Looking for a dominant design in car battery technologies: Influencing factors and strategic implications

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Abstract

Automotive industry is one of the most important and profitable industrial sectors worldwide with more than 85.5 million vehicles produced in 2022 (Placek, 2023) and a value of approximately $2520 billion in 2022 (Carlier, 2023). One of the grand challenges for incumbent companies and future competition is the transition towards a mobility based on electric vehicles, also deeply intertwined with the growing attention to the environmental critical issues connected to the use of fossil fuels and sustainability.

Vehicles based on electric powertrains have been recognized as one of the most disruptive and critical innovation in the entire automotive industry since the invention of the ICE (Internal Combustion Engine). It is indisputably considered as the innovation which can introduce a new dominant design in the sector (Jacobides et al., 2016) with the potential to lead to irreversible changes in future competition. In fact, the new propulsion system can potentially question the role of the OEMs (Original Equipment Manufacturers), such as Volkswagen, PSA, Toyota, etc., the architecture of the supplier relationships and the distribution of the value along the supply chain.

To date, the battery technology is identified as an important bottleneck in determining the competitive moves of incumbent OEMs and potential new entrants, and it is configured as one of the main - if not the most important - key factor for the success of electric vehicles. Broadly speaking, currently battery technologies can be divided into two broad categories: the lithium-ion batteries and the alternatives technologies such as the nickel based. Despite this broad categorization, there are numerous types of batteries commercially available, installed on vehicles, with common operating characteristics, but different with respect to specific key performance indicators (KPIs) that customers and car manufacturers are looking for.

This contribution analyzes from a technical point of view the battery technologies currently installed in vehicles, available worldwide, to evaluate the ongoing technological trajectories, within a sector that is experiencing an era of ferment still uncertain as for the future dynamics (Murmann and Schuler, 2023). The focus of the analysis, which adopts a historical perspective, is on passenger cars and the related electric-based models marketed between 2012 and 2023. For each model, subsequently reclassified by segments according to the Euro Car Segment classification, the technology at the base of the battery pack is evaluated. Data are collected from an international database which provides timely information on the topic. The results highlight how - to date - a dominant design from a technological point of view has not been achieved. Furthermore, the analysis of the differences which emerge in the adoption of types of batteries in relation to different electric powertrains and passenger car segments helps to understand the factors that influence the process of establishment of a dominant design. We observed also the relationship between the KPIs of battery technology and the users' priorities in terms of product attributes. Implications for world car manufacturers' strategies are finally drawn.

Key words: *electric vehicles; battery technologies; era of ferment; dominant design; automotive industry*

Framing of the research. *Throughout the evolution of the automotive industry, all technology developments have been focused on the improvements of the ICE (Internal Combustion Engine) technology, based on fossil fuels, and its surrounding sub-systems and components. Over time, in the ICE technology regime OEMs have strengthened their control on the two main technical bottlenecks of vehicles: the powertrain design and the system integration capabilities. The ability to manage the two main technical bottlenecks of ICEVs (Internal Combustion Engine Vehicles) and the hierarchical control on the supply and marketing chains have been turned into a strategic advantage (Baldwin, 2014), thus allowing OEMs to capture the largest share of rents across the value chain. Tesla's successful entry in the full electric vehicles market has given the start to an era of ferment, centered on the technological shift from ICEVs to BEVs*

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(Battery Electric Vehicles). This transition has been mostly represented in the literature as a competency-destroying innovation for OEMs, that makes their current knowledge obsolete, leads to a new dominant design in the sector (Foster, 1986; Jacobides et al., 2016), ultimately mining the OEMs possibility to establish for BEVs the same degree of control over the division of labor and the rent distribution across the value chain. Authors claiming for discontinuity in competitive positioning have highlighted four main points in supporting that view (MacDuffie, 2018; Perkins and Murmann, 2018). First, BE is configured as a completely different powertrain, with the most important core subsystems that differ from those that are key in ICE, thus impacting negatively on incumbent OEMs and favoring the new entrants. Second, the simpler structure of vehicles based on BE powertrain seems to favor modularity, thus removing some of the interfaces existing between the technical structures in ICE vehicles, and reducing the system integration requirements. Third, OEMs legal and certification capabilities related to ICE powertrain may become obsolete or irrelevant. Fourth, the relationships between OEMs and suppliers may be deeply reshaped, so as the business model to be adopted to capture the value along the supply chain.

However, there is no full consensus about the phase of transition the car industry is today living. Other contributions have recently introduced new elements into this debate, offering a more nuanced and multifaceted frame to understand the transition. While it is undisputable that ICE and BEV powertrains show strong differences in technical terms, new studies have argued that these technologies could be similar at the system level (Murmann and Schuler, 2023), so that it would be possible a transformation of OEMs design and system integration capabilities. The transition from ICEVs to BEVs is then likely to require changes for OEMs in a less disruptive way than what expected. This could be related to a couple of reasons mainly. First, recent analyses found a lower than expected level of modularity in BEVs at the system level, which means that the system integration requirements remain high in the new technology (Murmann and Schuler, 2023). Based on their high system integration capabilities, OEMs "will likely maintain their control of the architecture of the automotive industry" (Murmann and Schuler, 2023, p. 147), while new entrants could succeed only in few circumscribed cases. Second, in the BEVs system, the component that represents the most challenging technical bottleneck to manage for OEMs is the electric battery subsystem, whose technical attributes could limit the driving range of the vehicle and result into longer than accepted recharging breaks for user. Within this perspective, it is likely that the value associated with the new technology could migrate from incumbent OEMs to suppliers of car battery cells (e.g., CATL, Samsung) in a larger portion than to newcomers (e.g., Tesla). At the early stages of introduction of BEVs in the market, OEMs were forced to source from Chinese batteries producers who - meanwhile - rapidly expanded to keep the pace with the growing volume of batteries required by the national BEVs manufacturing industry, the largest in the world to date. To counteract the potential stronger bargaining power of battery suppliers, OEMs should react by investing massively in the design and manufacture of their own battery cells. Whether OEMs can succeed by simply revising the traditional system integration model will depend on the financial resources that they will be able to invest so as to reduce the R&D capabilities gap with respect to the specialized battery cell suppliers. In such a way, incumbents will be likely to reduce the technological dependence from battery suppliers, and preserve a part of the control over the supply chain for strategic components.

Purpose of the paper. *The extant debate on the transition towards electrification in car industry has been vibrant but up to now with unconclusive results about the degree of evolution in the process of establishment of a dominant design in technology and about the main effects on firms' strategies and future competition. There is still considerable design competition as firms experiment with different forms of the technology (Anderson and Tushman, 1990) and/or tend to adopt different battery technologies for different car segments. Based on a rich dataset, the purpose of the present exploratory contribution is to shed light on some factors that have an influence in the emergence of a dominant design in the battery technology and, in so doing, in shaping the transition to BEVs. To do that, among the various factors that may have an influence on the dominant design process, we will focus on powertrain types and car market segments.*

Methodology. *We adopt a historical analysis perspective (Nelson et al., 2018) based on data collected from secondary sources. The main source used for the data collection is an international database provided by ICE-Canton. The data collected refers to the time frame 2012-2023, the data relating to 2023 refers to the first nine months of the year. The database allows to collect data on vehicles marketed worldwide with identification by model, type of powertrain, and definition of the specific battery pack technology for BE based vehicles.*

From a technological point of view the alternative powertrains compared to the pure ICE are: plug in hybrid electric vehicles (PHEVs), full hybrid electric vehicles (FHEVs), mild hybrid electric vehicles (MHEVs) and pure battery electric vehicles (BEVs). We consider all of them as part of the electric powertrain vehicles (EPVs), as opposed to ICE powertrain. The focus of the analysis is on passenger car models, subsequently reclassified according to the Euro Car Segment (European Commission, 1999) (Tab. 1).

Tab. 1: Definition and examples of Euro Car Segments.

Euro Car Segment	Definition	Examples of models
	Microcar	Renault Twizy, Smart ForTwo
A	Minicars	Fiat 500, Renault Twingo
B	Small cars	Ford Fiesta, Opel Corsa
C	Medium cars	Honda Civic, Ford Focus
D	Large cars	Alfa Romeo Giulia, Audi A4
E	Executive cars	Audi A6, BMW 5 series
F	Luxury cars	Audi A8, BMW 7 series
S	Sports coupé	Mercedes-Benz S-Class, Porsche Panamera
M	Multi-purpose cars	Citroen C3 Picasso, Ford B-max

Source: Own elaboration

As for the battery type, from a technological point of view, llithium is the mineral used to realize most of the battery installed in electrified cars, while alternatives are based on nickel. It is then possible to classify the battery pack according to two large families: one including technological variations based on ternary lithium-ion depending on the metals used to improve the performance of lithium ions (LFP, LMO, LMP, NCA, NMC, NMX, SCiB); one including alternatives technologies based on nickel (Zebra, Ni-H, NiMH). Findings based on types of batteries are partially limited in terms of consistency, due to data constraints in the identification of the technology in the selected database (lithium-ion and tertiary lithium-ion batteries).

To enrich data interpretation, we identified a number of KPIs that we consider as relevant in the comparison of battery technologies (Battery University, 2021). In Table 2 a short list of some KPIs is exhibited, including definitions and evaluated performance by technology battery drawing on a collection of various technical sources and rated by one of the Authors with competences in chemical engineering. Due to the absence of a sufficiently homogeneous collection of technical data, other important KPIs are not considered in this assessment: Capacity; State of charge; Depth of discharge; Cost; Overall sustainability.

Tab. 2: KPIs in BEVs.

KPIs	*Definition*	*Most diffused types of battery technology: Comparative assessment (*)*
Voltage	*Amount of electrical potential a battery holds*	*NMC = 5; LFP = 4; SCiB = 2; NiMH = 1*
Energy density vol.	*Battery capacity in volume*	*NMC = 6; LFP = 5; SCiB = 3; NiMH = 2*
Energy density mass	*Battery capacity in weight*	*NMC = 6; LFP = 3; SCiB = 2; NiMH = 2*
Charging time	*Time taken for a fully discharged cell to be fully charged*	*NMC = 1; LFP = 6; SCiB = 7; NiMH = 1*
Energy efficiency	*Ratio of average discharging voltage to average charging voltage*	*NMC = 7; LFP = 7; SCiB = 3; NiMH = 1*
Life Cycle	*N. of charging and discharging cycles after that the battery capacity drops below 80% of the nominal value*	*NMC = 3; LFP = 6; SCiB = 7; NiMH = 3*
Self-discharge ratio	*Reduced state of charge of the battery due to internal chemical reactions*	*NMC = 4; LFP = 4; SCiB = 6; NiMH = 1*
Thermal runaway	*Risk of uncontrollable increase in temperature*	*NMC = 2; LFP = 4; SCiB = 4; NiMH = 7*

(*) Value from 1 (low performing) to 7 (high performing)

Source: Own elaboration from various authors

Results. *Tesla Motor has been the first firm to successfully commercialize a BEV, despite OEMs have tried before by launching experimental models without succeeding (Toyota and General Motors), at the end of last century. The success of Tesla in its pioneering effort in relation to BEV market (Perkins and Murmann, 2018) has paved the way to a growing worldwide diffusion of vehicles based on the wider family of electric powertrains (Tab. 3). Recent industry data show an acceleration in the growth of the overall number of BEVs new models and sold volumes.*

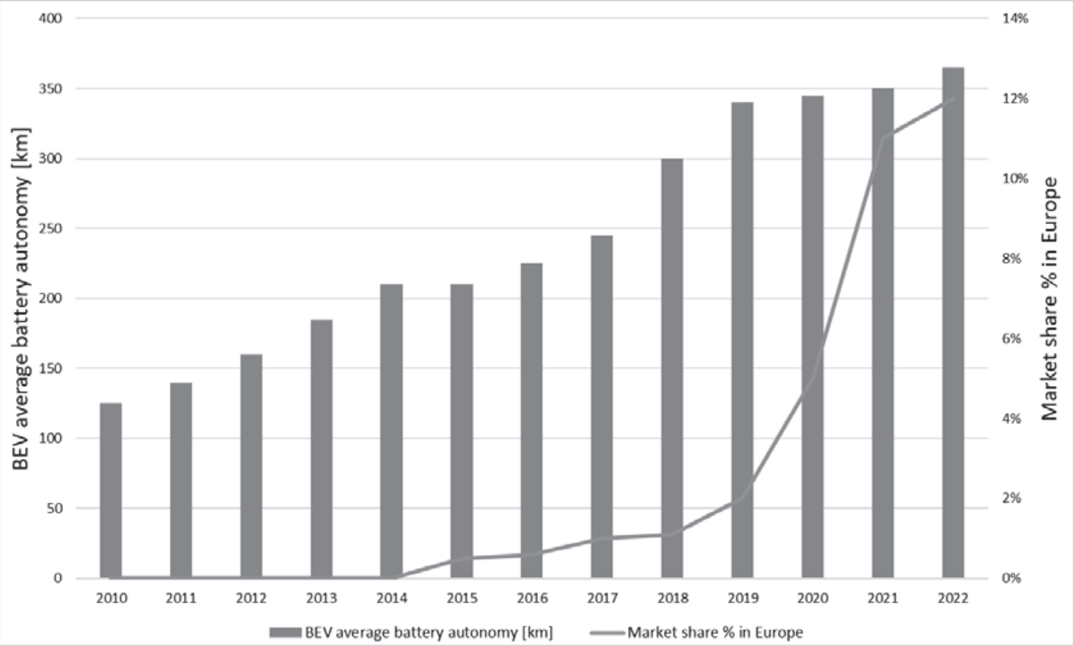
Tab. 3: Worldwide diffusion of BEVs.

Year	N. of vehicle models	% Cumulative	Stock (Million units)
2012	82	5.7%	0
2013	85	11.5%	0.4
2014	19	12.8%	0.7
2015	31	15%	1.3
2016	120	23.2%	2.1
2017	104	30.4%	3.1
2018	85	36.3%	4.9
2019	110	43.8%	7.3
2020	222	59.1%	10.2
2021	182	71.7%	16.4
2022	221	86.9%	26.1
2023 (*)	190	100%	Not available

(*) data updated at September 2023
Source: Own elaboration

The turning point occurred approximately in 2019. After that year, OEMs have strongly increased the introduction in the market of new models, at the time when batteries technology reached a sufficient level of maturity in terms of extended battery life (battery autonomy), presumably the main barrier slowing down consumers' preferences shift to BEVs. This confirms the strict relationship between technological evolution of the core batteries subsystem and market acceptance of the BEVs product, as for example data referred to the sophisticated European consumer markets for passenger cars seem to highlight (Fig. 1).

Fig. 1: Battery autonomy and market share for BEVs in Europe (2010-2022).



Source: Own elaboration

As far as different battery technologies, it emerges that some types of battery are not widely diffused, while there is a polarization towards certain technologies (Tab. 4). The most diffused appears to be the lithium-ion batteries (specifically NMC, LFP, SCiB) and the NiMH Nickel-based battery. Some of the technologies (NCA, LMP, LMO, Ni-H, NMX and ZEBRA) have a percentage of diffusion below or equal to 1% each at world level, so that they can be reasonably considered negligible in the overall evolutionary context of technology for batteries, and they will not be included in the analysis in relation to vehicles models.

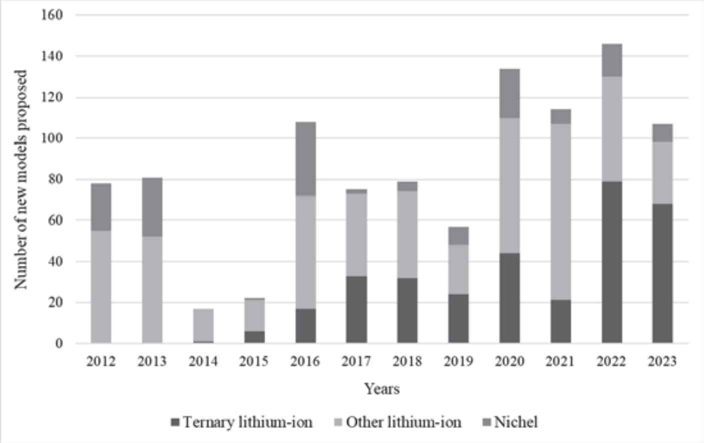
Tab. 4: Worldwide diffusion of types of battery technologies 2012-2023.

Family	Type of battery	% Cumulative
Lithium ion	Ternary-lithium ion (generic)	22.4%
	Tertiary Ternary Lithium-ion NMC	11.9%
	Tertiary Ternary Lithium-ion NCA	1%
	Tertiary Ternary Lithium-ion NMX	0.1%
	Other lithium-ion (generic)	36.7%
	Other Lithium-ion LFP	9.9%
	Other Lithium-ion LMO	0.5%
	Other Lithium-ion LMP	0.5%
	Other Lithium-ion SCiB	5.9%
Nickel	Ni-H	0.3%
	NiMH	10.8%
	Zebra	0.1%

Source: Own elaboration

The temporal analysis (Fig. 2) highlights that there has been a convergence in the last five years towards a battery pack in particular: the lithium-ion batteries. Thanks to their versatility, they are the most adopted by car-makers, while nickel-based batteries (NiMH and SCiB in particular) emerged as the main alternative technology in the last decade. However, while car-makers, especially for BEVs, seem to have started a convergence towards the lithium-ion battery family, it is not possible to anticipate which type of battery will emerge as the preferred for a future convergence into a clear dominant design. The most diffused types today are the NMC (Lithium Nickel Manganese Cobalt Oxides) and the LFP (Lithium Iron Phosphate) (Tab. 4). NMC currently offers the best compromise between low cost and high energy density, but the life cycle is still too short and safety issues persist. LFP is more based on cost-effective and environmentally friendly materials, with high safe and a long service life, and an excellent thermal stability. However, *the energy density is lower and the cold weather performance is weaker. The different technical characteristics of NMC and LFP are thus reflected into advantages and disadvantages in terms of users' evaluation of the product attributes, and no bundle of technical properties / product attributes is clearly crowding out less preferred combinations of properties / attributes. Not surprisingly, both technologies are still in a phase of constant technological evolution. Technological uncertainty is still high and no clearly dominant design has been emerged yet.*

Fig. 2: Worldwide diffusion of types of battery technologies 2012-2023



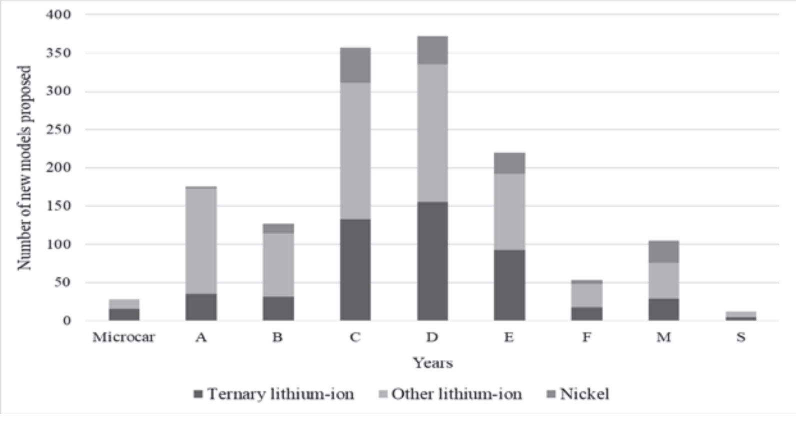
Source: Own elaboration

It is well known in the technology management literature that designs and standardization processes sometimes emerge as dominant not only for the technical superiority, but due to specific market conditions and users' preferences, that may incentive an alternative that not necessarily is the superior one in terms of intrinsic performance. In the context under investigation, for instance, this may happen because a particular battery technology is mounted in the most successful products or in the most rapidly growing markets segments. It is then important to explore the adoption of batteries technologies in relation with two variables: the type of BEVs powertrain considered, because different needs and technical conditions lead to different combinations of powertrains and battery technologies; and the technical-commercial segments where the car is positioned, that are sensitive to the market positioning choices of OEMs and to the product strategies they adopted to enter the electric vehicles market.

Concerning powertrains, findings show that: lithium-ion batteries are used systematically across all the different BEVs (a partial exception is given by the prevalent use of SCiB (LTO) technology for the MHEV powertrain); nickel-based batteries, while mounted in each type of powertrain, are highly concentrated on FHEVs (NiMH, in particular, is the nickel-based technology used by Japanese makers, primarily Toyota, on PHEVs). Considering the models proposed in the 2019-2023 period, the period of stronger evolution in the BEVs industry, the share of the different battery technologies installed in the two world most diffused powertrains (full electric and PHEV) did not change significantly. Overall, neither a clear convergence on a dominant technology nor a strong battery specialization by powertrain are observed at the level of data aggregation used in this analysis.

Concerning car market segments (Fig. 3), overall, the distribution of battery technologies seems to be influenced by different segments of adoption. There is a connection between the technology of batteries and the power input required by models addressing to different segments.

Fig. 3: Worldwide diffusion of battery technologies by type in relation to passenger cars segments



Source: Own elaboration

A valuable point of view is offered by adopting a temporal perspective in the use of battery technologies by segments. It unveils an incremental innovation path followed by OEMs, which, in the early years of market introduction of BEVs, when the battery technology was less developed, strategically addressed their new models to the lower car segments, hence vehicles requiring less power, so as to exploit at best the technologies available. Later, as the battery technology improves, producers invested more and more in new models positioned into higher segments (e.g., segments D, E, F), which require higher energy density, one of the most important KPI of a battery strictly associated with car riding performance. This suggests that, first, a clearly superior battery technology, able to cover all the market segments in a sufficiently performing way, has not yet been identified; second, even the slight degree of specialization of battery technologies by market segments is not likely to accelerate a process of convergence towards a dominant design, as the overall structure of car market segments is quite stable over time in terms of relative size and technical requirements by users.

Overall, the BE technologies are still in the fluid phase, in line with the classical model proposed by Utterback and Abernathy (1975). Analogously, at the level of firms' competition, we are still currently living in an era of ferment (Anderson & Tushman, 1990). While the BEVs are getting stronger in the market and gradually eroding shares to ICEVs, uncertainty persists at the supply side on which battery technology will emerge as dominant design (if any); and, at the demand side, on which will be the structure of the product attributes that will fit firms' product-market strategies and users' preferences. On the one hand, the BEVs technologies have reached a sufficient level of technological maturity to make them ready to enter the mass-market and strengthen the process of erosion of ICEVs shares. On the other hand, BEVs currently available in the market have some price-related (e.g., purchase prices; electricity vs fossil fuels costs) and performance-related (e.g., driving range; charging time; safety issues) issues which do not fully encounter the expectations of the majority of customers. Therefore, the establishment of a dominant design for batteries, and the consequent standardization of manufacturing process, will require additional effort and investments from both battery suppliers and OEMs.

Overall, the analysis shows that the product design able to bundle together, within a unique battery technology, a combination of features that could fulfill at best the demands of the majority of the market (Anderson & Tushman, 1990) has not emerged till now. While it could be reasonable to predict that future advancements in R&D, for instance towards cobalt-free and nickel-free batteries, or towards solid electrolyte batteries, will be likely to open new avenues for technological convergence, a potential dominant design is today very difficult to be anticipated. The rush for the battery of the future is fuelling a great technology excitement. However, whether the future dominant design will come out from significant improvements of already existing battery technologies or from a new or relatively young disruptive technology (e.g., hydrogen fuel cells) is something that cannot be so easily predicted.

The absence of a still consolidated dominant design in batteries technology leaves the room for different evolutionary scenarios in the worldwide car-makers competition. A first scenario is based on the vertical integration strategies of OEMs that are strongly investing in the internalization of the production of battery cells, with the main aim to become independent from the large Chinese battery producers (Moretti et al., 2022). A second scenario, that may partially overlap with the first one, is based on strategies of OEMs that respond with a systematic recourse to alliances with leading battery suppliers. Many OEMs have indeed already started to establish collaborations with the most relevant battery manufacturers (e.g., GM and Ford with LG, BMW with Northolt). In addition, world leading OEMs have established joint ventures with Chinese manufacturers that are fully-integrated in the production of batteries (e.g., BYD) or that can share strong relationships with local battery producers. A third scenario is based on strategies of OEMs (e.g., Toyota) that have not still opted for a full electric vehicle model, so that decisions on which battery technology to invest on are strictly related to the product strategy that will be adopted.

Research limitations. *This contribution is not exempt from some limitations. In particular, the nature of work-in-progress of this contribution presents a limited even if insightful overview of the emerging results, which can be further expanded and refined in the interpretation. First, the analysis can be further detailed by geographic area, in particular considering the relevant role of China and Chinese national companies in shaping potential dominant design for vehicle electrification. Second, the analysis can also extend to last mile freight transport vehicles in particular, and possibly, as a further step, also include trucks for long-distance freight transport which would however require additional KPIs for the technological analysis. Third, the analysis here deliberately did not distinguish by type of BE-based vehicle (EPVs): a more fine-grained analysis by single powertrain is likely to add new fruitful knowledge about how the technology convergence process is evolving or inhibited. Fourth, the analysis can be further detailed by brand and OEMs, also considering the strong impact that the strategies at a group level (e.g., Volkswagen) could have on accelerating technological convergence by stimulating competitors to adopt imitation strategies and isomorphic behaviors. Lastly, in this paper the simultaneous analysis of OEM battery technology strategies, with possible implications on the effects on convergence on economies of scale, has not been developed, due to data constraints.*

Managerial implications. *The managerial implications are linked to the issue of competition in the race for vehicle electrification. In particular, the technological analysis inherent to the heart of electric vehicles, i.e. the type of battery, is fundamental in evaluating the investment trajectories and strategies adopted by carmakers, as described at the end of the Results section.*

Furthermore, the recent great acceleration towards BE-based vehicles is not only the consequence of new technologies introduction, but rather the result of a more complex combination of factors that can be studied in terms of policy implications. The institutional pressure towards a paradigmatic shift from fossils fuels to sustainable technologies for mobility, in the specific case of the passengers cars, is based on announcements of progressive abandonment and *future ban on traditional ICE, and the massive introduction of incentives for the adoption of BEVs (Magnusson & Berggren, 2011; Moretti et al., 2022). A better understanding of the state of evolution of the process of technical convergence towards a dominant design and of factors that affect that convergence should inspire policies at the supply-side level that help companies to address effectively their technological investments.*

Originality of the paper. *While still in an exploratory phase, this paper aims to contribute to the extant literature on car industry transition towards electrification, by offering some reflections upon the centrality of the dominant design formation process. Despite the expected relevance of this topic in advancing knowledge on the overall phenomenon of transition to electrification, in the management literature scant attention has been devoted till now to the nature and stages of evolution of the process of establishment of a dominant design in the battery technologies field, and how it may shape competition during the era ferment. While we agree that the transition to BEVs from ICEVs has passed the point of no return (Moretti et al., 2022), the path is still long and further milestones are to be reached in terms of technical advancements and goals associated with firms' competitive strategies.*

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