost of ownership for a 48 V full hybrid are very similar to those of a current diesel. Since here a diesel car fulfilling the Euro 6d-temp regulation was selected and future emission requirements towards EU7 will require a much higher effort for the exhaust gas aftertreatment system, FHEVs will become more and more attractive. The 48 V FHEV will amortise after about 15,000 km or almost one year earlier than a HV system with the same power.

Fig. 14 additionally shows that subsidies are essential for the success of PHEV systems, even for cost effective solutions as the proposed 48 V PHEV. Taking into account

such subsidies (e.g. the German purchase bonus), the 48 V PHEV is highly attractive and an amortisation can be achieved already within one year. Taking additionally into account the good fuel efficiency as described in chapter 7, a 48 V plug-in hybrid is a good candidate for an affordable PHEV system for the volume market (B- and C-segment). And it is not a too bold assumption that such hybrid powertrains show a higher mileage, as the propulsion is provided by two sources.

Conclusions

With the innovative 48 V High Power electric drive, Vitesco Technologies has greatly improved electrification in different aspects. The underlying power characteristic was derived from comprehensive simulations as well as from real on road data and related data analytics.

The resulting electric motor delivers a peak output of up to 30 kW, thus offering torque to support the combustion engine electrically to a high extent and leading to a performance at low end rpm known so far only from diesel engines. Furthermore, '48 V High Power' enables quiet, purely electric inner-city journeys at significantly reduced system cost compared to state-of-the-art high voltage hybrid solutions and could bring such 48 V full hybrids to more popular vehicle segments.

The proven CO₂ results are equivalent to state-of-the-art hybrid power split systems, however in contrast, applying existing engine and transmission systems as described. This lowers the threshold for application from an industrial point of view.

The entire 48 V High Power electric drive unit comprising electric motor and integrated inverter is extremely compact and, at same time, offers a very high efficiency in all modes. This facilitates mechanical integration for different Px architectures and ensures high CO₂ reduction benefits for full hybrids.

The total cost of ownership of shown applications is very attractive in terms of a short amortization period comparable with diesel engines. Even a 48 V High Power plug-in variant as shown would realize a reasonable amortization. If public subsidies are available, then a 48 V plug-in hybrid converts into a highly attractive fuel saving concept, even when moderate charging intervals are assumed.

In essence, the 48 V High Power electric drive has the distinct potential to open up further market segments and shares for electrification. While all passenger car segments profit from the excellent fuel efficiency at an attractive price as well as from the highly improved vehicle dynamics thanks to electric boosting, the benefits are greatest for B- and C-segment cars, as they can take full advantage of the purely electric driving feature. Finally, 48 V High Power is a suitable electric drive for small battery electric vehicles (sub-A-segment), too, which are being developed as innovative car concept for future city access.

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