Deutscher Luft- und Raumfahrtkongress 2013
DocumentID: 301316

HYBRID POWER TRAINS FOR FUTURE MOBILITY

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Abstract

In an effort to improve efficiency and sustainability of future mobility concepts, new power trains beyond traditional combustion engines have been developed across all transport modes. For ground-based transportation, electric and hybrid-electric vehicles are now entering the market in increasing numbers. Exceeding the power and energy requirements of ground transport qualitatively and, for most applications, quantitatively, hybridization and electrification pose a significantly bigger challenge to aviation. In this paper, we discuss the development status of (hybrid-)electric power trains in the automotive and aviation industries, point out key differences and similarities, and suggest which lessons may be learned for electric air transport from its ground-based counterpart.

1. INTRODUCTION

Awareness of the unsustainable exploitation of non-renewable fossil resources has increased in recent years, as has concern for the human impact on the global climate. Manifold research efforts are underway to tackle causes and consequences of these problems. Via the combustion engine's unchallenged role as the leading transport facilitator, the pillage of fossil resources and the emission of greenhouse gases are invariably linked to the growing worldwide demand for transportation. With cars and other ground-based combustion vehicles accounting for 83.2% (as of 2008) of the European Union's (EU) mobility volume in passenger-kilometers, they contribute the lion's share of harmful emissions (e.g., 70.7% of CO_2 emissions in the EU in 2008) [1]. Aviation accounts for a smaller amount of passenger-kilometers (8.6% for intra-EU travel in 2008) and, consequently, greenhouse gases (12.7% of EU-wide CO_2 emissions in 2008) [1], but its emissions are more climate-effective because they are produced at a higher altitude [2].

As no significant future reduction in our need for mobility is to be expected, we must aim at minimizing the amount of emissions produced per passenger and kilometer of transport, hopefully to the extent that even a future increase in mobility can be accommodated [3]. Avoiding greenhouse gas emissions translates back into avoiding fuel combustion as much as possible, and the presently most promising road towards this goal is the electrification of transport [4,5,6,7]: Electric motors, which are not subject to the Carnot limit, are much more efficient than combustion engines and instantly reduce local emissions – to zero, if the vehicle is e.g. entirely battery-powered. Moreover, global emissions (in particular those produced during the generation of electricity) may, at least in theory, become negligibly small if future electricity production is 100% renewable through the use of energies such as water, solar or wind power [8,9].

Nevertheless, the introduction of (hybrid-)electric road vehicles has progressed slower, and their success has been more limited, than anticipated [10,11]. While predicted several times in the past [12,13], their mass entry into market is still to come. Today, many variants of electric and hybrid-electric vehicles exist, with each major manufacturer offering one or even several hybrid or fully electric solutions. Therefore, with their feasibility well demonstrated, improving the economic attractiveness of electric vehicles has become an important research focus, translating directly into environmental advantages through the positive correlation between economic and ecological benefits [14]. Moreover, there is a declared political will to promote the mass introduction of (hybrid-)electric road vehicles substantially in years to come [8,15,16].

While electromobility is taking its time to arrive on the streets, the wait promises to be even longer in the skies. Electrified airplanes so far only exist in the single-seater category and are usually retrofits of existing conventional designs at reduced payload. Their construction is often motivated by (academic) curiosity, while commercial interest, though emerging, at present is limited to the ultra-light aeroplane market. With the commercial "standard application" case of aviation, i.e. transport aircraft for several tens or even hundreds of passengers, being substantially larger than for cars (with four or five, but very often just one or two passengers), at current technology levels the development of hybrid- or fully-electric passenger aircraft seems extremely challenging. Even setting aside the qualitatively different (take-off-imposed) power requirement for airborne applications [9,17], the issue of range limitation, which is one of the major impediments for the mass commercialization of electric road vehicles, penalizes aviation still more, given that one of its traditional advantages over road transport is larger range[1] [18].

The goal of this paper is to compare and contrast the situation, the state of the art and the future perspectives for road and air vehicles with (hybrid-)electric power trains. We shall raise many qualitative or semi-quantitative points of comparison between the automotive and aviation industries as well as their products. We also discuss suitable parameters to characterize and compare (hybrid-)electric and conventional power trains in each case. To set the stage for our analysis, in Table 1 we have assembled a list of the stakeholders associated with development and use of ground and air vehicles, along with definitions of their roles and motivations. Table 2 contrasts various scales of time, costs and volume that arise in the two industries.

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[1] Note that the argument of range applies at the level of the individual passenger's decision which means of transport to choose (road vs. air transport), but also as a selling point for a particular type of aircraft, compare Table 1.

Stakeholder	***description of role***	**cars**	**city busses**	**aircraft**
producer (vendor)	*oversees production of transport vehicle and sells it under certain brand name*	car manufacturer (e.g. BMW, Daimler, Opel-GM, VW, …)	bus manufacturer (e.g. MAN, Volvo …)	aircraft integrator (e.g. Airbus, Boeing …)
customer (purchaser)	*procures / buys vehicle to offer / use transport service*	individual$^{(I)}$	public or private road transport service provider (bus service company, municipal public transport agency etc.)	commercial air transport service provider (airline$^{(II)}$)
	selects from vendors' offer based on multiple criteria decision making	top decision criteria: - price-performance ratio (61%); - fuel efficiency, design, comfort (46% each)$^{(III)}$	n/a	decision criteria: - economics (43%); - communality (5%); - added value (52%), of which: ○ performance 16% (e.g. range 6%), ○ comfort 15%, ○ environment 10%, ○ marketing / infrastructure 12%$^{(IV)}$
driver (active user)	*operates vehicle*	individual (certified layperson)	professional driver	professional pilot
passenger (passive user)	*pays for transport service*	individual, possibly other passengers	public transport users	airline passengers

TABLE 1: Overview of stakeholder roles and motivations in construction and operation of road and air vehicles of standard commercial size

(I) recently, increasing importance of company car fleets
(II) exception: business or corporate jets
(III) from **[19]**, multiple answers possible
(IV) from **[20]**

	cars	**city busses**	**aircraft**
product development			
time scale [years]	2-5	2-5	5-10
cost [mio €]	~500	n/a	5,000-10,000
no. of prototypes	10-20	3-5	~5 (mostly sold later)
no. of units produced	200,000-1,000,000	5,000-10,000	300-3,000
product properties			
no. of passengers	1-5	30-70 (seated)	100-200
range [km]	500-1,000	700-1,000	3,500-5,400
cost [mio €]	0.02-0.1	0.4-0.7	50-100
individual lifetime [years]	8-15	10-15	20-30

TABLE 2: Typical scales associated with the development and the operation of ground and air transport vehicles (of standard commercial size, e.g. for cars: sedan, for busses: typical city application, for aircraft: narrow-body segment).

2. HYBRID POWER TRAIN CONCEPTS

2.1. Classification of Hybrid Power Trains

In a hybrid power train, two (or more) different energy reservoirs and/or associated energy conversion devices are combined (in one or several possible ways) to achieve a better overall performance than each subsystem would on its own. The shaft power is then provided e.g. to the wheel axle of a road vehicle or an airplane propulsor shaft. Evidently, this definition encompasses numerous combinations of individual components, and it can be a non-trivial problem in itself to establish a consistent classification of hybrid power trains. For example, for some hybrid-electric vehicles, strictly speaking, there is only one energy reservoir[2], i.e. a gasoline tank, from which both a internal combustion engine and a motor/generator are driven, with the generator charging a battery and/or recuperating energy at braking events. The battery can then (via the electric motor) provide substitute power to the drive train e.g. for acceleration, but is not an independent energy source in the strict sense of the term because it is only used as an energy buffer. Nevertheless, the coexistence of two power conversion devices justifies the "hybrid" character of the system [7].

To classify a hybrid power train, one needs to know (i) its constituent components, (ii) their relative configuration and (iii) the amount of power contributed by each component. Concerning (i), in this paper we define a hybrid system as a combustion engine plus an electric power component; in particular, we do not consider fuel cell power systems. With respect to (ii), an important distinction is between systems in serial and parallel configuration. Finally, to quantify (iii), we introduce the (power) Degree of Hybridization (DoH), H_P, as a characteristic system parameter.

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[2] For example, as mentioned in [69], the International Electrotechnical Commission defines a hybrid vehicle as having two or more energy sources (of which at least one must be on board).

2.1.1. Hybrid Configurations

Assuming a combustive and an electric part of the power train, one then needs to establish whether they are combined in a *serial* or a *parallel* way. This distinction can be tied to the nature of the power node between the system constituents: In a serial hybrid, the node is electrical (see Figure 1), while in a parallel hybrid, it is mechanical (see Figure 2). In the car industry, there exist numerous further subdivisions of hybrids, see below. Notably, there are also mixed types of hybrids, i.e. an integrated serial-parallel configuration (see Figure 3).

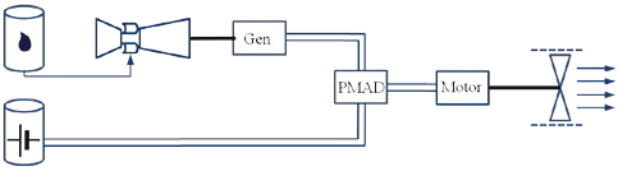

Figure 1: Example of an (aircraft) serial hybrid power train for aircraft with turbo-engine and battery connected by an electrical node (Gen.: Generator, PMAD: Power Management and Distribution). Double (blue) lines denote an electrical connection between components, while a solid (black) line corresponds to a mechanical connection. See e.g. **[21] [22]** for the respective road vehicle diagram.

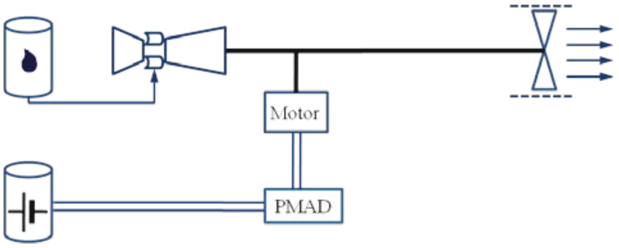

Figure 2: Example of an (aircraft) parallel power train, where the link between the components is mechanical; both components are connected to the power shaft. In the equivalent configuration for ground vehicles, conventional and electric motor would be both mechanically connected to the wheel axle (see **[21] [22]**).

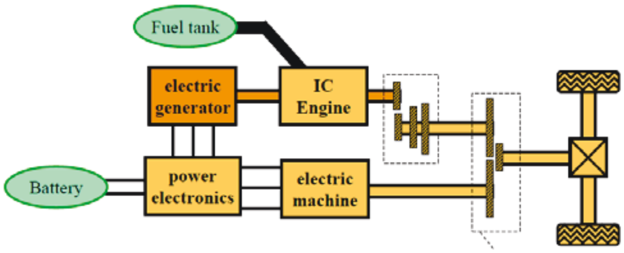

Figure 3: Example of a serial-parallel power train for a hybrid-electric car (source: **[21]**). Both electrical and mechanical power nodes are in place.

2.1.2. Degree of Hybridization

Finally, to classify a hybrid system entirely, one must, apart from its configuration type, also determine how much of the power required for propulsion is provided by which component. To this end, we define the DoH, H_P, as

$$(1) \quad H_P = \frac{P_{em}}{P_{tot}},$$

where P_{em} is the maximum *installed* electric motor power, and P_{tot} is the total power *installed*. With our restriction of hybrid systems meaning “internal combustion/turbo-engine + electric motor”, it follows that $P_{tot} = P_{em} + P_{conv}$, where P_{conv} denotes the installed power rating of the conventional engine. Note that, unless stated otherwise, we shall apply the definition (1) to both serial and parallel hybrid systems.

2.2. Discussion of Power Train Classifications

In Section 2.1.1 and 2.1.2, we provided the definitions of serial and parallel configurations as well as of the DoH which will be applied in the remainder of this paper. Note that several other definitions of the DoH have been used in the literature, including our own “reverse” definition (denoted there as $H = P_{co} / (P_{co} + P_{el})$) in [17]. In Appendix A, we include a list of several other definitions of the DoH found in the literature.

The parameter H_P of Eq. (1) *a priori* does not provide information about energy storage aboard the vehicle[3]. Instead, the amount of energy refillable to the fuel tank and/or the battery from external sources requires additional specification: Note that when sizing the electrical part of a hybrid system, the batteries are typically chosen such that they do not limit the power performance of the electric motor [4]. Since for electrochemical storage devices like batteries, specific power and energy are not independent (as illustrated by their representation in the Ragone diagram, see e.g. [23]), this means that the power sizing simultaneously influences the amount of electrical energy stored. In contrast, energy and power sizing are independent for fuel systems, because the power density of fuel *per se* is unlimited, while the energy amount stored is directly proportional to the fuel mass.

Hence, as a more comprehensive way to characterize hybrid power systems, we suggest adding a second energy-based hybridization parameter, defined as

$$(2) \quad H_E = \frac{E_{el}}{E_{tot}}.$$

Together with H_P defined in Eq. (1), hybrid power systems may then be identified with a point in the two-dimensional (H_E, H_P) parameter space, see Figure 4: The origin (0,0) corresponds to today’s conventional combustion engine power trains, for which the only energy reservoir aboard is a fuel tank. On the other hand, the point (1,1) is defined by a purely electrically powered vehicle with only (externally rechargeable) batteries as onboard energy carriers, of which –in the context of aviation– the recent *CeLiner* pre-concept study [24] (compare Section 4.2) is an example. In the automotive industry, examples of (1,1) power trains are purely electrically powered plug-in hybrids (see Section 3.1), such as the recently unveiled *BMW i3*[4] [25].

Let us point out some additional features of the (H_P, H_E) diagram shown in Figure 4: Recall that in parallel hybrid power trains, both electric and conventional motor are mechanically connected to the wheel axle or propulsor power shaft (see Figure 2). Consequently, for parallel hybrids, P_{em} in Eq. (1) is the electrical share of power that arrives *at the drive shaft* (which is the definition e.g. adopted in [26], see also Appendix A). With this “parallel configuration” interpretation of H_P, one may then conclude that the point (0,1) in Figure 4 corresponds to a pure serial drive train: A sole gasoline/kerosene energy reservoir fuels a conventional (turbo-)engine powering a generator, from which electrical energy is supplied to an electric motor, which in turn drives the wheel axle or propulsor shaft. On the other hand, the point (1,0), i.e. only batteries as an energy carrier with only a conventional engine as power

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[3] This was also commented on in [53].

[4] in its variant without range extender, compare Section 3.1

conversion device, lies within the unfeasible (shaded) region of the (H_P, H_E) parameter space in the context of transport systems: It does not make sense to carry more energy in electrical form than the system is able to extract and provide to the drive shaft with an electric motor. Note, however, that in reality the boundary of this unfeasible region, while depicted as a straight line with slope ½ in Figure 4, is expected to have a more complicated shape, depending on the transport task to which a given system is designed. Also, it is likely to at least locally have a steeper slope than ½: Electrical energy is extractable from batteries with higher efficiency than e.g. the thermal conversion of fuel to drive power in a heat engine, which means that a given percentage share of electrical power may be extracted from a smaller percentage amount of energy carried. In the particular case of airborne applications, altitude effects also have a by no means negligible effect.

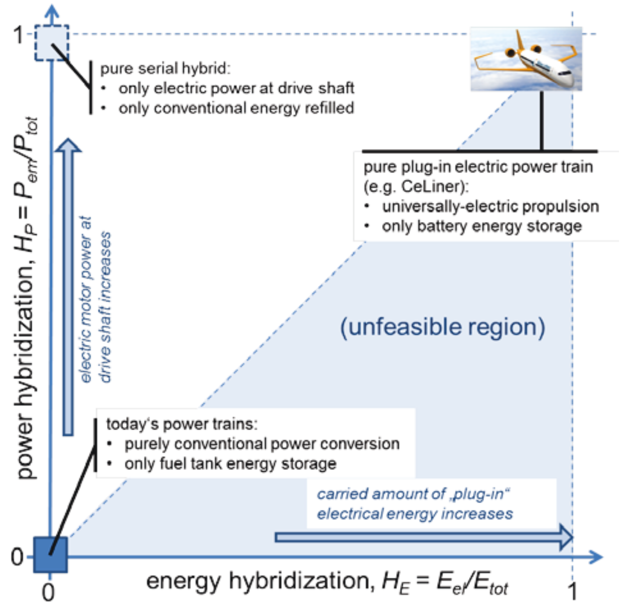

Figure 4: The (H_E, H_P) parameter space for classifying hybrid-electric power trains.

3. (HYBRID-)ELECTRIC ROAD VEHICLES

3.1. Micro, Mild, Full and Plug-In Hybrid Cars

For ground vehicles, an ever-increasing amount of hybrid-electric power train realizations exists, which may be classified into four main types[5], see e.g. [6,27,28,29], depending on the role of the electrical component in driving the Hybrid-Electric Vehicle (HEV). For example, for "micro hybrids" there is no electric contribution to traction itself, the motor is used to start the engine and to recuperate energy when braking. Since the combustion engine is least gasoline-efficient at its starting point, this micro-hybridization already has a big impact on the vehicles' fuel burn. Next, let us mention the "mild hybrid" configuration, in which the electric motor cannot by itself drive the vehicle, but merely acts as a support to the combustion engine. This is in contrast to the so-called "full hybrids", for which the electric motor is capable of providing vehicle traction on its own, if only for a short duration of time.

In principle, for full hybrids one must further distinguish between parallel and serial configurations (or their combination); however, hybrid cars are usually parallel hybrids [5], meaning that the electric motor helps with accelerating and that the combustion engine can be used for direct traction when the battery is empty[6]. Serial hybrids, on the other hand, have no mechanical connection between combustion and electric motor, and traction is via the electric motor only. When the primary electric energy source (usually a battery) is empty, the combustion engine can act as a generator to produce electricity (so-called "range extenders").

In all hybrid types discussed so far, the standard procedure to charge the battery is through the recuperation of energy at braking. If it is possible to charge the vehicle also by connecting it to an external power source (i.e. the electric power grid), this is referred to as "plug-in Hybrid".

3.2. (Hybrid-)Electric City Busses

While they represent an interesting data base and are also most studied theoretically [4,5,6,22], HEVs for individual passengers are far from the power requirements imposed by future electric transport aircraft. Moreover, we already mentioned the huge gap e.g. in passenger number between standard car applications and standard commercial aircraft, see Table 2. Interestingly, there is another category of ground-based transport that preferably lends itself to electrification: the transport of many passengers over short distances aboard city busses.

As for hybrid-electric cars, three hybrid power train configurations –serial, parallel, and combined– exist for busses. However, while for individual HEVs parallel configurations are most frequent, a preliminary evaluation of hybrid concepts on offer by major city bus manufacturers suggests that serial configurations are almost on equal footing. Note that city busses exhibit the ideal driving cycle profile for harvesting the benefits of ground-based hybrid-electric power trains, namely multiple start/stop (and hence braking) events that may be used for energy recuperation (see below). The increased importance of serial configurations for busses then ties in with the statement made in [6] that series hybrid vehicles primarily reduce fuel burn in city driving (by making the combustion engine work consistently at its highest point of efficiency[7] in start/stop traffic); parallel hybrids, on the other hand, are more suitable to highway driving. A comparative assessment of series and parallel drive train configurations specifically for heavy-duty applications was e.g. performed in [30,31].

While energy recuperation for aircraft e.g. by a windmilling propulsor in descent is limited by the propulsor's aerodynamic efficiency at inverse loading condition, the case of hybrid busses (and utility vehicles) is interesting in the context of future hybrid-electric aircraft for two reasons: On the one hand, as mentioned above, the power level of these applications is somewhat closer to the aircraft case, and on the other hand, busses etc. are usually operated by a professional driver, which is akin to the situation for aircraft, see Table 1.

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[5] A similar classification of hybrid types can e.g. be found in [8], which uses yet another definition of "degree of hybridization" as an integer number reflecting the different electrical contributions (from mild to full) of the power trains has been used.

[6] More precisely, they are so-called "charging sustaining" parallel vehicles in contrast to the "plug-in hybrids" which can be recharged from the electricity grid [5].

[7] See e.g. [4] for a detailed consideration of the internal combustion engine efficiency map in the design of HEVs.

4. (HYBRID-)ELECTRIC AIRCRAFT

The challenge of power train electrification presents itself in a very different light for aircraft. For road vehicles we discussed the notion of "micro", "mild" and "full hybrids", all of which feature an electric component of the power train. In the aviation context, however, "More Electric Aircraft (MEA)" are those with (partial) electrification of conventionally hydraulically or pneumatically powered *sub*systems[8] such as e.g. wing de-icing; an example is e.g. the recent *B787* airliner. The main purpose of the MEA approach is to improve engine overall fuel efficiency by minimizing the amount of bleed air offtake for subsystem power supply [32]. Consequently, one may dispense partially with hydraulic or pneumatic circuits, and the electric power transmission has less losses (and maintenance) than conventional systems.

For future aircraft with a complete electrification of subsystems (but no amount of electric propulsion), the term "All-Electric Aircraft (AEA)" has been coined as an extension of the MEA concept. However, with the recent advent of electric aircraft propulsion, AEA has also been used in this context (see e.g. [33]), rendering it increasingly ambivalent. When referring to propulsion, "all-electric" should therefore rather be replaced with "universally-electric" (i.e., the extension of hybrid-electric propulsion concepts). In this paper, we are only interested in aircraft which use, at least partially, electric power for propulsion.

4.1. Existing (Hybrid-)Electric Aircraft

At present, approximately 30 such aircraft have been developed and built [34], their vast majority being universally-electric and hence characterized by H_P = 1 (cf. Eq. (1)). (Note that we do not consider solar aircraft in this paper.) Most are exclusively battery-powered (i.e. "plug-in" with H_E = 1 in the sense of Section 2.2) and belong to the ultra-light (UL) and light sport aircraft (LSA) category.

There are very few examples of hybrid aircraft (or propulsion systems), which almost exclusively fall into the research and demonstrator category. Excluding two "fuel cell + battery" hybrid concepts [35,36], these are (i) the two generations (2011 and 2013) of the *DA36 E-Star*, resulting from the collaboration of *Diamond Aircraft, Siemens, Austro Engine* and *EADS* and jointly powered by a Wankel rotary engine and an electric motor (H_P = 0.70 and H_P = 0.73, respectively) [37,38,39]; and (ii) the *Flight Design* hybrid motor based on a Rotax 914 engine together with an electric motor (H_P = 0.23) [40]. For the *DA36 E-Star*, the two power systems are in a serial configuration[9] as shown in Figure 1, while the Flight Design concept is a parallel layout (compare Figure 2). Note that for both concepts the batteries can be recharged from the electric grid when on the ground, and from the generator during level flight when surplus power is available from the engine.

4.2. Future (Hybrid-)Electric Transport Aircraft

Although no transport category examples of airborne electric propulsion are in existence today, numerous concept studies for universally-electric passenger aircraft have been undertaken, exhibiting a varying degree of detail [41,42,24,43]. While their realization in the near- or mid-term future seems challenging because of the high and qualitatively new requirements for energy storage, electric power transmission etc. [17], it is not too early to raise awareness for the numerous implications of electrified aircraft systems[10]. For example, while often the construction of hybrid-electric cars does not entail a major redesign of the vehicle and may be achieved without an increase of gross vehicle weight [44], the integration of electric motors aboard aircraft –and of batteries, the weight of which, unlike kerosene, will stay constant over the flight envelope– requires an entirely new approach to structural design as well as to weight and performance prediction [45,26,46,47,48].

This is well illustrated by the *CeLiner* pre-concept study [24] undertaken at Bauhaus Luftfahrt in 2012. Designed as a short-range transport aircraft for 189 passengers (PAX) with 900 nm range, the *CeLiner* is a universally-electric[11] aircraft with 109.3 t Maximum Take-Off Weight (MTOW), of which approximately 30 t are accounted for by the advanced Lithium batteries used for energy storage. The aircraft's Entry Into Service (EIS) was set for 2035, when its PAX and range characteristics should allow it to conform to around 80% of worldwide flight movements.

Throughout the *CeLiner's* design process, it was evident that the challenge of electrifying commercial aviation will require substantial improvements with respect to all technologies associated with the electric propulsion system. For example, High-Temperature Superconducting (HTS) electric motors were chosen for the propulsor in order to close the gap to the required level of power density [49,50]. However, the most critical enabling technology is without doubt electrical energy storage [9].

The Bauhaus Luftfahrt integrated approach to concept development also allowed to identify remaining and new improvement potentials with respect to the airframe, structures and systems, which e.g. lead to the adoption of the innovative C-wing layout, see Figure 4. Also, with the *CeLiner's* aircraft top-level requirements derived from future market analysis, the results of [24] have created a direct and detailed link between the technological developments that will enable electric passenger flight and an attractive application perspective. The *CeLiner* study therefore defined what constitutes an integrated solution and technology target to create a major impact on emission reduction of aviation. One may hope that this concrete perspective will inspire targeted development efforts in the key enabling technology domains.

5. OVERVIEW OF GROUND AND AIR (HYBRID-) ELECTRIC POWER TRAIN CONCEPTS

Having discussed the status of HEV concepts in the automotive and in the aviation industry, we now provide a comparative overview of their present realizations, using H_P as defined in Eq. (1) and the total system power installed P_{tot} as parameters. It is evident that most of the aircraft concepts realized so far are purely electric and therefore clustered at H_P = 1. They are also very small, leading to the interesting situation that electric aircraft and cars actually almost fall into the same power categories today. Note, however, that for cars these concepts already

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[8] Note that it has also been argued [6] that hybrid-electric (traction) cars should be able to better meet the increasing electric power demands of electronic car "subsystems" e.g. for passenger comfort and safety (see also [28]).

[9] While the *DA36 E-Star* is a serial hybrid according to the definition of Section 2.1, it has also been referred to as a parallel hybrid, which could be argued based on the parallel configuration of the energy sources (fuel tank and battery).

[10] See e.g. also [74] for a perspective of the infrastructure integration fo future partially electric aircraft fleet at airports.

[11] Recall that we previously associated the *CeLiner* with the coordinates (1,1) in the (H_P, H_E) plane of Figure 4.

serve the market for standard applications, while for aircraft, the commercial application is still orders of magnitude beyond today's realizations. For example, the take-off power requirement established for the *CeLiner* is approximately 35 MW, which is more than a factor 10 beyond the highest electrical aircraft power installation today.

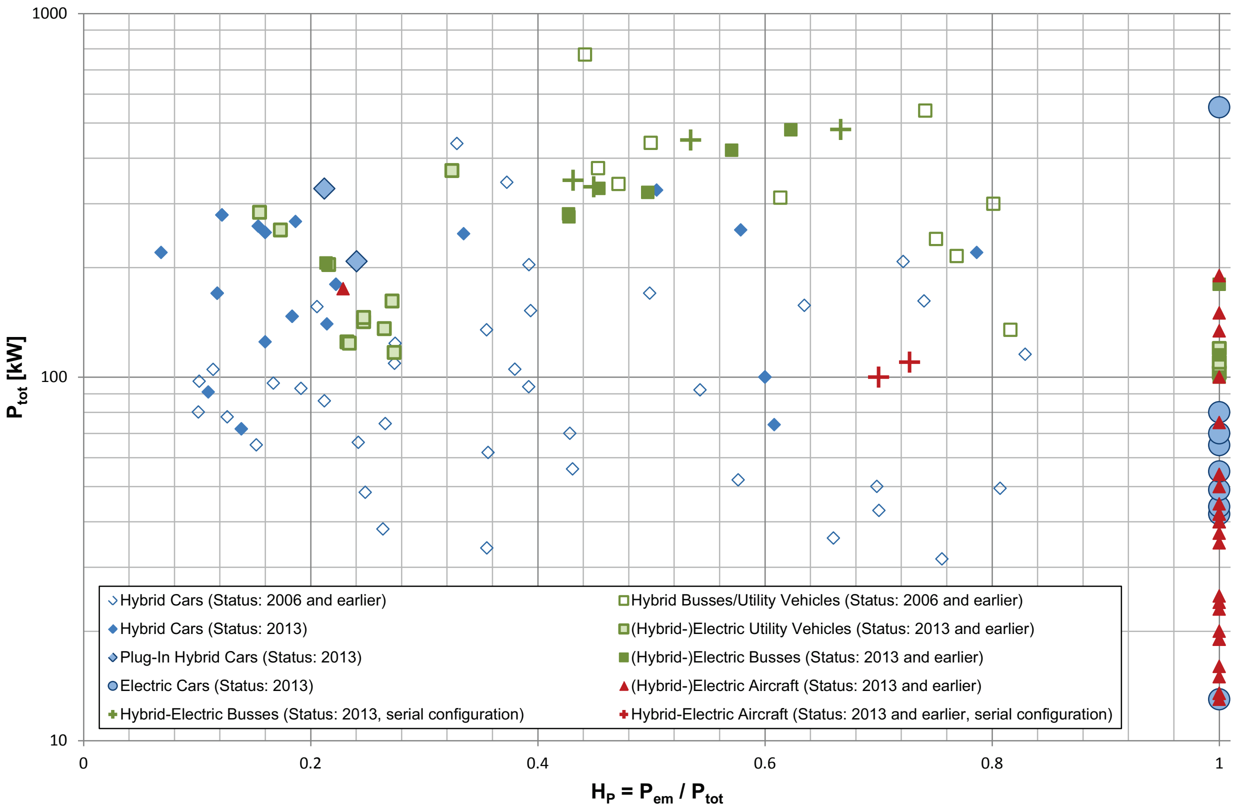

Figure 5: Overview of hybrid and electric ground and air vehicle concepts. The data sources used are cited in the text.

The data for hybrid[12] cars and utility vehicles for the technology status up to 2006 was taken from [44,51,52,53]. Data points for hybrid, plug-in hybrid and electric cars for 2013 technology status result from the respective overviews[13] published by the ADAC [54,55], whereas for city busses and utility vehicles, individual manufacturers' websites were consulted[14]. The (hybrid-)electric aircraft data are documented in a Bauhaus Luftfahrt internal research compendium [34], which is updated continuously. For all electric and hybrid-electric power trains, the most detailed information available was used to characterize them.

Based on these data sources, Figure 5 provides a (necessarily incomplete) snapshot of the hybrid power train development situation in both industries. We can try to tentatively interpret some of the features seen in this plot: For example, it is interesting that the older (2006 and earlier) data points for hybrid cars and utility vehicles are widely scattered across the H_P axis. Comparing them to the new hybrid and electric models available and/or introduced in 2013 [54,55], we observe that (i) on the one hand, several data points have appeared at $H_P = 1$, spanning almost an order of magnitude in P_{tot}, and that (ii) on the other hand, new hybrid cars seem to preferably have DoH values between 0.1 and 0.2. (Note, however, that the total number of data points for 2013 is roughly 25% less than those for up to 2006.) Given that hybrid cars' fuel burn advantages (see next section) over conventional models are largely caused by their ability to recuperate energy to the battery at braking events and then reuse it for acceleration, a possible interpretation of this clustering at lower H_P is that these DoHs reflect the most common amount of recuperation possible for typical car city driving patterns. Recall also that hybrid cars have usually parallel hybrid configurations because, unlike for city busses, highway driving is also part of their application profile [6].

Another observation from Figure 5 is that city busses typically have higher DoH values, both in serial and parallel configurations. Again, this can be connected with their typical driving patterns: In addition to the stop-and-go traffic experienced by both cars and busses inside cities, busses also have to brake and come to a halt at each bus stop, meaning they are effectively stationary for around 30% of their deployed time [56]. With more opportunities to benefit from energy recuperation, it makes sense to install a larger electric share to the power train, making city busses and delivery vehicles one of the forerunners of hybridization, where it can lead to 20-30% reduction in energy consumption [22].

Finally, we would like to add two comments about the aircraft concepts plotted in Figure 5. First, it is interesting that purely electric aircraft (usually ultra-light aeroplanes) almost trace a continuous line at $H_P = 1$. Possibly this can be seen as a reflection of the difficulty associated with

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[12] Note that for the (2006 and earlier) data points imported from [43] [51] [52] [53], it was not possible to separate serial and parallel configuration hybrid power trains. Also, there is no distinction between city busses and utility vehicles in the 2006 and earlier.

[13] For hybrid cars, the ADAC overview covers newly introduced models only; for electric cars, models that are or will become available in 2013 are listed.

[14] Some information on status 2013 hybrid-electric utility vehicles was also obtained as private communications.

progressing towards higher total system power, which often can be done in few kW steps at a time only. Second, while with just two data points (the 2011 and 2013 *DA36 E-Star* aircraft) one must be very cautious about detecting a trend, note that the 10% increase in power (from 100 kW to 110 kW) for these serial hybrid aircraft was accompanied by a 3% increase in H_P. It will be very interesting to observe how the correlation between P_{tot} and H_P will evolve in the development of future hybrid aircraft, in particular if these are new, dedicatedly hybrid designs beyond the retrofit approach applied in the *DA36 E-Star* projects.

6. ASSESSMENT OF HYBRID POWER TRAINS

With the classification of ground-based and airborne hybrid power trains established and following the documentation of existing systems, let us now turn to the question of optimizing these systems and quantifying their environmental benefit. In the past, the choice of hybrid power train for a HEV has usually not been made following a careful optimization process, but rather based on the available components, or the experience and existing development partnerships of the vehicle manufacturer [44]. This has led to a cornucopia of e.g. bus voltages for power electronics, battery types or motor sizes [5]. Moreover, car manufacturers have experimented with 10 to 20 prototypes [52] to find the optimum hybrid configuration for a given product. Evidently, the approach to developing future hybrid-electric aircraft must be different; for one thing, the significantly higher development effort (compare Table 2) puts tight constraints on the construction of prototypes. Hence, any step towards a new power train concept must be carefully planned, starting for instance, from the flight mission profile of the aircraft.

In general, one may say that hybridization efforts in the automotive industry are driven by the possibility to save fuel through the recuperation of (conventionally lost) kinetic energy at braking. The amount of recuperation possible in the vehicles' most common driving pattern together with a complicated trade-off of e.g. increased weight due to the battery etc. (see e.g. [5]) determines the feasible degree of hybridization. Since the potential for energy recuperation in the context of aviation requires further study, a convincing case for the hybridization of transport aircraft can most easily be made if the hybrid propulsion system has a mass benefit compared to the conventional power system. This depends crucially on the aircraft's mission profile, and some bottom-up assessment tools for identifying promising applications for airborne hybrid systems have been presented in [23]. Quite generically, one can state that a hybrid mass benefit is possible if the peak power demand is provided by a system component with high specific power, even when such a component is characterized by low specific energy (as it is often the case e.g. for batteries). However, the mission power profile (see below) must be "sufficiently peaked": Depending on the relative peak height, there is an associated critical peak time scale, after which the benefit disappears.

6.1. Assessment Metrics

One obvious assessment metric for the environmental impact of hybrid power train concepts is the amount of CO_2 emissions produced in operation. Further on this section, we discuss and compare the approach to measuring these emissions in both the automotive and aviation sector. Another useful parameter is the amount of energy required per passenger per 100 km of transport (see e.g. [57] for a general comparison of transport modes with respect to this parameter). Both of these metrics have been used in [17] for a preliminary assessment of a hybrid version of the *CeLiner* at constant MTOW[15]; see also [45] for related work on hybrid-electric UAV. Below, we present a related study using a different approach and keeping range fixed instead of the MTOW.

A comparison of hybrid vehicles based on fuel burn and construction price has been suggested in [44]. The life cycle cost of electric vehicles, in particular the trade-off between higher purchase price (due to battery cost) and lower maintenance costs, has been considered in [22]. In the present work, however, we do not use cost as a metric due to the inherent difficulty of estimating them for far-future concepts such as electric passenger aircraft.

6.2. Automotive Emission Assessment

The precise measurement of emissions is of key importance in many aspects of ground-based transportation, for example because it defines the level of taxation applied to a given car, or the access rights to e.g. restricted inner city areas. In the face of soaring gasoline prices, many customers also apply fuel efficiency as a decisive criterion when choosing a new car [19]. As such, the (societally desired) environmental benefit resulting from (supposedly) more fuel efficient vehicles developed by car manufacturers is linked to the same manufacturers' economic advantage through better sales arguments.

The established tool for determining emissions (and, calculated from their measurement, fuel burn) of road vehicles are so-called driving cycles which the vehicle must perform on a test stand. Many different driving cycles exist, which aim at illustrating different characteristics (i.e. city vs. highway driving, country-specific driving patters etc.) [58]. The prescribed standard driving cycle for cars in Europe is the New European Driving Cycle (NEDC), shown in Figure 6, and tests on new cars using the NEDC are performed by (mutually competing) testing institutes hired by the car manufacturers [59].

There are several problems with the emissions measurement procedure in place, resulting in considerable (and growing) differences between the fuel burn characteristics of new car models cited by the manufacturers and those observed on the road. First and foremost, an important criticism is that the NEDC, consisting in four repetitions of the Urban Driving Cycle (UDC, established in 1970) plus one Extra-Urban Driving Cycle (EUDC, established in 1990), does not realistically reflect today's driving patterns. Another general issue with this testing method is that the tests are conducted on a test stand[16], where the manufacturer has ample opportunity to optimize the vehicle's performance. For example, energy- and hence fuel-consuming equipment such as air conditioning is turned off during the test[17]. One may even argue that the incentives for all parties involved are wrongly configured: Manufacturers want to claim as low a fuel burn as possible for their new products in order to convince customers to buy

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[15] Note that in [17], the degree of hybridization was defined as $H = P_{co}/(P_{co} + P_{el})$, i.e. "reversed" with respect to H_P, with $H = 0$ corresponding to the original universally-electric *CeLiner,* and $H = 1$ a conventionally powered aircraft with same MTOW.

[16] The parameters (roller resistance etc.) to which the drive stand is set are previously determined in a separate road test of the vehicle; in this way, the test stand measurements are supposed to account for external factors such as e.g. wind resistance [59].

[17] It has been shown that the difference observed in the test with and without air conditioning can be as high as 37% for a small car or even 53% for a larger car [74].

them. The testing institutes compete for test orders distributed by the car manufacturers, which are likely to choose the institute promising the most advantageous results [59].

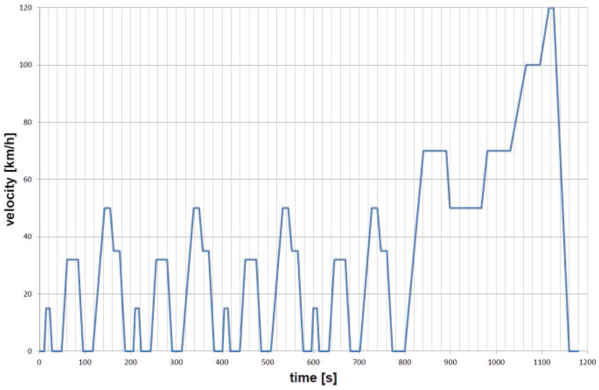

Figure 6: Velocity vs. time profile of the NEDC (compare also **[59]**). The cycle is defined as a sequence of accelerations and decelerations and consists in four repetitions of the UDC (195 s each) followed by the EUDC (of 400 s). Total duration of the NEDC is 1180 s.

It has been documented that, with the present procedure, there is a growing gap between the fuel burn characteristics advertised by car manufacturers and those observed in real driving situations [59]. For example, with the NEDC applied, the start/stop automatic (micro-hybridization) already has a big impact because the vehicle is stationary 20% of the time (241 s out of 1180 s [58]), see Figure 6.

The key benefit of HEVs comes into play every time there is a deceleration event in the plot of Figure 6: The power requirement imposed on the drive train then becomes negative and, using the electric motor as a generator, kinetic energy can be recuperated to the battery. The more frequently the HEV has to brake, the more energy is stored; hence, city busses with their programmed halts at closely spaced bus stops in addition to the stop-and-go movement imposed by city traffic[18] have a very advantageous driving cycle for energy recuperation.

As a consequence of the issues with the official testing procedure cited above, independent tests lead to 19-18% higher CO_2 emissions and fuel consumption measured, which are roughly the same as the real-world fuel consumption observed and documented in vehicle use reports by individual drivers e.g. in Germany [59]. Such reports are a useful benchmark in particular because they can (on average) account for the impact of many factors irreproducible on the test stand such as

1) different individual driving styles,
2) varying traffic conditions,
3) different use of cars (loading conditions, extra equipment used etc.), and
4) different level of maintenance.

Note that all of these conditions are much more standardized for transport category aircraft; in particular, aircraft are operated by professionals (much like city busses), therefore the realization of fuel savings in real-world situation will depend less on the individual "flying style".

6.3. Aviation Emission Assessment

We now present some considerations about the measurement of aircraft emissions over an entire mission envelope analogous to the NEDC. At present, emission regulations for aircraft exist with respect to local air quality near airports, established in the so-called Landing and Take-Off (LTO) cycles defined by the International Civil Aviation Organization (ICAO) and characterizing the operational conditions of aircraft engines in the vicinity of the airport and below 3,000 ft of altitude [60,61]. The LTO and the corresponding engine settings and time intervals are shown in Figure 7. Note, however, that the amount of taxiing varies greatly between airports, and that 26 min in total for taxi in and taxi out, as assumed in the LTO, is a very optimistic estimate [61]. Also, airports are exposed to different influences on their air quality due to e.g. local meteorology, or wind and air-flow patterns changed by surrounding land use [62]. This must be considered when assessing local air quality around airports according to the Air Pollutant Emission Inventory Guidebook [63] issued by the European Monitoring and Evaluation Programme and the European Environment Agency.

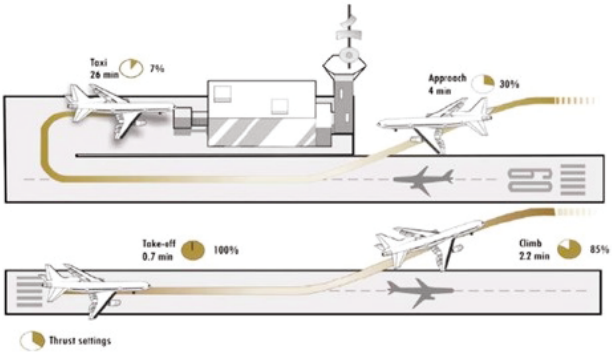

Figure 7: Illustration of the Landing and Take-Off cycle used in the ICAO Emissions Certification Procedure (figure source: ICAO). The percentage values are the engine thrust settings (take-off: 100% for 0.7 min, climb out: 85% for 2.2 min, approach: 30% for 4.0 min, taxi (in *and* out): 7% for 26 min).

Recall that for the NEDC in the previous chapter, accelerations and decelerations were prescribed (including directions on when to shift gears for manual transmission cars). Since today's cars are equipped with much more powerful engines than when the NEDC was designed, the acceleration events in the official test cycle are much slower (i.e., correspond to much lower "engine settings") than what occurs in practical use. While it may be unrealistic with respect to the taxiing time interval, the LTO definition in terms of the percentage engine settings may be more appropriate to emission measurement because it scales with the engine's power rating. Engine emission characteristics are documented in the ICAO Aircraft Exhaust Emission Databank [64].

Being limited to altitudes below 3,000 ft, the LTO and its emission restrictions do not cover climb, cruise and descent in the flight mission, which usually account for the bulk fuel use [2]. New certification methodologies under preparation by the Committee on Aviation Environmental Protection of the ICAO should take into account emissions in flight as well. The approach is to establish a reliable correlation between emission measurements carried out on the ground and the exhaust emissions in flight [61].

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[18] This is clearly visible in the EU legislative driving cycle in place for busses, the so-called Braunschweig City Driving Cycle [58].

For the purpose of comparison with Figure 6, we plot below a typical true air speed profile simulated for an advanced narrow-body aircraft, see Figure 8. The design range for this aircraft at maximum structural payload is 2380 nm; other mission parameters are described in the figure caption. For a more comprehensive emission assessment in the future, one may consider establishing standardized “Flying Cycles”, analogous to the NEDC or other driving cycles.

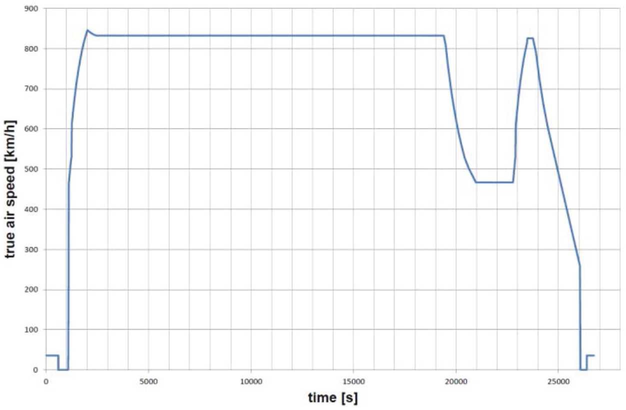

Figure 8: True air speed mission profile for a typical advanced narrow-body aircraft with 2380 nm design range at MTOW. Clearly discernable from this profile are the taxi out phase (18 min), take-off, climb and cruise followed by 30 min hold and a 200 nm diversion flight; taxi in is 11 min. (Climb profile: 250KCAS/290KCAS/M0.78; cruise at M0.78, FL350; for diversion flight, identical climb and descent profile, diversion cruise at FL290.)

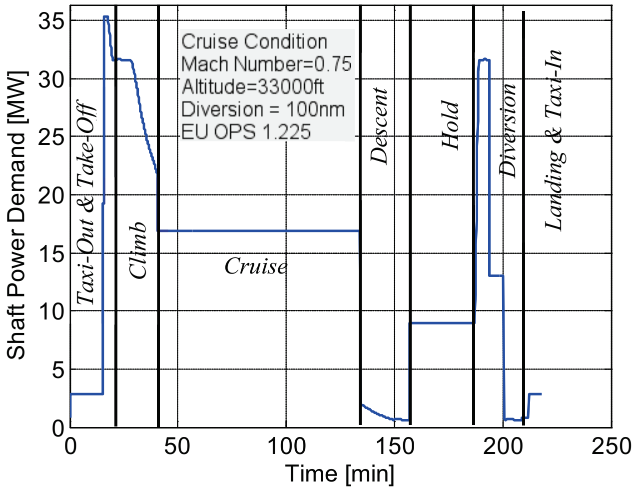

Figure 9: *CeLiner* mission power profile (source: **[46]**).

Evidently, many more parameters than the true air speed over time must enter the definition of a “Flying Cycle”, in particular because of the varying engine characteristics at different altitudes[19]. A decisive quantity to consider, especially in the context of hybrid- or universally-electric power trains, is the power profile over the mission time. In particular, it is to the maximum power demand (e.g. at take-off) that the components of the (possibly hybrid) power train aboard have to be sized. As mentioned earlier, a high specific power system used for peaks in the mission profile can lead to a mass advantage, even if the associated specific energy is small. As a final example, in Figure 9 we show the detailed *CeLiner* mission power profile [46].

7. HYBRIDIZATION STUDY FOR FUTURE ELECTRIC PASSENGER AIRCRAFT WITH FIXED MISSION

We already repeatedly mentioned the *CeLiner* pre-concept study of a universally-electric, medium capacity, short haul transport aircraft recently performed at Bauhaus Luftfahrt. Featuring advanced technologies for an EIS year 2035, the *CeLiner* has a design range of 900 nm for a design payload of 189 PAX, assuming suitable reserves and contingencies [24]. This useful range would cover almost 80% of all transport mission distances served in 2035. However, in comparison with conventional aircraft of similar payload capacity, the range achievable with a universally-electric systems architecture is significantly reduced. Therefore, range extension by allowing for a certain amount of fuel burn (and hence emissions) has been explored for the *CeLiner* concept.

In the study presented in [17], range extension was realized through the addition of conventional energy storage and conversion, i.e. kerosene fuel and turbo-shaft gas-turbines, which were incrementally added for delivering the required energy and power for the aircraft as hybridization increased. As an invariant boundary condition, aircraft MTOW was retained constant in [17], which allowed the assumption of fixed airframe structural weights. Weight savings due to the reduction of electric energy and power installation were translated into carried fuel and thus an increase in range.

In the study, all components of the energy and propulsion system were sized according to the corresponding share of overall required power. The component efficiencies and gravimetric power densities were expressed as functions of the individual sizing powers. The specific power characteristics versus installed power for HTS motors were taken from [65] [50], and extrapolated to reflect technology status 2030+. The specific power of the battery and Power Management and Distribution (PMAD) system was taken from [24] and treated constant against variations in power sizing. The dependency of turbo-shaft engine power density on the installed power was mapped based on an empirical correlation given in [17]. The correlation was calibrated to reflect advanced engine characteristics in the relevant shaft power class. Using the determined power densities, the masses of the energy transmission components, i.e. PMAD, electric motors and gas turbines, were determined. The sizing power of the battery system was treated as directly coupled to the PMAD system, i.e. the mass and available energy from the battery system were scaled proportionally to PMAD sizing power. The efficiency of the installed gas turbines was expressed as a function of take-off power, while the efficiencies of the electrical Energy and Propulsion System (EPS) components were treated invariant against variations in sizing power.

For the present paper, a new hybridization study was performed, retaining a constant air transport task, i.e. a design range of 900 nm, versus the degree of hybridization defined in the Section 2.1.2. The same component characteristics for the energy and propulsion system were employed as in the previously described study [17], but in this new, refined setup, variations of aircraft MTOW, and thus structural weights, received adequate consideration. Besides the universally-electric *CeLiner* ($H_P = 1$), an advanced conventional aircraft ($H_P = 0$) designed for the

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[19] Note that this already has an impact for the LTO cycle applied to different airport locations [73,74].

same mission role and EIS year 2035 was selected as a baseline for the hybridization study. A comprehensive benchmarking exercise between the *CeLiner* and the advanced conventional aircraft (referred to as *B787-3+* below) can be found in [24]. In Table 3, an overview of basic data is given for both aircraft. It can be seen that the total aircraft weight penalty, i.e. the delta in MTOW, is significant due to a universally-electric systems architecture design, even if take-off constraints are relieved.

TABLE 3: Basic data overview of baseline aircraft **[24]**.
*at ISA, SL, M0.2
**adjusted to CeLiner value

Aircraft Properties	Unit	B787-3+	*CeLiner*	Delta
MTOW	kg	73300	109300	+49%
OWE	kg	47900	59410	+24%
Wing Span	m	36	36	0%
MTOW/Sref	kg/m²	636	635	~0%
Thrust/MTOW*	-	0.310	0.233	–25%
TOFL @ ISA,SL	m	1830	2245	+23%
L/D @ Initial Cruise	-	20.5**	20.5	0%
Range @ Max. Payload	nm	900	900	0%

In this hybridization study, aircraft component weight and performance characteristics were interpolated appropriately between both baseline aircraft designs, as a function of H_P. For main structural components such as the wing and landing gear, weights were scaled as a function of actual aircraft MTOW. The lift to drag ratio, *L/D*, of the conventional baseline was adjusted to the *CeLiner* value in order to avoid a bias of study results due to varying aerodynamic efficiency against H_P. The aircraft performance impact due to differing power plant installation locations of *CeLiner* and the B787-3+ was considered to be second order, and thus neglected in first approximation. It should be noted that both baseline aircraft feature similar specific thrust levels and propulsive device efficiencies, η_{pd}, i.e. the ratio of net thrust times aircraft velocity to required (in case of turbofan power plants, equivalent) shaft power. Hence, efficiency changes in the energy and propulsion system due to varying H_P focus on the hybrid power train between the energy storage and the propulsor shaft only.

The vehicular efficiency was established on the recently proposed Energy Specific Air Range (ESAR) figure of merit which, independently from the type or combination of energy sources, relates the change of aircraft range to the change of energy in the storage system [66]. ESAR, thereby, incorporates the aircraft's lift-to-drag ratio, *L/D*, aircraft mass, $m_{A/C}$, and, the overall efficiency, η_{ov}, of the energy and propulsion system. The latter represents the product of η_{pd} and the complete efficiency chains of the individual power trains included in the hybrid system layout, power-weighted based on H_P. Based on the ESAR metric, the achievable range for a given H_P and aircraft gross weight estimate was derived. In order to ensure identical design ranges for all hybrid-powered aircraft in the study, a simple iteration scheme for aircraft scaling was applied. The results obtained for the full range of power hybridization between conventional and universally-electric are shown in Figure 10.

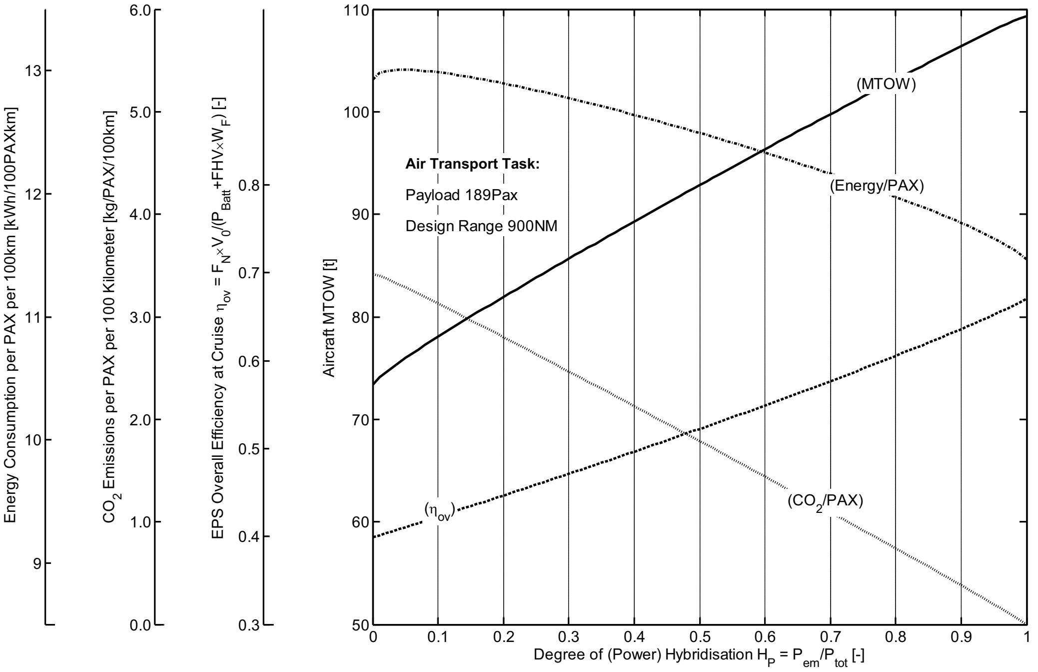

Figure 10: Hybridization study for 189 PAX, 900 nm air transport task based on advanced conventional and universally-electric baseline aircraft.

In Figure 10, a synposis of essential aircraft characteristics is given, including aircraft MTOW, EPS overall efficiency, as well as the trip energy consumption and CO_2 emissions per 100 PAX kilometers. The overall efficiency of the EPS combinations illustrated in Figure 10 show a significant improvement as power train electrification, i.e. H_P, increases. Starting from an η_{ov} of approximately 0.40 for the highly advanced geared turbofan architecture in the conventional baseline case, a value of about 0.67 is reached for the universally-electric EPS. At identical propulsive device efficiencies, this relative improvement of 67.5% directly emanates from the higher energy conversion efficiency of the electrical power train components relative to the Joule/Brayton cycle engine.

The aircraft energy consumption per PAX kilometer reveals an interesting trend, in particular, for small values of H_P. While for high values of H_P, the increasing overall efficiency of the energy and propulsion system is dominant over the energetic penalty of increasing aircraft gross weight, for small degrees of hybridisation ($H_P \leq 0.15$), slight increases in energy per PAX are encountered. This trend is driven by the relatively steep increase in electrical component weights added to the overall aircraft as electrification is introduced in small portions starting from the conventional baseline design. The reduction of fuel and gas turbine weights, but more importantly, improved EPS overall efficiency cause the directional change in the energy per PAX kilometer trend as H_P is further increased. It can be seen from Figure 10 that the trend of energy consumption per PAX kilometer is also reflected in the convex bend of the aircraft MTOW curve as electrification is increased.

CO_2 emissions per PAX kilometer are monotonically reduced as H_P is increased until zero CO_2 emissions are reached in the universally-electric case of $H_P = 1$. This trending behaviour emanates from the monotonically reduced fuelburn as electrical power and energy are introduced to the system. In this respect, the CO_2 benefit due to increasing electrification of the aircraft propulsion power train differs significantly from the previous study [17], in which a CO_2 benefit over the conventional case required a minimum electrification threshold of 50% due to the simultaneous reduction in range as electrification was increased. The newly obtained trend of an instaneous CO_2 benefit for a given short range mission distance is in good agreement with results based on retrofitted hybrid-electric aircraft presented in [26]. It should be noted, however, that the CO_2 emission of approximately 3.4 kg per 100 PAX kilometers for the case $H_P = 0$ already indicates the progressiveness of the conventional baseline aircraft over today's in-service aircraft.

8. LESSONS LEARNED FOR THE DESIGN AND DEVELOPMENT OF ELECTRIC AIRCRAFT

Let us now address the question which lessons may be learned for future (hybrid-)electric passenger aircraft from the experience acquired in the automotive sector. Important categories in this respect are e.g. the selection of development partnerships and targets, the definition of industry standards and the necessary level of redesign.

8.1. Product Development Aspects

In the car industry, development partnerships for hybrid-electric vehicles have included multiple constellations: For example, different manufacturers have joined forces to develop the electric part of the hybrid power train, while supplementing it with different conventional engines. In the aviation industry, recently *EADS-IW* and *Siemens* have announced a long-term partnership for the development of electric aviation [67], following up on their previous collaboration on the retrofitted *DA36 E-Star* hybrid aircraft. Note that the example of the automotive industry also shows that one must be prepared for changes in the envisaged development goal along the way. For example, in terms of battery technology, originally and until the late 1990s the push was for higher and higher energy densities to extend vehicle range [8]. However, when the current mild hybrid configurations, in which often the battery is employed as a booster temporarily supplying additional energy to the drive train, became the focus of development, power density came into focus.

A key aspect to assist in a technology's breakthrough is the early adoption of standards. It has been an avoidable difficulty for HEV development that the adoption of a standard for charging plugs has been problematic [10]. (See also [6] for an extensive discussion of the development requirements of power electronics and motor drives for HEVs, and [28] for the HEV voltage levels.) To avoid similar issues in the aviation industry, for example an early agreement on acceptable and standardized voltage levels could foster the development of electric propulsion concepts. A recent suggestion is the three-part universally-electric system with 3000/540/28 V aboard the *CeLiner* [24,46]. These voltage levels may still be feasible despite the increased arcing tendency at higher altitudes, yet do not jeopardize aircraft weight too much because of the large cable diameters and weight penalties to transmit the necessary amount of power for propulsion. For example, one of the more surprising findings of the *CeLiner* study [24] was the big MTOW impact of the necessary power electronics considering all necessary redundancies in order to comply with the Extended Twin-engine Operational Performance Standards (ETOPS).

Another aspect is the necessary level of redesign one may expect or even target for a new type of product such as an electric vehicle. For example, just recently, *BMW* has unveiled the first dedicatedly redesigned electric car, the *BMW i3* [25]. While it is too early to judge whether the retrofit design of previous HEV concepts is partly responsible for their limited success, it is interesting to note that in aviation, at least for the commercial airliner category, one may not have any other choice but opt for a clean-sheet design: An important result of the *CeLiner* pre-concept study was that the integration issues raised by e-mobility components, in particular the batteries, must be used as guiding principles all along the design process. The current retrofit approach to the design of (hybrid-) electric aircraft may only be successful because they are in a MTOW category where the electric system can still be meaningfully accommodated by reducing payload, which will not be the case for future commercial applications.

8.2. Innovation Gap of Future Hybrid Aircraft

Finally, as a top-level approach to the problem at hand, let us consider Europe's competitive position relative to Asia and North America in terms of patent share in specific areas pertaining to electric hybrid vehicles and aviation. In a working paper related to the “Horizon 2020” EU Framework Programme for Research and Innovation [68], the European Commission has illustrated technological leadership and innovation capability using the global share of patents as a metric, see Figure 11. In the context of this paper and with respect to today's technology fields, this plot serves as visualization of Europe's innovation gap in key enabling technologies for future hybrid-electric aircraft. The plot shows the number of patents held as a suitable indicator for Europe's competitive position relative to Asia on the horizontal axis, and relative to North America on the vertical axis, creating four quadrants of global innovation leadership situations. Of all technologies, we are interested in electric hybrid power systems and subsystems that may foster innovation in future automotive and aviation applications.

A most striking observation is the almost diametrically opposed competitive situation in the directly relevant technology fields. First, consider “Aeronautics” (orange, roughly at coordinates (1.0, 0.03) in Figure 11) and “Electric hybrid vehicles” (blue, at plot coordinates (-0.4,-0.03)). Concerning the latter, Asia is in the lead, while the coordinates of “Aeronautics” illustrate that Europe and North America are at a tie in this domain: Recall that the global market for commercial airliners today is predominantly divided into almost equal shares by Airbus on the European and Boeing on the North American side.

Next, consider “Automobiles” (orange, located roughly at (0.4, 0.4)) and “Energy storage” (red, at (-0.5, -0.3)) as well as “Fuel cells” (red, at (-0.37, -0.3)). The innovation gap suffered by European companies in the two latter technologies, which are key to electro-mobility and the development of hybrid-electric power systems, is obvious.

An eminent conclusion from Figure 11 is that European companies presently enjoy a position of leadership with respect to automotive patents and, shared with North America, with respect to aeronautics-related patents. However, this leadership is at risk in the advent of hybrid-electric mobility concepts. As these two transport industries undergo a transformation towards electric and hybrid-electric vehicles, the relevant knowhow in “Enabling technologies”, shown in blue in Figure 11, and in “Energy” technologies, shown in red, must be aggressively developed, or possibly acquired through cooperations. Any effort expended on research and innovation in one of these domains will have an impact in the other ones as well – or, on the contrary, failure to suitably promote any one of these research areas will penalize the competitive situation of European companies in the other ones.

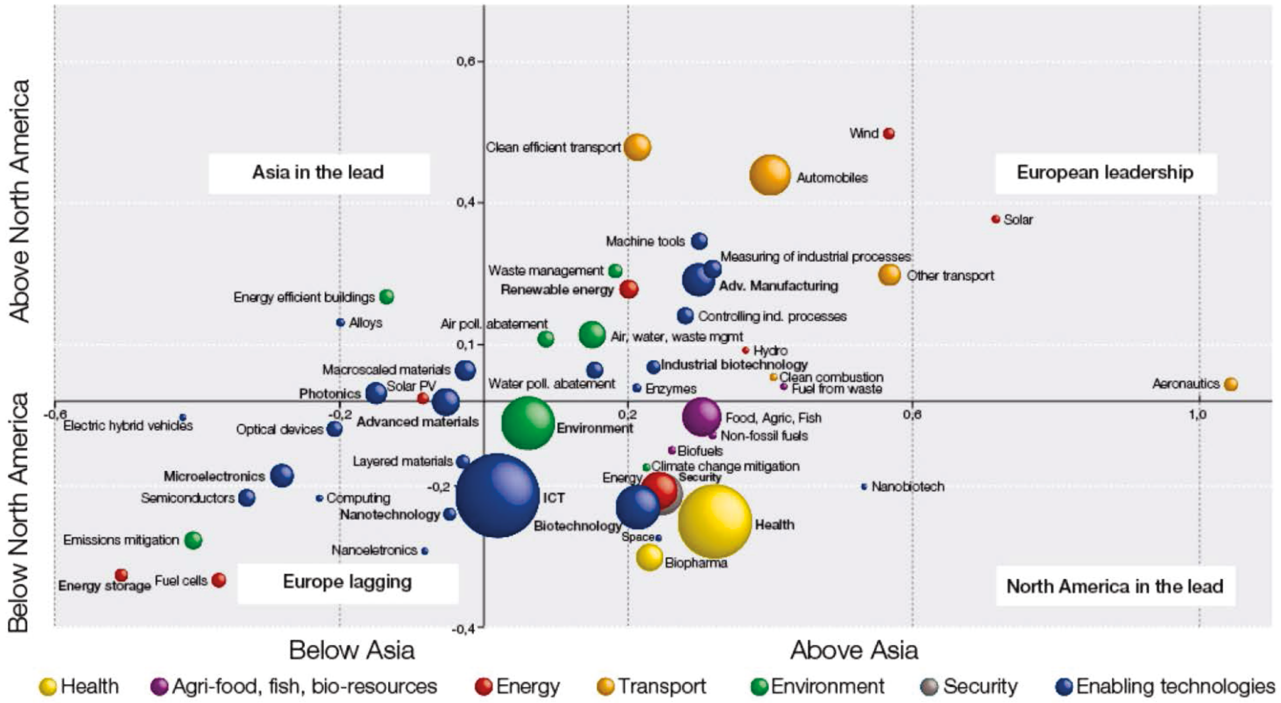

Figure 11: European vs. Asian and North American EPO/PCT patent shares for different technology fields (source: **[68]**). The *x* axis shows the (logarithm of the) European global market share of Europe in EPO/PCT patents compared to the Asian one, while the *y* axis depicts the same quantity for Europe vs. North America. (I.e., the origin (0,0) is defined as the point where all three continents hold an equal number of patents.) Broad technology domains are shown in bold (big dots). Interesting for the development of hybrid power trains are mostly technologies associated with the fields transport (orange) and energy (red). Further discussion of the plot can be found in the text.

9. CONCLUSIONS

The importance of fast and efficient transport for economic success and societal progress stands beyond doubt. However, in recent years it has become increasingly clear that our future transport needs can only be met in a sustainable way if the environmental impact per passenger kilometer is substantially reduced. As the vast majority of transport missions are carried out in vehicles powered by combustion engines, this translates into a requirement to minimize fuel burn. A promising avenue to pursue in this direction is the introduction of (hybrid) electrified power trains, in which a traditional combustion engine is combined with an electric motor. However, while significantly surpassing conventional motors in terms of efficiency, electric motors and their associated components like batteries etc. can constitute a substantial weight penalty. For both ground-based and airborne transport, this manifests itself in a reduction of range and performance, but for aviation, its more demanding power requirements for take-off can challenge the feasibility of electric flight itself for larger transport missions [17,23].

In this paper, we pointed out parallels and differences, both qualitatively and quantitatively, between the development and the introduction of hybrid power train concepts in the automotive and the aviation industries. Let us now summarize our findings under three main categories.

At the technological level, one must ask which domains have the potential to trigger a knock-on effect for the development of electric passenger flight. First and foremost, one must name battery technology: As soon as future batteries will be able to reach sufficient specific energy and power values, the very high efficiency of electric power transmission and conversion can be trusted to become a major driver for the implementation of electrified propulsion systems. Note that the need for such improvements is urgently felt in the car industry as well, from which aviation-specific research efforts can benefit largely. Nevertheless, instead of evolutionary developments, break-through advances using new cathode-anode material combinations (such as e.g. those studied in [23]) will be necessary to enter into the regime interesting for commercially interesting airborne applications.

Next, we state that air-proof power electronics at high voltage levels could have a catalyzing effect for airborne electromotive applications. Again, this is an illustration of a finding from the automotive industry, where the correct control and electric combination of hybrid systems was termed key to harvesting their benefits [4,6,7,22]. Obviously, the existing integrated solutions found for hybrid-electric car electronics can provide substantial guidance to related efforts for airborne power systems. Nevertheless, because of its special safety requirements at high altitudes, aviation will have to make a dedicated and decisive further development step on its own.

At the ecological level, a key prejudice to break for the automotive industry was that ecologically responsible mobility invariably requires renunciation with respect to performance. To understand the importance of overcoming this stigma, recall from Table 1 that for small ground-based vehicles (cars), the roles of customer, driver and passenger are usually confounded. Therefore, emotional or subjective sales arguments related to design and comfort are considered as important as fuel efficiency (46% [19]). On the other hand, hybrid-electric vehicles today primarily target the latter (rational) criterion, which, moreover, is strongly affected by the individual driving style, which may weaken the correlation of ecological and economic advantages. With 61% of customers naming the price-performance ratio as one of their key decision factors when buying a new car [19], the compromises imposed by earlier generations of hybrid-electric vehicles have proven a hard sell. The influence of high-end applications, such as electric cars from *Tesla* or *Porsche*, is therefore not to be underestimated.

It remains to be seen which applications can take the corresponding role for aviation. At present, airborne electro-mobility is developed furthest in the market closest to the automotive industry in terms of power requirements (and possibly also in terms of stakeholder roles), compare Figure 5 (and Table 1). However, a substantial contribution to emission reduction from the installation of (hybrid-) electric power trains in aviation is only to be expected if they can break through to the realm of significantly larger commercial applications. Note, however, that in this case the positions of customer and driver are held by professionals (airline and pilot, respectively), compare Table 1. Since economic considerations are a key buying factor for airlines, and the cost of fuel is likely to continue to increase, ecological responsibility can very rationally be argued to pay off.

Finally, key differences between the automotive and aviation industries at the level of economy were also listed in Table 2. Let us begin with relevant time scales: It is easy to show that the cycles required for innovation and product development (or, more generally, time to market) are much longer for aircraft than for cars. Also, the lifetime, or useful life for which the product has to be engineered, is longer by a factor of two to three. While safety requirements have increased steadily for both applications, in aviation these are most rigorously enforced already at the development stage. Therefore, a semi-experimental approach towards electrification (with many different prototypes), as it has been pursued by car manufacturers in the past, is not feasible for aircraft because the construction of a single prototype requires hundreds of millions in investments. There is, however, another economic observation from the automotive industry that is very likely to carry through to the aviation sector: The mass introduction of HEVs on the streets will only be possible with substantial political encouragement in the form of tax reductions [15]. It is very likely that a similar involvement of politics will be necessary to boost the development of electric aviation.

In conclusion, let us revisit the findings of the hybridization study undertaken in Section 7, which benchmarked –for a fixed transport task– a future universally-electric aircraft against an advanced conventionally powered airliner for EIS 2035. In Figure 5, aircraft MTOW, overall energy and propulsion system efficiency (η_{ov}), energy per PAX kilometer and CO_2 emissions per PAX kilometer were shown as a function of the degree of hybridization H_P. MTOW and η_{ov} both monotonically increase with H_P, illustrating the well-known fact that electric components perform better than a conventional turbo-engine propulsion system in terms of efficiency, but that –at the assumed specific power and specific energy levels and for the selected air transport task– this efficiency benefit is insufficient to compensate for the increase in weight of the energy and propulsion system.

Also evident in Figure 5 is the direct correlation between increasing fuel burn (that is, decreasing H_P) and CO_2 emissions per PAX kilometer. Hence, for the study conditions adopted here, (local) emission savings are achieved (almost) as soon as any amount of electric power is installed. This is an interesting illustration of the different boundary conditions chosen here and in our earlier work [17] (where MTOW –and PAX– were held constant, but range increased with a bigger conventional share of the propulsion system): In [17], a minimum amount of electrification (approximately 50%) was identified, below which no CO_2 reduction per PAX kilometer was achieved.

However, the strongest argument for hybridization comes from the more responsible use of energy by hybrid systems documented in Figure 5: Except for very small degrees of hybridisation ($H_P \leq 0.15$), hybrid-electric systems monotonically improve the energy per PAX kilometer characteristic achieved on the selected transport task. It should be very interesting to explore the trend in energy per PAX kilometer with H_P for other typical air transport applications.

ACKNOWLEDGEMENTS

The authors wish to thank Guido Wortmann for help in obtaining the data used in the preparation of this work. LL also wishes to thank Valentin Batteiger, Corin Gologan, Kay Plötner, Annika Paul, Michael Schmidt and Patrick Vratny for interesting discussions. AS would like to thank Askin Isikveren and Corin Gologan for valuable feedback on the performed hybridization study.

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APPENDIX

A. Degree of Hybridization Definitions in the Literature

Several different definitions of the degree of hybridization (sometimes also called hybridization factor) have been used in the literature over the years, and in this Appendix we provide a brief (and necessarily incomplete) overview of them. We refer the reader to the cited publications for more details on the respective definitions.

The earliest definition of a degree of hybridization encountered in the preparation of the present work is due to Baumann et al. (2000). Introduced in [4], it reads

$$(3)\quad DOH_{\mathrm{HEV}} = 1 - \frac{|P_{\mathrm{max,EM}} - P_{\mathrm{max,ICE}}|}{P_{\mathrm{max,EM}} + P_{\mathrm{max,ICE}}},$$

where $P_{max,EM}$ and $P_{max,ICE}$ are the nominal power outputs of the electric motor (EM) and the internal combustion engine (ICE), respectively. Note, however, that in the design process described in [4], the first choice made when developing a hybrid power train is whether it will be ICE or EM dominated. In this way, confusion between purely conventional vehicles (CV) and purely electric vehicles (EV) can be avoided despite their equal *DOH* values resulting from the definition given in (3), namely $DOH_{CV} = 0$ and also $DOH_{EV} = 0$. (See [4] for a detailed discussion and examples of how this *DOH* can be used as a tool in mechatronic vehicle design.) The definition *DOH* of Eq. (3) was also used later by Faiz and Moayed-Zadeh (2005), see [69], where a starter/generator for HEV was developed (i.e. small *DOH*).

Lukic and Emadi (2004) introduced the hybridization factor *HF* in [5] as

$$(4)\quad HF = \frac{P_{EM}}{P_{EM} + P_{ICE}} = \frac{P_{EM}}{P_{vehicle} = \mathrm{const.}},$$

where P_{EM} and P_{ICE} are the maximum power of the electric machine and the internal combustion engine, respectively. $P_{vehicle}$ is the vehicle's maximum total traction power; consequently $HF = 0$ for a conventional and $HF = 1$ for an electric vehicle.

Bolvashenkov, Herzog and Engstle (2006) defined the factor of hybridization in [44] as

$$(5)\quad K_H = \frac{P_{em}}{P_{vm}},$$

where P_{em} again is the electric motor power and P_{vm} the combustion engine power[20]. Note that, unlike the previously introduced parameters, K_H as defined in Eq. (5) is not bounded and can assume values greater than 1. K_H was also used as a parameter for both serial and parallel or combined hybrids, for which [44] found different ranges of optimal K_H.

This factor of hybridization was then used in a subsequent series of papers [51] [52] [53] by the same authors and collaborators. Among these publications, Buecherl, Bolvahsenkov and Herzog (2009) rewrote Eq. (5) as

$$(6)\quad HF_1 = \frac{P_{\mathrm{EM}}}{P_{\mathrm{ICE}}}$$

and added a second hybridization factor

$$(7)\quad HF_2 = \frac{P_{\mathrm{EM}}}{P_{\mathrm{EM}} + P_{\mathrm{ICE}}},$$

which is equivalent to the definition of H_P used in the present paper. Note that [53] also commented that Eqs. (6) and (7) do not take into account the energy storage. Schmitz and Hornung (2013) [70] referred to the quantity of Eq. (7) as the "degree of electrification (DE)", stating that its definition is also possible with respect to installed energy.

The definition of Eq. (7) was adopted by Pornet et al. in [26] (denoted there as *HF*, hybridization factor) for the performance estimation and sizing of hybrid energy aircraft. Note that in [26], the definition was used in the strict sense of (electric or conventional) power arriving at the drive shaft, i.e. restricted to parallel hybrid configurations.

Finally, let us mention our own previous definition of the degree of hybridization *H* in [17], which was written as

$$(8)\quad H = \frac{P_{co}}{P_{co} + P_{el}},$$

with the conventional (P_{co}) and electric (P_{el}) power shares, respectively.

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[20] vm: „Verbrennungsmotor“ (internal combustion engine)