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Battery Electric Vehicles

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In the early years of motor vehicle history, the most frequently used propulsion system was an electric drivetrain with batteries as energy storage. Power sockets were more common than petrol stations. From the 1920s, the increasing density of fueling stations made battery electric vehicles less desirable due to the longer recharging times.

It took many decades before the aspect of emissions and scarcity of primary energy resources (re)surfaced and, as of today, a significant number of series production vehicles from major car manufacturers are available to end customers. E-mobility stakeholders also stress the potential linkage of battery electric vehicles and the energy sector to create a smart grid where vehicles could act as balancing loads when plugged into the charging pole.

In general terms, and with electricity being a secondary energy carrier just like hydrogen, this underlines the necessity to assess the well-to-wheel efficiency, emissions, and sustainability of such drivetrains.

Figure 1.1 illustrates a simplified overview of the well-to-wheel energy conversion for the main propulsion technologies, with focus on the battery electric vehicle (BEV). Electricity can be produced from any of the primary or secondary sources, including hydrogen.

It becomes clear that electric vehicles benefit from the versatile electricity pathways, making them in theory the most sustainably propelled types of vehicles. This includes battery and hydrogen fuel cell electric vehicles (FCEV).

These differ only by the delivery of electricity to the traction motor(s), and this synergy is beneficial when creating BEVs and FCEVs with identical motors.

Battery electric vehicles have several benefits over conventional vehicles. They feature low noise emissions and do not produce local pollutants like NO_x,

Fuel Cells: Data, Facts, and Figures, First Edition. Edited by Detlef Stolten, Remzi C. Samsun, and Nancy Garland.

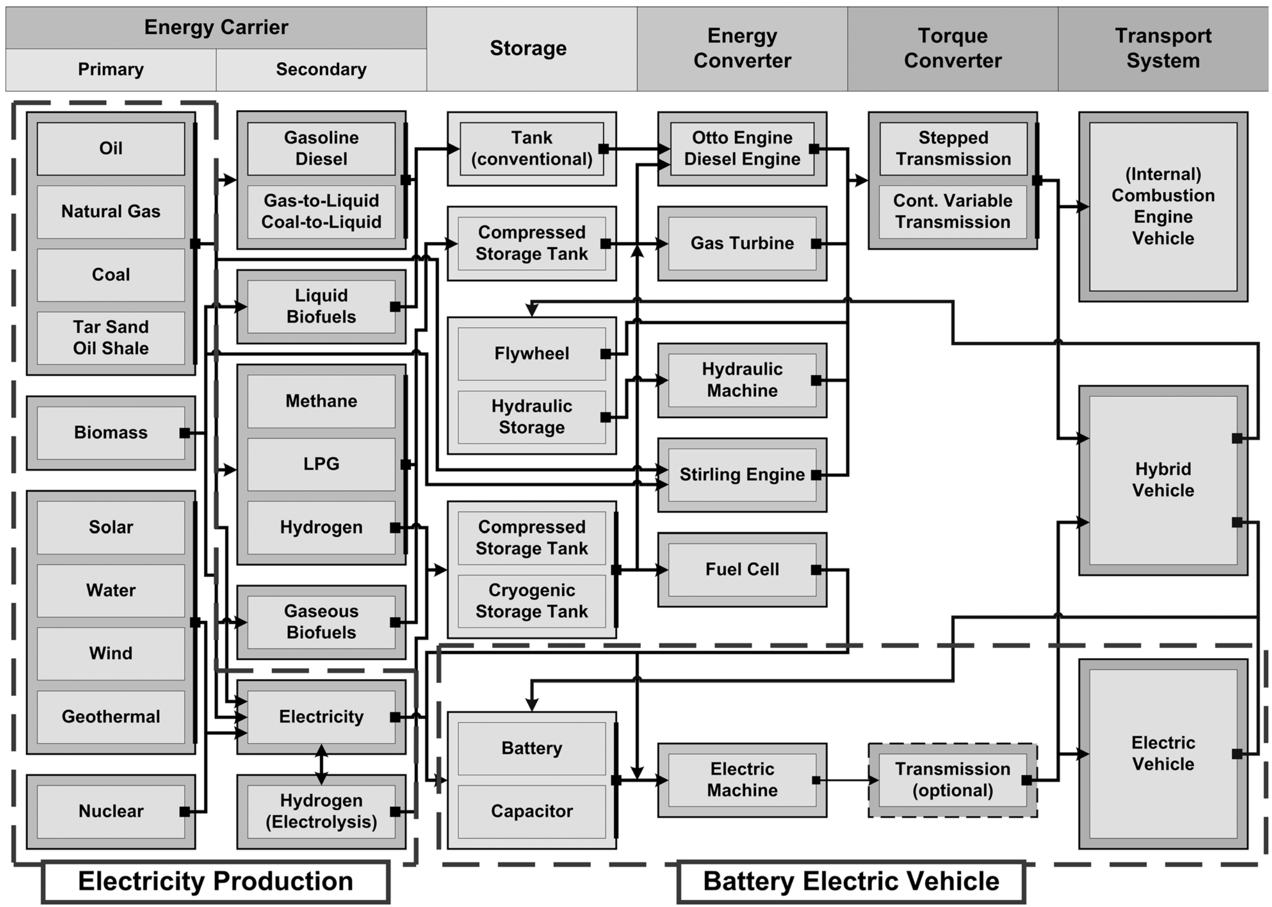

Figure 1.1 Energy conversion pathways for motor vehicles with focus on BEVs [1].

particulate matter, or other toxic substances and gases. They therefore are predestined for urban traffic, where the limited driving range does not obstruct adequate usage.

The average driving range of any passenger vehicle in Germany in 2012 was 49.2 km per day, over an average of 3.9 journeys [1]. The power requirement in urban traffic is approximately 10–15 kW_{mech}, which is significantly lower than the requirement for extra-urban traffic (>30 kW at 100 $km\,h^{-1}$). The main bottleneck in this market is the lack of acceptance of a vehicle with limited driving range and high purchase costs.

The only full-range BEV as of early 2015 is the Tesla Model S with its large 85 kWh battery and a range of up to 500 km. Tesla has used a combination of conventional Li-ion battery technology and powerful motors in a very aerodynamic body ($c_d = 0.24$) to create a well-received vehicle in the luxury car segment. It mainly addresses markets with government subsidies, substantial CO_2 emissions taxation, or good coverage of quick-charging infrastructure, Tesla's *Supercharger* stations.

Several BEVs are so-called purpose-designed vehicles that have been specifically developed as electric vehicles and that are not derived from an internal combustion engine (ICE) vehicle (Table 1.1). Tesla's Model S aside, such vehicles are mostly in the micro to compact car segment, like the Peugeot iOn, BMW i3, or Nissan Leaf. Conversion design examples include the Volkswagen e-Golf and the Smart fortwo electric drive. In the case of newly developed vehicles such as the Mercedes-Benz B-class, different propulsion options have been considered from the start of the development process, using one platform for conventional versions and an adapted platform for natural gas powered and electric versions.

In general, electric drivetrains have a moderate amount of drivetrain components and a straightforward structure. The novel components are the battery system and the electric motor. Furthermore, auxiliary components need adjusting such as the steering and braking system as well as the heating and cooling systems (thermal management).

The latter has become a vital aspect of drivetrain development and aims to combine energy demand analyses and efficiency optimization across all on-board energy requirements. Examples include the use of thermal inertias of components such as the battery, the passenger compartment, or thermochemical storage systems and to include thermal management in the vehicle energy management system.

Battery electric vehicles use high-energy *batteries* to maximize driving range. Today, almost all BEVs use Li-ion batteries with energy densities of up to 150 $Wh\,kg^{-1}$. For example, the Volkswagen e-Golf has a battery with a density of 140 $Wh\,kg^{-1}$ (230 $Wh\,l^{-1}$) and a total energy capacity of 24 kWh at 323 V [2]. This results in a total driving range of up to 190 km. The driving range is influenced by several factors, like driving resistance (e.g., tyre pressure, load, topography), driving speed pattern (acceleration, velocity), and battery specific parameters like temperature and its state of health. The aim to increase the energy density is therefore a high priority. From an automotive point of view,

Table 1.1 Series production battery electric vehicles. (Source: manufacturers.)

	Parameter	Smart fortwo ed	Peugeot iON	Nissan Leaf	BMW i3	VW e-Golf	Mercedes B-Class	Tesla Model S
Vehicle data	Class	Sub-compact	Compact	Compact	Lower middle	Lower middle	Lower middle	Luxury class
	Price (2015) (€)	23 680	29 393	23 790	34 950	34 900	27 102	85 900
Driving performance	Range (km)	145	150	200	190	190	200	502
	Consumption (kWh per 100 km)	15.1	15.9	12.4	12.9	12.7	16.6	18.1
	0 to 100 km h^{-1} (s)	11.5	15.9	11.3	7.2	10.4	7.9	4.6
	Maximum speed (km h^{-1})	125	130	145	150	140	160	250
Battery	Type	Lithium ion	Lithium ion	Lithium ion	Lithium ion	Lithium ion	Lithium ion	Lithium ion
	Capacity (kWh)	17.6	16	24	18.8	24.2	28	85
	Max. charging power (kW)	22	62.5	6.6	4.6	17.6	11	120
Electric motor	Type	PSM	PSM	SM	HSM	PSM	SM	ASM
	Nominal power (kW)	55	49	80	125	85	132	2 × 384
	Torque (Nm)	130	196	280	250	270	340	491

Table 1.2 Specifications of different battery types used in electric vehicles (BEV/HEV). (Source: manufacturers.)

	NiMH	Li-ion	Li-ion	Supercapacitor
Manufacturer	PEVE	Hitachi	Sanyo	Maxwell
Shape	Prismatic	Cylindrical	Prismatic	Cylindrical
Cathode	$Ni(OH)_2$	$LiMn_2O_4$	LiNiMnCo	Graphite
Anode	Rare earth AB_5	Amorphous carbon	Amorphous carbon	Graphite
Cell capacity (Ah)	6.5	4.4	25	0.56
Cell voltage (V)	1.2	3.3	3.6	2.7
Energy density (Wh kg^{-1})	46	56	76	5.4
Power density (Wh kg^{-1})	1300	3000	600	6600
Operation temperature (°C)	−20 to +50	−30 to +50	−30 to +50	−40 to +65
Market	Toyota HEV	GM HEV	VW BEV	Faun HEV

the specifications must also cover costs, thermal management, durability, and end-of-life aspects.

Notable technologies today are mostly based on lithium ion batteries but also on nickel-metal-hydride batteries (e.g., Toyota) and double layer capacitors (supercapacitors) for use in high-power applications (e.g., KERS, heavy duty) (Table 1.2). In BEVs, they could be used as an optional add-on for high-performance applications.

Electrochemical high temperature cells (e.g., ZEBRA) are no longer considered for most applications in passenger cars due to their critical thermal management. Apart from capacitors, all automotive battery technologies are secondary cells with reversible electrochemical energy conversion, an essential prerequisite for electric cars.

In principle, all of the energy storage technologies presented here are feasible for traction application in road vehicles. Due to their limited energy and power density, lead-acid batteries only play a role in niche applications and two-wheel vehicles.

Electric machines are electromechanical converters, where energy conversion takes place by means of a force on the mechanical and induced voltage on the electrical side. In principle, every electric machine can be operated as motor or as a generator. For every electric machine, operational limits for speed, torque, and power exist (Figure 1.2). A distinction must be made between nominal values and maximum values. Nominal values (M_{Nom}, P_{Nom}) can be applied permanently; maximum values (M_{max}, P_{max}) only for a short period, otherwise mechanical and thermal failure may occur and affect the durability of the machine [1].

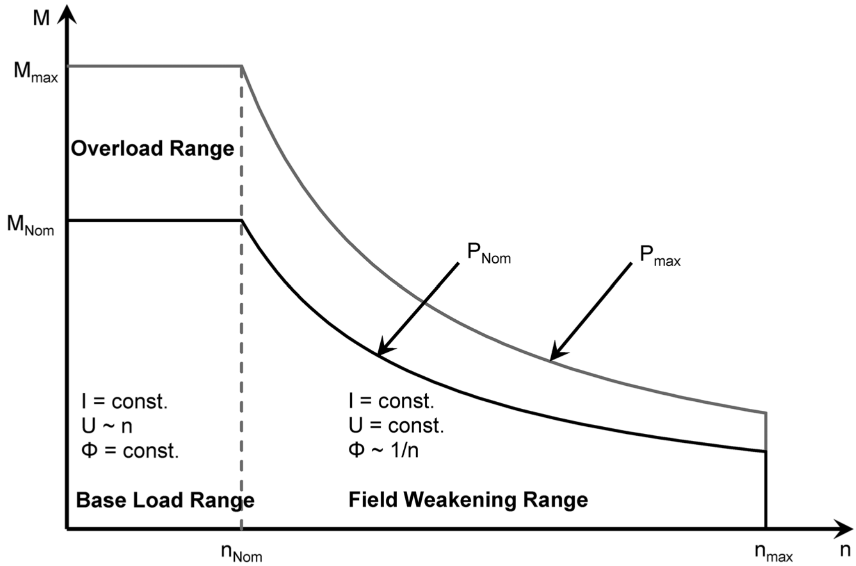

Figure 1.2 Operating range of electric machines [1].

Operation of electric machines can be divided into two areas: base load range and field weakening range. In the base load range the machine is capable of delivering maximum torque (M_{Nom} or M_{Max}) at all speeds from standstill. Nominal power is then available at nominal speed (n_{Nom}):

$$n_{\mathrm{Nom}} = \frac{P_{\mathrm{Nom}}}{2\pi M_{\mathrm{Nom}}} \tag{1.1}$$

For a permanent operation the nominal power must not be exceeded. As a result, the output torque decreases with higher speeds:

$$M = \frac{P_{\mathrm{Nom}}}{2\pi n} \text{ with } P_{\mathrm{Nom}} = \text{const.} \tag{1.2}$$

Equation (1.2) describes the area of constant power, achieved by a weakening of the magnetic field.

DC machines use DC current to induce an electromagnetic field to drive the rotor, whereas AC machines are driven by alternating current. Today, almost all machines used in electric vehicles are synchronous or asynchronous three-phase AC machines due to their high efficiency (Table 1.3). High efficiency can also be achieved with permanently excited machines, but their permanent magnets are expensive. Transverse flux or reluctance machines combine the characteristics of the other machine types.

Induction (asynchronous) machines (ASM) are powered by electromagnetic induction from the magnetic field in the stator winding. The rotation of the magnetic field is asynchronous to the operating speed of the machine. This is referred

Table 1.3 Basic categories and examples of electric machines.

Electric machines				
DC machines	**AC machines**			
	Asynchronous	**Synchronous**		
		Electrical excitation	**Permanent excitation**	**Advanced**
(BL) DCM (brushless) DC motor	ASM induction (asynchronous motor)	SM (synchronous motor)	PSM (permanent magnet synchronous motor)	SRMPSM (switched reluctance motor) TFMPSM (transverse flux motor) HSMPSM (hybrid synchronous motor)

to as the slip of the ASM, and is necessary for torque transfer (Table 1.4). Example vehicles are Tesla's Roadster and Model S.

Synchronous motors (SMs) contain three-phase electromagnets and create the magnetic field rotating synchronous to the rotor speed. Renault's Fluence Z.E. uses a synchronous machine as traction motor. Permanent magnet synchronous machines (PSM) contain neodymium magnets or other rare earth magnets to create the electromagnetic field. Example vehicles are the Smart fortwo electric drive and the Volkswagen e-Golf.

Table 1.4 Technical assessment of selected types of electric machines [3].

Motor type	ASM	SM	PSM	HSM
Control	O	+	O	O
Noise emissions	O	+	++	++
Thermal limits	++	+	O	O
Costs	+	O	–	–
Safety	++	++	O	O
Maximum speed (min^{-1})	>10 000	>10 000	>10 000	>12 000
Continuous torque ($Nm\ kg^{-1}$)	0.60–2.65	0.60–0.75	0.95–1.72	2.08–3.43
Continuous power ($kW\ kg^{-1}$)	0.20–0.89	0.15–1.10	0.30–1.07	1.12–1.82
Maximum efficiency (%)	83–91	81–95	81–95	95
Example vehicle	Tesla Model S	Renault Fluence Z.E.	Smart Fortwo ed	BMW i3

Hybrid synchronous machines (HSM) are a specific type of synchronous machine containing both permanent magnets and electromagnetic winding. This permits higher motor speeds due to the stronger magnetic field. The BMW i3 uses HSM technology.

Depending on the concept, electric machines can be placed at different positions of the drivetrain. There are many possibilities from a simple connection to the gearbox to direct integration into the gearbox. A special configuration is the wheel hub drive, which represents an integration of the electric machine directly into the wheel hub. This is beneficial with regard to the vehicle package, as differentials and drive shafts become superfluous, and in view of functionalities that can be implemented into the propulsion algorithm, such as ABS, traction control, and torque vectoring. However, the higher unsprung mass needs to be addressed in suspension design. Wheel hub motors are not yet deployed in any series (passenger) vehicle. Integrative solutions featuring lower mass are currently being developed, for example, the *Active Wheel* system by Michelin with a nominal power of 30 kW per wheel and a mass of 7 kg [4].

Electric machines for traction applications in road vehicles are currently substantially more expensive than combustion engines of identical power. Synchronous machines cost approximately €50 kW_{mech}^{-1} including voltage converter, which is four-time higher than for combustion engines [5].

Drivetrain topologies in battery electric vehicles can consist of twin motors powering individual wheels to permit versatile control strategies such as torque vectoring for e-differential applications or innovative steering geometries for minimal turning circles, as seen in the recent *SpeedE* BEV concept car (Figure 1.3) [6]. It features 400 V twin motors at the rear wheels and a 48 V steer-by-wire system with a maximum steering angle of 90°.

The SpeedE vehicle also features steering with sidesticks instead of a steering wheel, which allows for new interior design layouts and innovative operability concepts (Figure 1.4).

Recent *BEV developments* and *market success* of some vehicles show that electric vehicles are mature and that they will grow their share in the vehicle

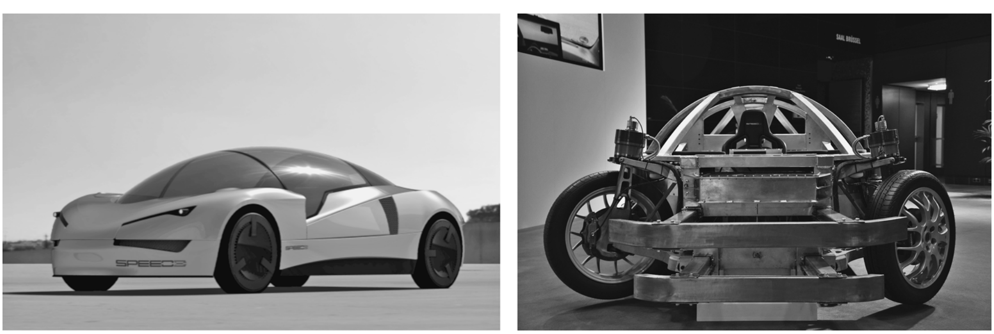

Figure 1.3 Innovative steering sytsem in the SpeedE BEV concept car with twin RWD motors and torque vectoring. (Source: fka.)

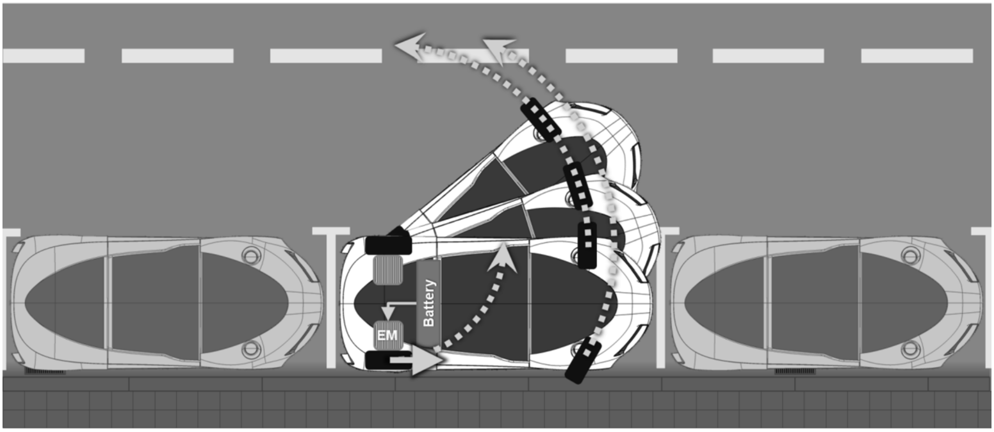

Figure 1.4 Minimal turning circle with electric torque vectoring in the SpeedE BEV concept car.

population for the foreseeable future. R&D progress, especially in battery and motor technology, will strengthen electric and sustainable mobility.

It may be the new driving experience features that pave the way for even more EVs in the future, regardless of the drivetrain technology itself. X-by-wire, connectivity, and user interface novelties will have an impact on the EV market prospects, since these innovations will need electric energy to function.

This underlines the fact that developments for BEVs are not necessarily showstoppers for FCEVs but can complement the effort to create clean and sustainable mobility for the future.

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