sustainability

Article

Electric Cars in Brazil: An Analysis of Core Green Technologies and the Transition Process

Charles Lincoln Kenji Yamamura [1,*], Harmi Takiya [1], Cláudia Aparecida Soares Machado [2], José Carlos Curvelo Santana [3], José Alberto Quintanilha [4] and Fernando Tobal Berssaneti [1]

[1] Department of Production Engineering, Polytechnic School, University of São Paulo, São Paulo 05508-010, SP, Brazil; harmi.harmi@gmail.com (H.T.); fernando.berssaneti@usp.br (F.T.B.)
[2] Department of Transportation Engineering, Polytechnic School, University of São Paulo, São Paulo 05508-070, SP, Brazil; claudia.machado@usp.br
[3] Department of Management Engineering, Federal University of ABC, Alameda das Universidades, Anchieta, São Bernardo do Campo 09606-045, SP, Brazil; jose.curvelo@ufabc.edu.br
[4] Institute of Energy and Environment, University of São Paulo, São Paulo 05508-010, SP, Brazil; jaquinta@usp.br
* Correspondence: charles.yamamura@usp.br

Abstract: This paper explores the transition to electric cars in Brazil. The country has been successful to reduce its carbon footprint using biofuels, but it is facing a dilemma in vehicle electrification. It cannot shift abruptly to battery electric vehicles, as current consumers are unable to afford them and investment in recharging infrastructure is uncertain. However, it has a significant manufacturing base, and it cannot isolate itself from global industrial trends. This study relies on the inductive case study method, identifying the core green technologies in vehicle electrification and extrapolating their trends, to explain how the transition process is feasible. The emergence of a dominant design (set of core technologies defining a product category and adopted by the majority of players in the market) in small and affordable segments is essential for the diffusion of electric cars in developing countries. Biofuel hybrid technologies may support the transition. The Brazilian industry can engage in electric vehicle development by designing small cars based on global architectures, targeting consumers in emerging markets. The article contributes by using a dominant design core technologies framework to explain and map the transition to electric vehicles in developing countries, supporting academic research, government, and industry planning.

Keywords: electric car; technology transition; dominant design; vehicle electrification; clean energy; materials usage; vehicle battery; hybrid car; developing countries; Brazil

check for updates

Citation: Yamamura, C.L.K.; Takiya, H.; Machado, C.A.S.; Santana, J.C.C.; Quintanilha, J.A.; Berssaneti, F.T. Electric Cars in Brazil: An Analysis of Core Green Technologies and the Transition Process. *Sustainability* **2022**, *14*, 6064. https://doi.org/10.3390/su14106064

Academic Editor: Domenico Mazzeo

Received: 15 April 2022
Accepted: 13 May 2022
Published: 17 May 2022

1. Introduction

Climate change is one of the great challenges of our time. The Paris Agreement—an international treaty signed in 2015 by 196 states and the European Union—aims to limit global warming to below 2 and preferably 1.5 degrees Celsius compared to pre-industrial levels, to mitigate the harmful effects of climate change [1]. Human-generated greenhouse gas (GHG) emissions must be reduced to close to zero to achieve that objective.

As the transport sector is one of the major global greenhouse gas emitters (21%) [2], a group of national governments, municipalities and regional governments, automobile manufacturers, and many other institutions and businesses signed a declaration at COP26—the 2021 United Nations Climate Change Conference—to transition to zero tailpipe emission vehicles by 2035 in leading countries and no later than 2040 in emerging countries [3]. Among the signatories were the UK, Sweden, Canada, Mexico, Chile, Ford, General Motors, Mercedes-Benz, Volvo, and Jaguar Land Rover. However, there were abstentions from the United States, China, Germany, Brazil, Volkswagen, Toyota, and BMW, among several others. Completely abandoning internal combustion engines is still a significant challenge in many parts of the world, considering technical, economic, social, political, and geographic factors.

1.1. Decarbonization of Light Vehicles in Brazil

Brazil has a successful history of using biofuels in transport. The 1973 Oil Crisis motivated the creation of the National Alcohol Program (Proalcool), establishing ethanol as an alternative to oil-derived fuels. The program contributed to reducing air pollution by replacing lead as an anti-knocking agent and reducing carbon monoxide and hydrocarbon emissions [4]. Biofuels are considered carbon-neutral on exhaust emissions as the emitted CO_2 has been previously captured from the atmosphere by photosynthesis. However, there are greenhouse gas emissions in fuel production and transportation. The first Brazilian ethanol-powered automobile was launched in 1979.

Automotive gasoline in Brazil is a blend of 27.5% anhydrous ethanol (E27). Ethanol for vehicles (E100) contains up to 4.5% of water. Flex fuel engines can run on any mixture between E27 and E100. There are about 44 million active light vehicles in the domestic fleet and 74% of them are flex fuel [5]. It is estimated that 70% of flex fuel vehicles run on gasoline. Ethanol consumption is influenced mainly by the ethanol to gasoline price ratio. Ethanol prices are affected by weather, government policies, international sugar prices, crude oil prices, and transport costs [6].

Out of 1.98 million new light vehicles registered in 2021 (79% passenger cars and 21% light commercial vehicles), 84% were fitted with flex fuel engines, 3% with gasoline engines, and 13% were diesel-powered [5]. Only 2,851 electric cars were sold in 2021, just 0.14% of light vehicle sales [7]. In 2020, 85% of electric power in Brazil was generated from renewable sources (Figure 1), led by hydropower 63.8%, followed by wind generation 9.2%, biomass 9.0%, and solar energy 1.7% [8].

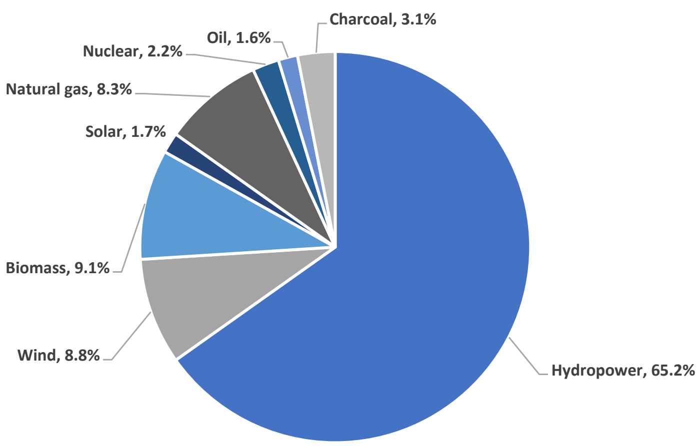

Figure 1. Brazilian sources of electricity in 2020. Source: [8].

The Vehicle Emissions Control Program (PROCONVE) started in 1986, and it progressively reduces new vehicle emission targets [9]. Although it sets targets for carbon monoxide, nitrogen oxides, hydrocarbons, soot, aldehydes, and sulfur oxides, it does not establish CO_2 limits directly. New phases in 2022 and 2025 will introduce progressively more stringent limits on non-methane organic gas and nitrogen oxides, both ground level ozone forming substances [4,10]. Although there is no current legislation explicitly mentioning vehicle electrification as a route to energy efficiency and decarbonization in Brazil [9], the PROCONVE requirements will demand improvements in current engine technology and possibly an increase in the share of electrified vehicles [4].

Vehicle electrification is the transition from pure internal combustion engine vehicles (ICEVs) to full battery electric vehicles (BEVs), often with intermediate stages of electric hybridization—the combination of combustion engines and electric motors [11–13]. Electrification is inevitable for carbon neutrality in transport [4,11–14]. Besides climate damage, sticking to carbon fuels would isolate a country from the global industry, which would seriously affect its competitiveness and access to technology [11,12,15,16]. However, Brazil is not ready to shift abruptly to pure battery electric vehicles, as most of its population would be unable to afford them, and the massive investment in infrastructure is beyond its current capacity [4,11,12,17,18].

1.2. Technology Evolution and Dominant Design

Green innovations are technologies and practices that improve the quality of human life and reduce the impact on the environment. They minimize the usage of energy and materials, as well as reducing pollutant emissions and waste [19]. Incremental innovation (continuous change) occurs along an existing technology path, while radical innovation (discontinuous change) is related to the emergence of a new technology [20]. A new technology path usually starts with an *innovation shock*, a rupture from the existing technology [21].

The emergence of a dominant design is a landmark in the transition of technology from the stage to radical innovation to incremental innovation [22]. A dominant design is a set of product features that defines a product category and is widely adopted by the industry as a de facto standard competitors must adhere to [19,20,23]. The phase prior to the dominant design is called the era of *ferment* and is characterized by discontinuous innovation, many competitors, intense experimentation, and high growth rates [22,24,25]. Electric cars are in the fermenting stage of industrial evolution [20].

A dominant design marks the transition from a focus on product innovation to process innovation [20]. Although the radical product innovation phase is over, there is an increase in incremental product variations. A key aspect of the emergence of a dominant design is the dramatic reduction in product costs [22,24]. The increase in production volumes accelerates learning, standardization, and modularization of components [25,26]. Prices fall and most potential consumers adopt the new product.

A systems view provides a better understanding of technology innovation and dominant designs [19,26]. Dominant designs emerge not at the product system level but first in components or subsystems [27]. When dominant designs in the set of central or core subsystems consolidate, a system dominant design emerges. Core components are those that affect the largest number of product characteristics or features, i.e., they have many connections [19,26]. Peripheral components, affect few characteristics and thus have fewer connections. The larger the number of connections in a product, the higher its complexity (i.e., it has many variables) [19].

Architecture is the way components of a system are connected and organized [27]. A dominant design is a family of designs with common and stable core subsystems and architecture [28]. However, dominant designs are unlikely to be present in all components (subsystems). Once the core components of a design are settled, development shifts to peripheral components. Core components become invariants that are not revisited in a new design [27,29], reducing the design space, and restricting variations to peripheral features [26]. A replacement of core components implies a change in the dominant design and new technology.

Adner and Kapoor [30,31] expanded the notion of technology evolution by adding the *ecosystems* dimension. Most technologies depend on complementary technologies to come to fruition, delivering value. An ecosystem is a community of multiple actors and activities aligned to create and deliver value to customers. It includes producers, suppliers, competitors, distributors, customers, and other stakeholders, and adds *complementors*, such as BEV recharging infrastructure, energy utilities, battery reutilization, and recycling firms [32].

Beyond products, competition happens among ecosystems. Substitution depends on the capacity of a new technology to overcome its challenges, and on the existing technology to keep improving [33–35]. In *creative destruction*, the new technology overcomes its challenges quickly and the old technology is unable to catch up, being rapidly superseded. The *illusion of resilience* happens when the existing technology is unable to evolve, but it lives a bit longer because the new technology struggles to solve its challenges. However, it is a matter of time before the old technology is disrupted.

When a new technology faces significant entry barriers and the incumbent technology still has room for significant improvement, substitution tends to be slow, with *robust resilience*. Battery electric vehicles in emerging countries are such a case. There are considerable barriers for the dissemination of battery vehicles, and internal combustion engine vehicles can still be improved. However, if the new technology surmounts its difficulties quickly but the incumbent also improves vigorously, replacement is gradual, in a period of *robust coexistence.* The relation between pure internal combustion engine vehicles and hybrid vehicles is akin to that situation. The need to create a new ecosystem for battery vehicles can generate considerable tension and resistance. Hybrids may bridge the gap using existing manufacturing and fuel infrastructure (Figure 2).

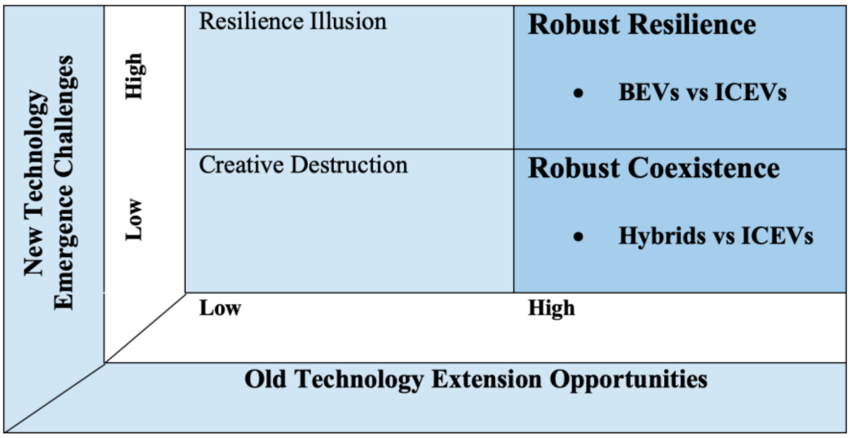

Figure 2. Technology substitution. Source: [34].

Electric vehicle technology depends on the development of batteries with enough energy storage and power delivery, vehicle design (electric motors, control systems, architecture), on recharging infrastructure, power supply from the grid, battery reutilization, and recycling. The competition is not only between technologies but between the ecosystems supporting internal combustion vehicles (manufacturers, oil industry, biofuels industry, suppliers, dealers) and electric vehicles (manufacturers, battery makers, charging firms, power suppliers, battery reuse, and recycling firms).

This paper posits large-scale diffusion of electric cars in developing countries is unlikely to happen before the emergence of a dominant design for small passenger vehicles. Those vehicles should be affordable but practical, comfortable, and safe for small family usage, including enough driving range for holiday trips. The significant cost reduction necessary to make battery electric vehicles accessible to current automobile buyers can only be achieved with the economies of scale that follow the emergence of a dominant design [27]. The transition to electric cars promises more efficient use of energy and materials in the automobile industry. As the industry moves from fuel intensive to materials and energy intensive [36,37], battery reutilization and recycling—still in the early stage and with no established standards and procedures—will also be a key element in the transition.

This article originally contributes by using the dominant design core technology framework to analyze, explain, and map a feasible transition process to electric cars, applied to the specific case of a developing country. The study provides knowledge to support academic research, policy, and decision-making in both industry and government. The existing literature on vehicle electrification in Brazil and the theory of dominant designs was explored in this section. Materials and methods are discussed next. The core technologies for vehicle electrification and the convergence to dominant designs are explained after. From the analysis, relevant electrification technologies are framed, mapped, and discussed. The study is concluded and suggestions for future research are offered.

2. Materials and Methods

We rely on the inductive case study method, seeking relevant factors and the explanation of a complex phenomenon under the logic of theory [38]. The case of transition to electric vehicles in Brazil combines both extreme and typical elements of the vehicle electrification general case. Following Eisenhardt et al. [38], extreme cases provide a broad and clear perspective of a problem and can facilitate new insights. This study aims to understand the emergence of a dominant design in electric vehicles, their dissemination in developing countries, and a potential bridging process using hybrid technologies, to support strategy and policy making.

Our research draws on the academic literature on industrial evolution, product innovation, technology transition, and dominant designs. To investigate the Brazilian light vehicle electrification case, we relied on secondary data on energy policy, powertrain technologies, alternative fuels, vehicle electrification, electric cars, biofuels, clean energy, materials reuse, recycling, and value chains, from government agencies, research institutes, and think tanks, technical reports, and articles from consulting firms and specialized press. From the analysis of those documents, we extracted the major trends in the core green technologies relevant to the emergence of electric cars—batteries, electric motors, control systems, architectures, charging infrastructure, battery reutilization, and recycling. Next, we inferred the main implications for developing countries and for Brazil, in particular, considering the biofuels experience. Then we draw a map of the technology transition, with ensuing explanations (Figure 3).

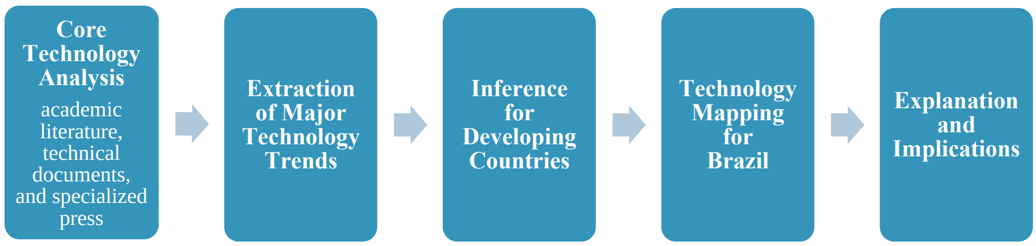

Figure 3. Summary of method. Source: the authors.

The most difficult task is not to understand what will happen but when and how it will happen. For instance, will the transition process be gradual or abrupt? Beyond the study of competing technologies, it is necessary to explore ecosystems—institutions, customers, manufacturers, suppliers, complementors, and infrastructure—in complex interactions, and their unfolding dynamics. Since this is an investigation of the emergence of dominant designs, following Murmann and Frenkel [26], we make explicit both the level of granularity and the unit of time of the study. We focus on the subsystem level (batteries, electric motors, control systems) to understand the integration into the overall vehicle architecture, at a system level. This is an inquiry on the automobile evolution from a developing country's point of view, neither from an isolated firm's nor from the global industry perspective. The time scale of reference is in years.

This research refers to light-duty four-wheeled land vehicles, to the exclusion of other terrestrial transports such as heavy trucks, buses, trains, tractors, and motorcycles. The Brazilian National Environment Council (CONAMA) [39] defines two categories of light vehicles: light passenger vehicles and light commercial vehicles (LCVs). In Brazil, diesel engines are used in heavy vehicles (trucks and buses) and light commercial vehicles but are not allowed in passenger cars. Light commercial vehicles are those: (a) with a payload over 1000 kg; (b) capable of carrying eight passengers or more, plus the driver; or (c) with off-road characteristics. LCVs fall below heavy trucks and buses in capacity, which are also legally defined. Some four-wheel-drive SUVs (sport utility vehicles) clear the CONAMA off-road vehicle criteria and are diesel-powered—as they are classified as LCVs—although they are typically used as private vehicles [10]. Although there is no legal definition or global consensus on the concept of SUV, we refer to closed bodywork passenger vehicles that are taller than traditional passenger cars, with higher ground clearance and elevated ride height [29].

3. Results

3.1. The Emergence of a Dominant Design in Electric Cars

Electric cars are propelled by electric motors fed with energy from batteries, which are charged either from the power grid or by brake energy recovery [40]. Electric cars are praised for energy efficiency (about 90% compared to 25–50% for combustion engines), low emissions, low operating costs (energy and maintenance), instant torque, smooth linear acceleration, and silent operation [41]. Among their weaknesses are high purchasing prices, limited real-world driving range, lack of charging infrastructure, long recharging times, and not having a charger at home [40,41]. In emerging countries such as Brazil, consumers need affordable vehicles that cover their full usage spectrum, not just daily commuting, including three or more annual holiday trips [16,40].

The core subsystems in electric vehicles are power batteries, electric motors, and power control systems [26,27,42–45]. BEVs are currently in full ferment mode of technology evolution and core subsystems are undergoing intense development, in wait for a dominant design to emerge (Figure 4).

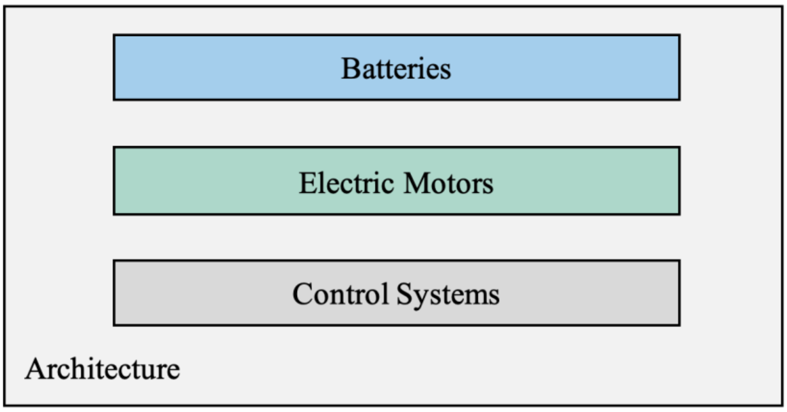

Figure 4. Dominant designs in core subsystems—integrated into the vehicle architecture—define a system dominant design. Sources: [26,27,42–45].

3.1.1. Batteries

Lithium-ion batteries, with their high energy density, durability, and low self-discharge, were originally developed in the consumer electronics industry and made electric vehicles feasible [46]. The most common lithium-ion batteries are the NMC622-graphite type, with nickel, manganese, and cobalt present at 6:2:2 molar ratios in the cathode, and the anode made of graphite. Lithium ions flow between the electrodes through a liquid electrolyte and electrons run in the outer circuit, generating electricity. Nickel, manganese, and cobalt contents determine a battery’s capacity, safety, and charge/discharge rate, respectively. NMC111-graphite batteries are no longer used. By 2030, NMC811-graphite is expected to be the common battery chemistry [46,47].

NMC batteries held 71% of the EV battery market in 2020, nickel-manganese-aluminum (NMA) 25%, and lithium-iron-phosphate (LFP), less than 4% [2]. However, LFP batteries are increasing their market share, due to their long life, thermal stability, performance, lower cost, and no use of cobalt—which is often sourced from strategically sensitive countries [48–50]. LFP batteries are about 25% less energy-dense at the cell level than NMC batteries. Solid-state lithium batteries—using solid instead of liquid electrolytes—promise significant improvements in cost, energy density, safety, packaging, and weight, but manufacturing at a commercial scale is a challenge, unlikely to be surmounted before 2030 [46].

There is a lot of variation in battery chemistry, geometry, and thermal management systems [51]. There are battery cells in cylindrical, prismatic, and pouch geometric forms. Usually, battery cells are assembled in modules and then in battery packages. Battery packages need strong casings to protect them in collisions and to accommodate cooling systems and connectors [52]. Some recent LFP batteries skip modules and assemble cells directly in packages, reducing their weight and hence the disadvantage in specific energy compared to NMC batteries [49]. Structural architectures that eliminate package casings are also being developed [53]. Since battery technology is in the fermenting stage, the industry will need to find the right balance between standardization—to achieve economies of scale—and flexibility, making room for the fast pace of change and competition [52,54].

Batteries can cost between thirty and fifty percent of an electric vehicle, depending on battery and vehicle size [41,55]. In 2020, the average lithium-ion battery pack cost was USD 137 per kWh [2]. The MIT projects battery packs will still cost USD 124 by 2030 [46], as it foresees an increase in the cost of the minerals used to produce batteries. The current energy density of lithium-ion batteries is about 220~250 Wh/kg. Solid-state lithium batteries are expected to deliver 400 Wh/kg by 2030 [2].

Battery manufacturing is a logistics conundrum. Batteries are difficult and costly to transport in containers because of their bulk and weight. From the logistic point of view, battery production is better located close to vehicle manufacturing facilities [7,56]. Local battery production—at least at the package assembly level—is deemed essential for establishing a BEV industry [55].

3.1.2. Electric Motors

Among the electric motors currently applied to vehicle propulsion are the permanent magnet synchronous motor (PMSM), AC asynchronous induction motor, and reluctance motor [43,57]. Permanent magnet motors currently hold 90% of the EV market [9], due to their energy efficiency and power density. Besides the common radial flux type (magnetic flow perpendicular to the output shaft), the axial (parallel to the output shaft) flux permanent magnet motor is receiving attention recently, due to its higher torque density and compact packaging [58]. However, permanent magnet motors use rare earth metals in their magnets, raising concerns about both toxic extraction wastes and sourcing concentrated in a few countries [9,59].

Induction motors do not use permanent magnets (hence no need for rare earth metals), are less costly, but are also less efficient than permanent magnet synchronous motors, due to energy losses in their copper windings [9]. A reluctance motor uses imbalances produced in the magnetic fields of multiple mismatched poles between the stationary (stator) and rotating (rotor) parts of the motor to produce torque. It provides a good power density to cost ratio. However, they can produce torque ripples and noise, and some applications use small permanent magnets in the rotor to mitigate those effects [43,57].

Although some vehicle manufacturers currently outsource electric motors, there is a trend to design and build motors in-house, as a source of efficiency, performance, and competitive advantage [59]. However, in-house development can delay the emergence of dominant designs [27].

3.1.3. Control Systems

Control systems are devices and software that manage battery energy, to provide powerful, smooth, silent, and efficient operation of electric motors. Controllers achieve those tasks by varying the electricity voltage, shifting from direct current to alternating current, and changing the frequency of the alternating current [43]. Control systems are the brains of electric vehicles. Superior levels of system refinement and efficiency are achieved only with top-notch expertise and painstaking development and testing. For instance, it took Nissan ten years to perfect the control of motors and batteries [25].

Masiero et al. [15] recommend that Brazilian suppliers engage in the development of control systems, which manage the power from the battery to modulate the electric motor operation. Control systems are a core BEV technology, and they tend to be centralized in company R&D headquarters. Although Brazil may have the competence, government policy and incentives would be needed to encourage global manufacturers to engage their subsidiaries, sharing the development of control systems.

3.1.4. Architectures

The system architecture is the way subsystems are connected and integrated [27]. Battery electric vehicle architecture is intimately linked to battery packaging as this is the bulkiest and heaviest component in the vehicle. Incumbent vehicle manufacturers usually start the incursion in electric cars by adapting existing combustion engine vehicle architectures, to reduce capital expenditures, lower volume risks, and time to market. Those manufacturers also tend to adopt off-the-shelf modular components and sometimes build electric cars in assembly lines shared with conventional vehicles [60].

Dedicated architectures are expected to replace internal combustion engine vehicle-derived platforms in the future, to improve vehicle packaging, weight, efficiency, and costs [60,61]. Since electric motors are smaller than internal combustion powertrains (engine and transmission), wheels can be moved to the corners of the vehicle in native architectures, and spaces for transmission tunnels and fuel tanks are eliminated, freeing the central floor area for batteries and cabin space. Dedicated architectures also improve vehicle dynamics, by locating the batteries in positions of low center of gravity.

3.1.5. Charging Infrastructure and Energy Management

Despite 80–85% of EV charging being conducted at home [46], an adequate public charging network is essential to meet user requirements [62]. In Brazil, there are only about 750 public EV charging stations [63] —most of them level 2 chargers with 7.4 and 22 kW of power. There are very few 100-kW level 3 fast chargers, and no connection standards [64]. Building the charging infrastructure is challenging in countries with large territories, such as Brazil and India [16,40,65]. The cost of installing an EV supply equipment is in the USD 30,000–USD 80,000 range [62]. According to the Brazilian Automobile Industry Association (ANFAVEA), Brazil will need approximately 150,000 charging points by 2035 [18], requiring between USD 4.5 and USD 12 billion in investment. This will require a joint effort among vehicle manufacturers, companies interested in providing charging infrastructure, and the government. Considering the history of limited investment capacity from the government, the infrastructure is going to take considerably longer than in leading countries [17].

A smart grid incorporates sensing and monitoring technologies to the power network, allowing the bidirectional flow of both energy and information [40]. It is an important element in the integration of electric vehicles, as it provides energy supply and demand management and can help alleviate the demand for grid expansion [40,64]. The increase in EV power demand generates the risk of system overload—power fluctuations, service degradation, and even blackouts [6,66,67]. Studies indicate there is an overlap of EV charging and residence peak loads between two and six o'clock PM. Machine learning methods are being developed to improve charging network management, optimizing the vehicle energy demand side [66,67].

3.1.6. Battery Echelon Utilization and Recycling

Batteries no longer fit for use in electric vehicles can be reused in less demanding applications such as powering residences and commercial buildings, as they retain approximately 80% of the original energy density. The reuse of retired batteries from electric vehicles in other applications is known as *battery echelon utilization* [68]. Among the benefits of echelon utilization are extended battery service life, energy efficiency, economic rents, and reduction of environmental impacts.

Since echelon utilization is an intermediate solution, those batteries will still need to be eventually disposed of and recycled [46,69,70]. About 80–85% of the weight content in an internal combustion vehicle is currently recycled [71]. Since 30 to 50% of an electric vehicle weight is in batteries, adequate battery recycling and disposal are deciding factors to achieve similar indices in battery vehicles. It is an arduous task, as there is a diversity of battery chemistries and formats, and there is no established recycling procedure—most current batteries are not even designed with recycling in mind [46,69,72].

A lithium-ion battery is composed of several recyclable materials (Table 1) [73], and the most valuable ones—such as nickel and cobalt—are in the cathode. 100% of lithium, nickel, manganese, and cobalt, and 90% of aluminum, copper, and plastics in a battery can be recycled. It is estimated the world will need 250,000–450,000 t of lithium, 1.3–2.4 million tons of nickel, and 250,000–420,000 t of cobalt to produce batteries in 2030. Although known reserves are sufficient to meet the demand for metals in batteries, temporary shortages and price increases are expected, caused by fluctuations in demand, and exporting issues, as the extraction of minerals such as lithium and cobalt is highly concentrated in a few countries [36,73].

Table 1. Lithium-ion battery materials (percentage of weight at package level). Source: adapted from [73].

Aluminum	32%
Graphite	18%
Nickel	10%
Electrolyte	9%
Copper	6%
Plastic	5%
Manganese	3%
Cobalt	2%
Electronics	2%
Lithium	2%
Steel	1%
Residual	10%
	100%

Among the methods used to separate materials in battery recycling are melting (pyrometallurgy) and dissolving them with acids (hydrometallurgy). Direct recycling recovers battery cathodes using mechanical and chemical processes, without breaking them down into primary materials. It is a promising method but is still in the early development stage [10,46,69,70]. Battery recycling is complex, can be energy intensive, may emit GHGs, and may be hard to be competitive economically with raw materials mining [69,72].

Battery technology is in full ferment mode, but reuse and recycling are in infant stages. It is important that battery and vehicle manufacturers incorporate echelon utilization and recycling at the design stage, making it easier to identify and separate battery components and materials. Lithium-ion will continue to be the battery chemistry of choice for at least the next ten years [73]. However, future batteries may require different metals in the cathode, making demand for those materials uncertain ten to fifteen years ahead [37,72]. To find a sweet spot between standardization and freedom of innovation is a major ordeal [56,58]. Machine learning techniques are being developed to improve battery echelon utilization, increasing service life, energy efficiency, and environmental benefits [68].

3.2. Hybrid Transition

Existing firms challenged by radical innovations sometimes choose *hybrid* strategies to fill the gap between traditional and new technologies [74]. Hybrids contain features of the emerging innovation combined with others from the existing technology. For instance, hybrid cars combine electric motors and internal combustion engines. However, the effect of hybrids is controversial, and they are sometimes disliked as inelegant technology adaptations. However, they can be useful to learn and bridge transitions under the right circumstances [74].

It is important to understand why a hybrid technology is being adopted [75]. Hybrid strategies are employed to learn, to shape, to buy time, or to prevent a new technology from taking hold. In most cases, they are temporary, and a major risk is sticking to a hybrid for too long, hoping it will be a permanent solution.

Biofuel hybrid electric vehicles (HEVs) are a compelling way to bridge the transition to battery vehicles in countries such as Brazil. They are means to learn some elements of the EV technology, to bridge the transition while the new technology and infrastructure are not yet economically feasible, and to shape the transition process, accommodating the needs of both market and industry. However, they should not be a way to block the transition [15].

Hybrid electrification is a significant step forward in energy efficiency, compared to the conventional internal combustion engine, while still employing most of the existing product and production competencies. They can smooth the transition until a battery vehicle dominant design emerges and complementary technologies—charging infrastructure, battery reuse and recycling, power grid, etc.—are ready. Hybrids can be used to understand EV technology, value chain, distribution, and marketing [75].

3.2.1. Hybrid Electric Vehicles (HEVs)

A hybrid vehicle combines an internal combustion engine with at least one electric motor powered by a battery. Electrification improves the efficiency of an internal combustion engine vehicle by recovering energy from braking and storing it in batteries, to assist engine start and acceleration [47]. The combination of combustion engines and electric motors in hybrids broadens the optimal operation range of speed and loads, reducing both energy usage and emissions [41]. The battery is charged either by brake energy recovery or by a generator driven by the combustion engine. If the combustion engine propels the vehicle with a mechanical link to the wheels, it is a *parallel* hybrid. In a *series* hybrid, the combustion engine works just like a battery recharger and it is not connected directly to the wheels [40,76].

Plug-in hybrid electric vehicles (PHEVs) can charge the batteries from the grid, besides being charged by the combustion engine or by brake regeneration [40]. Their batteries are usually larger than in non-plug-in hybrids and they can operate as pure battery electric vehicles for short distances [47]. Plug-in hybrid electric vehicles can also have parallel or series configurations. A series PHEV is also called a *range extender electric vehicle* (REEV), as the combustion engine supplements energy from the power grid for range increase, operating as an energy generator only, without driving the vehicle wheels [40].

Parallel hybrids usually have larger combustion engines than series hybrids. Conversely, series hybrids tend to have larger electric motors than parallel hybrids. In a parallel hybrid, the main source of propulsion is still the combustion engine, while in the series hybrid, the electric motor is supplemented by a combustion engine. Parallel hybrids tend to be more efficient to operate at high speeds on highways and series hybrids are cleaner and smoother in urban environments [77].

3.2.2. Fuel Cell Electric Vehicles (FCEVs)

A fuel cell electric vehicle can be understood as a range extender vehicle (series hybrid) that uses a fuel cell instead of a combustion engine to power the electric motor. It uses electrical energy generated by the chemical reaction between hydrogen and oxygen (from the air) in fuel cells, charging batteries, and powering electric motors that propel the vehicle [40]. The most common fuel cell in vehicles is the proton exchange membrane (PEM) type, which uses hydrogen from fuel tanks. The ethanol-powered solid oxide fuel cell electric vehicle (SOFCEV) extracts hydrogen from ethanol using a device called a *reformer*, eliminating the need for hydrogen production and supply infrastructure [78]. The electrodes in solid oxide fuel cells are separated by a rigid oxygen ion conducting ceramic membrane [79]. There are no hydrogen tanks and no connection to the power grid in solid oxide fuel cell vehicles. Batteries are charged by the fuel cells and are smaller than in pure electric car batteries, making solid oxide fuel cell vehicles potentially more cost-competitive [79].

If current development obstacles—durability and reliability—are overcome, ethanol fuel cell vehicles may reach the market by 2030 [79]. However, direct hydrogen proton exchange fuel cell vehicles (PEMFCEVs) are uncompetitive in Brazil. Direct hydrogen fuel cell vehicles are considerably more expensive than battery electric vehicles, due to the need for precious metals—e.g., platinum—to catalyze reactions (precious metal catalyzers are not needed in solid oxide fuel cells because of their higher operating temperatures). Hydrogen production and distribution are even more complex, challenging, and expensive than the battery charging infrastructure, and Brazil is unlikely to mobilize in that direction [79,80].

4. Discussion

In isolation, neither market nor technology can explain the emergence of a dominant design. The selection process is strongly influenced by political and social dynamics, making the prediction of the exact shape of a dominant design difficult, if not impossible [22,24]. However, it is possible to understand the evolution of the core technologies and the dominant design emergence process, to estimate both its probability and timing [81]. It is important to evaluate the capabilities and resources needed to accomplish the transition. The hybrid strategy life cycle must be mapped to understand the technology transition, remembering most hybrids are stopgap solutions and resisting the temptation to stick to them for too long. Firms (and countries) that strive to learn and embrace the future are more successful than those that are recalcitrant [75]. Table 2 summarizes major facts and events affecting the transition to battery vehicles.

Table 2. Main events affecting the transition to electric cars in Brazil.

Event	References	Time Estimate
COP26, zero tailpipe emissions declaration	[3,65,82]	2035/2040
Dominant design emergence, from the study of patents	[19,20,27]	2030
Dominant design emergence, from the automobile history pattern	[15,24,83]	2032–2050
Battery high energy density (~400 Wh/kg)	[2,46,84]	2030
Battery cost competitiveness	[46,84]	2035–2040
Vehicle acquisition cost parity	[17,64]	2035–2040
Adequate charging infrastructure in developing countries	[4,14,17,18]	2035
Emission regulations impact on pure gasoline and diesel	[4,10,18]	2035
Zero emissions traffic in urban perimeters	[4,77]	2040
Global industry ceasing internal combustion engine production	[3,4,61,65,82]	2045
Ethanol fuel cell electric vehicle maturity	[8,85]	2030–2035
Small pure electric car diffusion in developing countries	[17,19,83,86]	2040–2050

4.1. Lessons from History

The competition among battery and combustion engine cars is not new. It happened at the beginning of automobile history, in the late nineteenth and early twentieth century [43,83,87]. Electric cars lost because batteries were unable to provide an adequate driving range, recharging infrastructure was more complex than supplying liquid fuel, oil was cheap (in the United States), Electric cars were more expensive, and electricity was not even available in certain regions—especially in rural areas [61].

The introduction of the steel closed body in the 1920′s increased vehicle comfort, room, practicality, and safety, creating the concept of a *touring car*, and the aspiration for motorized traveling on holidays [43,83]. The touring car was largely responsible for the victory of gasoline cars. Touring was not possible with early twentieth century batteries, due to range and lack of infrastructure. In 1911, Charles Kettering invented the electric starter, eliminating the dangerous operation of hand cranking to start a combustion engine, and removing a major disadvantage of the internal combustion engine car [43]. From that event, battery technology became subordinate to the combustion engine and was used to engine start, ignition, and lighting [83].

The Ford Model T, made from 1908 to 1927, introduced mass personal motorization to both rural and urban populations, and eventually set the dominant design for automobiles [43,83]. The automobile was no longer a toy for rich customers. The Model T was comfortable, useful, versatile, reliable, safe, reasonably powerful, and efficient—a respectable automobile that could be used for both commuting and traveling—and still affordable [15,83]. At the end of its life, it incorporated the core elements that defined the dominant design—gasoline-powered engine, steel closed body, steering wheel (some cars were steered using a tiller), electric starter, and electric lighting [83].

From the study of 2.6 million patents in a vast range of industries, Brem et al. [20] concluded dominant designs take between fifteen and twenty years on average (the mode was eighteen years) to emerge from their first applications. It took twenty-two years, between the first internal combustion engine car (the 1886 Benz Patent-Motorwagen) and the 1908 Ford Model T [43]. However, the Model T incorporated the whole set of core elements—such as a closed steel body and electric starter—only eighteen years later, in 1926 [83].

New attempts to make the electric car viable happened in the 1970s, 1990s, and early 2000s [59]. After the 2009 great recession, electric cars finally gained traction, to no small degree due to achievements in battery technology—lithium-ion chemistry was developed by the consumer electronics sector [87]. The first modern-era series production BEV was the Nissan Leaf, launched in 2010 [25]. Tesla launched the Model S in 2012 [43].

Innovations are driven not only by cost and performance but from emotional factors such as status and luxury [17,88]. Some electric vehicle trials of the past, such as the Norwegian Th!nk (2008–2012), did not take emotional factors into consideration and failed. In contrast, Tesla vehicles—largely responsible for the widespread interest in electric cars—sell on attributes such as performance and style, while still making their owners feel both intelligent and good about themselves, due to smaller carbon footprints than in combustion vehicles [88,89].

Products such as automobiles and smartphones create experiences that establish emotional connections with people's ethos and culture [83]. It is not possible to change behavior solely with technology and policy, without consumers' acceptance. Research shows the aspiration for personal transportation will not vanish [55,83,86]. Electric vehicles will need to have the same basic capacities as combustion engine vehicles, such as range, cost, performance, comfort, space, safety, and convenience [83].

An intriguing assessment from the patent study by Brem et al. [20] is, that once a dominant design is established, it lasts in the original form for a maximum of only six years. The increasing acceleration of technology change in some industries may make the emergence of a dominant design ever more difficult and, when it happens, shorten their life spans.

4.2. Stricter Emission Regulations in Brazil

Emission regulations in Brazil (and other emerging countries) will be ever more rigorous, following benchmarks in developed countries, albeit with some delay [18]. Progressively more stringent emission limits of greenhouse gases and other pollutants will make gasoline, diesel, and even flex fuel vehicles struggle to comply and increase the need for electrification [4,10]. Non-flex gasoline and diesel-powered light vehicles may be phased out by the middle of the next decade, with flex fuel and hybrid vehicles remaining for a little longer.

Although ethanol-powered combustion engine vehicles present low carbon emissions, they release other air pollutants (CO, NO_2, C_XH_Y, particulate matter). Legislation in municipalities may forbid using combustion engines within urban perimeters, allowing traffic in electric mode only [4,77]. This will effectively ban internal combustion engine vehicles and conventional hybrids around 2040. Plug-in hybrid vehicles will be electronically controlled to operate in local zero emissions mode in urban areas and to fire combustion engines only outside city boundaries. To meet consumer needs, the electric mode range must increase from the current 30–50 km to about 90 km to be practical [77].

4.3. The Global Automotive Industry

Some of the world's major automobile manufacturers have announced plans to stop selling internal combustion engine light vehicles between 2030 and 2040, especially in leading countries [3,4,61,65]. Although they will continue to offer combustion engines in emerging markets for a few additional years, their demise (including hybrids) is most likely by mid-century. Although electric car adoption is a challenge in countries with large territorial extension, limited purchasing power, and modest charging infrastructure, battery technology is expected to mature in power, energy content, convenience, and cost to replace other types of energy by that time.

All large automobile manufacturers in Brazil are either subsidiaries of transnational companies or local companies that license foreign technology. Most core products are designed in engineering centers abroad from global architectures. A few existing derivatives, such as small SUVs, pickups, and light cargo vans are locally developed, but usually based on global architectures. Most incumbent global manufacturers currently adapt battery vehicles from existing combustion engine vehicle architectures, to reduce investments, risk, and time to market. In the future, they will be developed from dedicated architectures and R&D activities tend to be even more centralized than they are today, seeking optimal returns on investment [87]. It will be hard for countries in the periphery to engage in the core technologies of the battery vehicle industry.

4.4. Developing Countries

Competitive advantage is the set of skills, knowledge, and resources to create value that is superior to what competitors are offering [30,83]. It is unlikely that two companies or countries starting at different points in time will achieve the same results in the battery electric vehicle industry. The United States, Europe, China, Japan, and Korea are likely to concentrate on the technology as they have a significant head start and have been investing heavily in research and development. It will be difficult for emerging countries to catch up without government intervention. Access to the knowledge is likely to happen only after a dominant design is consolidated globally [17,19,86].

Brazil may consider the development of region-specific applications. One venue is the exploration of biofuel hybrids to bridge the transition to battery vehicles [15]. Another is to develop vehicles for emerging markets based on global battery vehicle architectures (small SUVs, light-duty small pickup trucks, and cargo vans), as it currently happens in a few combustion engine vehicle cases. However, designing small and affordable electric cars with bona fide driving range, comfort, safety, and practicality attributes is challenging because of the cost, size, and weight of batteries.

Mass market electric cars will need to accommodate four people with luggage, offer a real-world driving range of over 400 km (about 250 miles), and to be priced at around USD 20,000. Currently, battery vehicles are almost three times more expensive than equivalent combustion engine vehicles [90]. For instance, an electric Peugeot e-208 (a small hatchback) costs BRL 265,900 (USD 51,700; 16 March 2022 exchange rate) in Brazil—a comparably equipped combustion engine version costs BRL 90,990 (USD 17,692) [91]. Electric car prices will need to decrease a lot to be affordable to current vehicle buyers [64]. Considering batteries may account for half the cost of a small car [41,55], electric vehicles will take significantly longer than the 2030′s (projected for the leading countries) to disseminate in emerging markets. In the meantime, hybrids will be needed to fill the gap (Figure 5), helping to mitigate climate change.

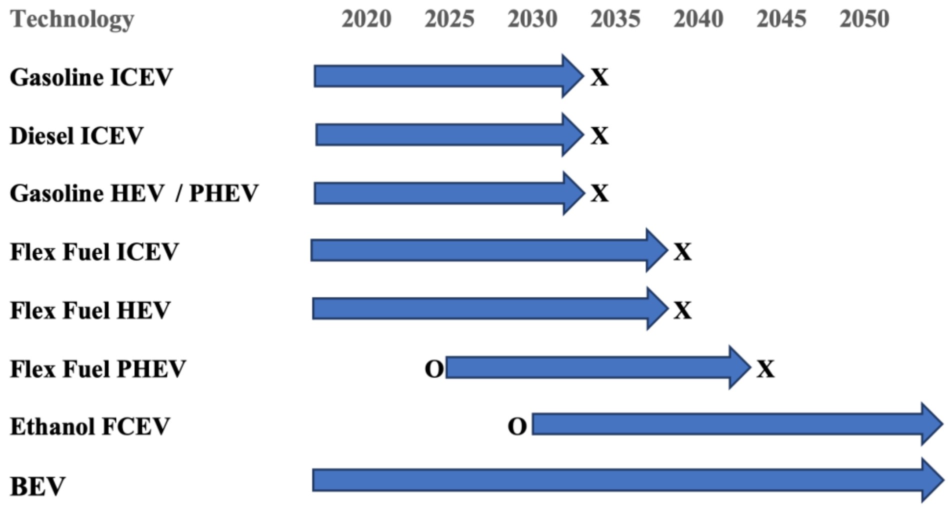

Figure 5. Plausible technology transition map of Brazilian light vehicles. "O" means market introduction; "X", market phase-out. Source: the authors.

5. Conclusions

The objective of this investigation was to analyze current policy, legislation, market, and technology developments in light vehicles, to explain the transition to electric cars in Brazil. It was accomplished with a case study, analysis, and interpretation of both academic literature and secondary documents. Flex fuel hybrids can bridge the transition process from combustion engines to fully electric vehicles. Evermore stringent emission standards may demand hybrids to operate only in electric mode in urban settings. As batteries improve in both energy density and cost, and infrastructure is built, pure electric vehicles will eventually take over, but with a considerable delay compared to advanced economies.

Mass diffusion of electric cars in developing countries is unlikely to happen before the emergence of dominant designs in core vehicle technologies—batteries, electric motors, control systems, and architectural integration—and the advent of affordable and practical vehicles that can replace current vehicles in the full spectrum of needs and usages. Dominant designs are not necessarily performance optimal in all core components, but they are satisficing value propositions that accommodate technical, economic, and sociopolitical requirements. The success of a design is determined not by its technical performance but by cost. Brazil can support the development and manufacturing of relatively affordable light electric vehicles (small SUVs, light pickup trucks, and cargo vans) based on global architectures, catering to both domestic and export emerging markets.

The transition involves both biofuels and gradual electrification, but it should not lose sight of electrification for the sake of biofuels. Although biofuels will bridge the transition, simultaneous development of both series hybrids and battery vehicles will be needed to build technical knowledge and competencies. Hybrids and parallel plug-in hybrids may be adapted from combustion engine vehicle platforms, but a battery vehicle is better deployed from a native architecture. The onboard use of biofuels to extract hydrogen and to power fuel cells is also being actively investigated and shows promise.

The emergence of dominant design may take about twenty years (if it emerges at all) but may last in its original form for only six years. That is approximately a single life cycle or generation of an automobile. It is also close to an individual product development cycle. It means once a dominant design emerges, its successor is already in gestation. Among the promising emerging core technologies are solid-state batteries, axial motors, structural architectures, direct battery recycling, and machine learning technologies to optimize both charging network management and battery echelon utilization. The supply chain crisis triggered by the COVID-19 pandemic exacerbated some challenges such as strategic dependence on some materials sourcing for batteries (cobalt, lithium) and permanent magnets in electric motors (rare earth metals), as the industry moves from fuel intense to materials intense. The vehicle electrification process is extremely dynamic and hard to follow. The window of opportunity may be very narrow. Clear government policy, support, and investment are essential to developing the skills and resources needed to do a successful transition to electric cars.

Future Research

Since the objective of innovation is to deliver value to customers, market acceptance is a natural mirror image of technology. Dominant designs may emerge in certain regional markets without converging into a global dominant design. It is equally plausible dominant designs emerge at a specific market segment level, reflecting customers' economic and psychological profiles. As the global automobile industry transitions to battery electric vehicles, understanding how dominant designs are ramified and delineated in both geographic regions and market segments—and their impact on transport decarbonization—is an important and fertile field for further investigation.

Batteries are the heaviest and more expensive components in electric vehicles, and they need specific attention. Battery echelon utilization and recycling are in early experimental stages and achieving a balance between standardization and flexibility is a distant and uncertain goal. Despite intense ongoing research, it is still an issue waiting for answers, especially in developing countries.

Author Contributions: Conceptualization, C.L.K.Y., H.T., C.A.S.M., J.C.C.S., J.A.Q. and F.T.B.; methodology, C.L.K.Y., C.A.S.M., J.C.C.S., J.A.Q. and F.T.B.; validation, J.C.C.S. and F.T.B.; formal analysis, C.L.K.Y., H.T. and J.C.C.S.; investigation, C.L.K.Y., H.T., C.A.S.M. and J.C.C.S.; writing—original draft preparation, C.L.K.Y. and J.C.C.S.; writing—review and editing, C.L.K.Y., J.C.C.S. and F.T.B.; supervision, J.C.C.S., J.A.Q. and F.T.B.; project administration, J.C.C.S., J.A.Q. and F.T.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Coordination of Superior Level Staff Improvement of the Brazilian Ministry of Education (CAPES), Finance Code 001; and the Brazilian National Council for Scientific and Technological Development (CNPq), Financial Code: 305188/2020-8.

Acknowledgments: The authors thank the University of São Paulo (USP) and the Fundacão Carlos Vanzolini (FCAV) for financial support.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. UNFCC—United Nations Framework Convention on Climate Change. Paris Agreement. 2015. Available online: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement (accessed on 10 June 2021).
2. IEA—International Energy Agency. Net Zero by 2050—A Roadmap for the Global Energy Sector. 2021. Available online: https://iea.blob.core.windows.net/assets/7ebafc81-74ed-412b-9c60-5cc32c8396e4/NetZeroby2050-ARoadmapfortheGlobalEnergySector-SummaryforPolicyMakers_CORR.pdf (accessed on 18 May 2018).
3. U.K. Government. COP26 Declaration on Accelerating the Transition to 100% Zero Emission Cars and Vans. Policy Paper. 10 November 2021. Available online: https://www.gov.uk/government/publications/cop26-declaration-zero-emission-cars-and-vans (accessed on 11 November 2021).
4. Leal, A.C.B.; Consoni, F.L. Emissões Poluentes Dos Veículos: Impacto Dos Combustíveis Utilizados E Potencialidades Da Mobilidade Elétrica (Pollutant Emissions from Vehicles: Impact of Fuels and Potentialities of Electric Mobility). Brazilian Federal Senate, Legislative Consulting Studies and Research Center, Discussion Text No. 293. 2021. Available online: https://www12.senado.leg.br/publicacoes/estudos-legislativos/tipos-de-estudos/textos-para-discussao/td293 (accessed on 30 June 2021).
5. ANFAVEA—Brazilian Automotive Industry Association. Brazilian Automotive Industry Yearbook. 2022. Available online: https://anfavea.com.br/anuario2022/2022.pdf (accessed on 25 March 2022).
6. OECD-FAO. Agricultural Outlook 2020–2029. 2021. Available online: https://www.oecd-ilibrary.org/agriculture-and-food/oecd-fao-agricultural-outlook-2020-2029_1112c23b-en (accessed on 29 May 2021).

7. ABVE—Brazilian Association of the Electric Vehicle. Eletrificados Batem Todas as Previsões Em 2021 (Electric Cars Exceed All Predictions in 2021). January 2022. Available online: http://www.abve.org.br/eletrificados-batem-todas-as-previsoes-em-2021/ (accessed on 24 January 2022).
8. EPE—Energy Research Company. *Brazilian Energy Balance, 2020*; Brazilian Ministry of Mines and Energy: Brasilia, Brazil, 2021. Available online: https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-601/topico-596/BEN2021.pdf (accessed on 22 July 2021).
9. Ferreira, A.L.; Tsai, D.S.; Boareto, R. *The Brazilian Automotive Industry Transition*; IEMA (Institute for Energy and the Environment): Sao Paulo, Brazil, 2021. Available online: https://energiaeambiente.org.br/produto/the-brazilian-automotive-industry-transition (accessed on 25 January 2022).
10. ICCT—International Council on Clean Transportation. Brazil PROCONVE L-7 and L-8 Emission Standards for Light-Duty Vehicles. 2020. Available online: https://theicct.org/sites/default/files/publications/Brazil_L7L8_policy_update_01302020.pdf (accessed on 30 January 2020).
11. Mello, A.M.; Marx, R.; Souza, A. Exploring scenarios for the possibility of developing design and production competencies of electrical vehicles in Brazil. *Int. J. Automot. Technol. Manag.* **2013**, *13*, 289–314. [CrossRef]
12. Marx, R.; De Mello, A.M. New initiatives, trends and dilemmas for the Brazilian automotive industry: The case of Inovar Auto and its impacts on electromobility in Brazil. *Int. J. Automot. Technol. Manag.* **2014**, *14*, 138–157. [CrossRef]
13. Machado, C.A.S.; Takiya, H.; Yamamura, C.L.K.; Quintanilha, J.A.; Berssaneti, F.T. Placement of infrastructure for urban electromobility: A sustainable approach. *Sustainability* **2020**, *12*, 6324. [CrossRef]
14. Consoni, F.L.; Oliveira, A.; Barassa, E.; Martinez, J.; Marques, M.C.; Bermudez, T.; Estudo de Governança E Políticas Públicas Para Veículos Elétricos (Study on Electric Vehicles Governance and Public Policy). Bilateral Technical Cooperation Project between the Brazilian Industrial Development and Competitiveness Secretariat and the German Sustainable Development Cooperation (PROMOB-e). 2018. Available online: http://www.pnme.org.br/biblioteca/estudo-de-governanca-e-politicas-publicas-para-veiculos-eletricos/ (accessed on 27 March 2022).
15. Masiero, G.; Ogasavara, M.H.; Jussani, A.C.; Risso, M.L. The global value chain of electric vehicles: A review of the Japanese, South Korean and Brazilian cases. *Renew. Sustain. Energy Rev.* **2017**, *80*, 290–296. [CrossRef]
16. Pompermayer, F.M. Etanol e Veículos Elétricos: Via de Mão Única ou Dupla? (Ethanol and Electric Vehicles: One or Two-Way Street?). 2010. Available online: https://www.ipea.gov.br/radar/temas/industria/308-radar-n-07-etanol-e-veiculos-eletricos-via-de-mao-unica-ou-dupla (accessed on 20 March 2022).
17. Costa, E.; Horta, A.; Correia, A.; Seixas, J.; Costa, G.; Sperling, D. Diffusion of electric vehicles in Brazil from the stakeholders' perspective. *Int. J. Sustain. Transp.* **2020**, *15*, 865–878. [CrossRef]
18. ANFAVEA—Brazilian Automotive Industry Association. O Caminho da DescarbonizaçÃo do Setor Automotivo No Brasil (The Way to Decarbonization in the Brazilian Automotive Sector). 2021. Available online: https://anfavea.com.br/docs/apresentacoes/APRESENTAÇ~{A}O-ANFAVEA-E-BCG.pdf (accessed on 25 November 2021).
19. Nylund, P.A.; Brem, A.; Agarwal, N. Enabling technologies mitigating climate change: The role of dominant designs in environmental innovation ecosystems. *Technovation* **2021**, 102271. [CrossRef]
20. Brem, A.; Nylund, P.A.; Schuster, G. Innovation and de facto standardization: The influence of dominant design on innovative performance, radical innovation, and process innovation. *Technovation* **2016**, *50*, 79–88. [CrossRef]
21. Argyres, N.; Bigelow, L.; Nickerson, J.A. Dominant designs, innovation shocks, and the follower's dilemma. *Strateg. Manag. J.* **2015**, *36*, 216–234. [CrossRef]
22. Chen, T.; Qian, L.; Narayanan, V. Battle on the wrong field? Entrant type, dominant designs, and technology exit. *Strateg. Manag. J.* **2017**, *38*, 2579–2598. [CrossRef]
23. Brem, A.; Nylund, P.A. Maneuvering the bumps in the new Silk Road: Open innovation, technological complexity, dominant design, and the international impact of Chinese innovation. *R&D Manag.* **2021**, *51*, 293–308.
24. Anderson, P.; Tushman, M.L. Technological discontinuities and dominant designs: A cyclical model of technological change. *Adm. Sci. Q.* **1990**, *35*, 604–633. [CrossRef]
25. Cecere, G.; Corrocher, N.; Battaglia, R.D. Innovation and competition in the smartphone industry: Is there a dominant design? *Telecommun Policy* **2015**, *39*, 162–175. [CrossRef]
26. Murmann, J.P.; Frenken, K. Toward a systematic framework for research on dominant designs, technological innovations, and industrial change. *Res. Policy* **2006**, *35*, 925–952. [CrossRef]
27. Brem, A.; Nylund, P.A. Home bias in international innovation systems: The contingent role of central technologies in the emergence of dominant designs in the electric vehicle industry. *J. Clean. Prod.* **2021**, *321*, 128964. [CrossRef]
28. Tushman, M.L.; Murmann, J.P. Dominant Designs, Technology Cycles, and Organization Outcomes. *Acad. Manag. Proc.* **1998**, *1*, A1–A33. [CrossRef]
29. Yamamura, C.L.K.; Santana, J.C.C.; Masiero, B.S.; Quintanilha, J.A.; Berssaneti, F.T. Forecasting new product demand using domain knowledge and machine learning. *Res. Technol. Manag.* 2022, *submitted*.
30. Adner, R. Match your innovation strategy to your innovation ecosystem. *Harv. Bus. Rev.* **2006**, *84*, 98.
31. Adner, R.; Kapoor, R. Value creation in innovation ecosystems: How the structure of technological interdependence affects firm performance in new technology generations. *Strat. Manag. J.* **2010**, *31*, 306–333. [CrossRef]

32. Adner, R.; Euchner, J. Innovation ecosystems. *Res. Technol. Manag.* **2014**, *57*, 10–14.
33. Adner, R.; Kapoor, R. Innovation ecosystems and the pace of substitution: Re-examining technology S-curves. *Strateg. Manag. J.* **2016**, *37*, 625–648. [CrossRef]
34. Adner, R.; Kapoor, R. Right tech, wrong time. *Harv. Bus. Rev.* **2016**, *94*, 60–67. [CrossRef]
35. Adner, R. Ecosystem as structure: An actionable construct for strategy. *J. Manag.* **2017**, *43*, 39–58. [CrossRef]
36. IEA—International Energy Agency. The Role of Critical Minerals in Clean Energy Transitions. 2021. Available online: https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions (accessed on 10 April 2022).
37. Castelvecchi, D. Electric cars and batteries: How will the world produce enough? *Nature* **2021**, *596*, 336–339. Available online: https://www.nature.com/articles/d41586-021-02222-1 (accessed on 17 August 2021). [CrossRef] [PubMed]
38. Eisenhardt, K.M.; Graebner, M.E.; Sonenshein, S. Grand challenges and inductive methods: Rigor without rigor mortis. *Acad. Manage. J.* **2016**, *59*, 1113–1123. [CrossRef]
39. CONAMA—National Environment Council. Resolution No. 492. 20 December 2018. Available online: https://www.in.gov.br/materia/-/asset_publisher/Kujrw0TZC2Mb/content/id/56643907/do1-2018-12-24-resolucao-n-492-de-20-de-dezembro-de-2018-56643731 (accessed on 27 March 2020).
40. Teixeira, A.C.R.; da Silva, D.L.; Neto, L.D.V.B.M.; Diniz, A.S.A.C.; Sodré, J.R. A review on electric vehicles and their interaction with smart grids: The case of Brazil. *Clean Technol. Environ. Policy* **2015**, *17*, 841–857. [CrossRef]
41. Yu, X.; Sandhu, N.S.; Yang, Z.; Zheng, M. Suitability of energy sources for automotive application—A review. *Appl. Energy* **2020**, *271*, 115169. [CrossRef]
42. MacDuffie, J.P. Response to Perkins and Murmann: Pay attention to what is and isn't unique about Tesla. *Manag. Organ. Rev.* **2018**, *14*, 481–489. [CrossRef]
43. Enge, P.; Enge, N.; Zoepf, S. *Electric Vehicle Engineering*; McGraw-Hill: New York, NY, USA, 2021.
44. Yoshimoto, K.; Hanyu, T. Nissan e-Power: 100% electric drive and its powertrain control. *IEEJ J. Ind. Appl.* **2021**, *10*, 411–416. [CrossRef]
45. Xiong, J.; Zhao, S.; Meng, Y.; Xu, L.; Kim, S. How latecomers catch up to build an energy- saving industry: The case of the Chinese electric vehicle industry 1995–2018. *Energy Policy* **2022**, *161*, 112725. [CrossRef]
46. MIT—Massachusetts Institute of Technology. *Insights into Future Mobility*; MIT Energy Initiative: Cambridge, MA, USA, 2019. Available online: https://energy.mit.edu/wp-content/uploads/2019/11/Insights-into-Future-Mobility.pdf (accessed on 20 March 2020).
47. Bieker, G. *A Global Comparison of the Life-Cycle Greenhouse Gas Emissions of Combustion Engine and Electric Passenger Cars*; The International Council on Clean Transportation: Berlin, Germany, 2021; Available online: https://theicct.org/sites/default/files/publications/Global-LCA-passenger-cars-jul2021_0.pdf (accessed on 20 July 2021).
48. Xu, C.; Dai, Q.; Gaines, L.; Hu, M.; Tukker, A.; Steubing, B. Future material demand for automotive lithium-based batteries. *Commun. Mater.* **2020**, *1*, 99. [CrossRef]
49. Yang, X.G.; Liu, T.; Wang, C.Y. Thermally modulated lithium iron phosphate batteries for mass-market electric vehicles. *Nat. Energy* **2021**, *6*, 176–185. [CrossRef]
50. Agathie, C. The Main Types of Li-Ion Batteries Explained and What Is the Best for Electric Vehicles. *Autoevolution*, 12 February 2022. Available online: https://www.autoevolution.com/news/the-main-types-of-li-ion-batteries-explained-and-what-is-the-best-for-electric-vehicles-181498.html(accessed on 12 February 2022).
51. Arribas-Ibar, M.; Nylund, P.A.; Brem, A. The risk of dissolution of sustainable innovation ecosystems in times of crisis: The electric vehicle during the COVID-19 pandemic. *Sustainability* **2021**, *13*, 1319. [CrossRef]
52. Arora, S.; Shen, W.; Kapoor, A. Review of mechanical design and strategic placement technique of a robust battery pack for electric vehicles. *Renew. Sustain. Energy Rev.* **2016**, *60*, 1319–1331. [CrossRef]
53. Tesla. Battery Day Presentation. 20 September 2020. Available online: https://www.tesla.com/2020shareholdermeeting (accessed on 21 September 2020).
54. Brereton, P. Should We Standardize Electric Vehicle Batteries? *Electric and Hybrid Vehicle Technology International*, 7 May 2020. Available online: https://www.electrichybridvehicletechnology.com/opinion/should-we-standardize-electric-vehicle-batteries.html(accessed on 7 May 2020).
55. Jetin, B. Who will control the electric vehicle market? *Int. J. Automot. Technol.* **2020**, *20*, 156–177.
56. Mosquet, X.; Arora, A.; Xie, A.; Renner, M. *Who Will Drive Electric Cars to the Tipping Point?* Boston Consulting Group: Boston, MA, USA, 2020. Available online: https://www.bcg.com/en-br/publications/2020/drive-electric-cars-to-the-tipping-point (accessed on 2 January 2020).
57. Motor Trend. The green issue—The future of electric vehicles. *Mot. Trend* **2021**, *6*, 10–71.
58. Jenkins, J. A Closer Look at Axial Flux Motors. *Charged—Electric Vehicles Magazine*, 19 May 2021. Available online: https://chargedevs.com/features/a-closer-look-at-axial-flux-motors/(accessed on 19 May 2021).
59. Anderson, B. New Electric Motor Technology Will Push EVs to the Next Level. Carscoops. 2022. Available online: https://www.carscoops.com/2022/02/new-electric-motor-technology-will-push-evs-to-the-next-level/ (accessed on 3 February 2021).

60. Erriquez, M.; Schäffer, P.; Schwedhelm, D.; Wu, T. How to Drive Winning Battery- Electric-Vehicle Design: Lessons from Benchmarking Ten Chinese Models; McKinsey & Company. 2020. Available online: https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/how-to-drive-winning-battery-electric-vehicle-design-lessons-from-benchmarking-ten-chinese-models (accessed on 10 July 2020).
61. Guan, M.; Gao, P.; Peng, B.; Zhou, T.; Hsu, A. The Race to Win: How Automakers Can Succeed in a Post-Pandemic China. McKinsey China Auto Consumer Insights. 2021. Available online: https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/the-race-to-win-how-automakers-can-succeed-in-a-post-pandemic-china (accessed on 13 August 2021).
62. Hussain, S.; Kim, Y.S.; Thakur, S.; Breslin, J.G. Optimization of waiting time for electric vehicles using a fuzzy inference system. *IEEE Trans. Intell. Transp. Syst.* **2022**, 1–12. [CrossRef]
63. ABVE—Brazilian Association of the Electric Vehicle. Rede de Recarga Aumenta 50% Em Quatro Meses (Recharging Network Grows by 50% in Four Months). 2021. Available online: https://www.abve.org.br/eletropostos-no-brasil-crescem-50-em-quatro-meses/ (accessed on 20 March 2022).
64. Schiavo, F.T.; Calili, R.F.; de Magalhães, C.F.; Fróes, I.C. The Meaning of Electric Cars in the Context of Sustainable Transition in Brazil. *Sustainability* **2021**, *13*, 11073. [CrossRef]
65. Singla, A.; Bansal, R. *Sustainability of Electric Vehicles: A Short Study of the Indian Electric Vehicle Market*; Shiv Nadar University: Greater Noida, India, 2022. Available online: https://www.researchgate.net/publication/357648886_SUSTAINABILITY_OF_ELECTRIC_VEHICLES_A_short_study_of_the_Indian_Electric_Vehicles_Market (accessed on 1 May 2022).
66. Hussain, S.; Ahmed, M.A.; Kim, Y.C. Efficient power management algorithm based on fuzzy logic inference for electric vehicles parking lot. *IEEE Access* **2019**, *7*, 65467–65485. [CrossRef]
67. Hussain, S.; Ahmed, M.A.; Lee, K.B.; Kim, Y.C. Fuzzy logic weight based charging scheme for optimal distribution of charging power among electric vehicles in a parking lot. *Energies* **2020**, *13*, 3119. [CrossRef]
68. Li, C.; Wang, N.; Li, W.; Li, Y.; Zhang, J. Regrouping and echelon utilization of retired lithium-ion batteries based on a novel support vector clustering approach. *IEEE Trans. Transp. Electrif.* **2022**, 1. [CrossRef]
69. Beaudet, A.; Larouche, F.; Amouzegar, K.; Bouchard, P.; Zaghib, K. Key challenges and opportunities for recycling electric vehicle battery materials. *Sustainability* **2020**, *12*, 5837. [CrossRef]
70. Parajuly, K.; Ternald, D.; Kuehr, R. *The Future of Electric Vehicles and Material Resources: A Foresight Brief*; The United Nations University: Tokyo, Japan, 2020. Available online: http://collections.unu.edu/eserv/UNU:7820/n2020_Future_of_Electric_Vehicles_Foresight_Brief.pdf (accessed on 11 April 2022).
71. Passos, E.R. *Reciclagem de Automóveis (Automobile Recycling)*; Instituto Mauá de Tecnologia: Sao Paulo, Brazil, 2013. Available online: https://maua.br/files/monografias/completo-reciclagem-automoveis-161657.pdf (accessed on 9 April 2021).
72. Morse, I. A dead battery dilemma. *Science* **2021**, *373*, 780–783. [CrossRef] [PubMed]
73. Backhaus, R. Battery raw materials—Where from and where to? *ATZ Worldwide* **2021**, *123*, 8–13.
74. Christensen, C.M.; McDonald, R.; Altman, E.J.; Palmer, J.E. Disruptive innovation: An intellectual history and directions for future research. *J. Manag. Stud.* **2018**, *55*, 1043–1078. [CrossRef]
75. Furr, N.; Snow, D. The Prius Approach. *Harv. Bus. Rev.* **2015**, *93*, 102–107.
76. Tran, M.K.; Bhatti, A.; Vrolyk, R.; Wong, D.; Panchal, S.; Fowler, M.; Fraser, R. A review of range extenders in battery electric vehicles: Current progress and future perspectives. *World Electr. Veh. J.* **2021**, *12*, 54. [CrossRef]
77. Plötz, P.; Moll, C.; Li, Y.; Bieker, G.; Mock, P. Real-World Usage of Plug-In Hybrid Electric Vehicles: Fuel Consumption, Electric Driving, and CO_2 Emissions. International Council on Clean Transportation. 2020. Available online: https://theicct.org/publications/phev-real-world-usage-sept2020 (accessed on 28 August 2021).
78. Silva, E.P. Etanol e Hidrogênio: Uma Parceria de Futuro Para o Brasil (Ethanol and Hydrogen: A Promising Partnership for Brazil). 2021. Available online: http://cienciaecultura.bvs.br/pdf/cic/v60n3/a15v60n3.pdf (accessed on 1 June 2021).
79. Vargas, J.E.V.; Seabra, J.E.A. Fuel-cell technologies for private vehicles in Brazil: Environmental mirage or prospective romance? A comparative life cycle assessment of PEMFC and SOFC light-duty vehicles. *Sci. Total Environ.* **2021**, *798*, 149265. [CrossRef]
80. Plötz, P. Hydrogen technology is unlikely to play a major role in sustainable road transport. *Nat. Electron.* **2022**, *5*, 8–10. [CrossRef]
81. Srinivasan, R.; Lilien, G.L.; Rangaswamy, A. The emergence of dominant designs. *J. Mark.* **2006**, *70*, 1–17. [CrossRef]
82. Sacchi, R.; Bauer, C.; Cox, B.; Mutel, C. When, where and how can the electrification of passenger cars reduce greenhouse gas emissions? *Renew. Sustain. Energy Rev.* **2022**, *162*, 112475. [CrossRef]
83. Bladh, M. Origin of car enthusiasm and alternative paths in history. *Environ. Innov. Soc. Transit.* **2019**, *32*, 153–168. [CrossRef]
84. Rathi, A.; Murray, P.; Dottle, R. *The Hidden Science Making Batteries Better, Cheaper and Everywhere*; Bloomberg: New York, NY, USA, 2021. Available online: https://www.bloomberg.com/graphics/2021-inside-lithium-ion-batteries/ (accessed on 7 May 2022).
85. Dogdibegovic, E.; Fukuyama, Y.; Tucker, M.C. Ethanol internal reforming in solid oxide fuel cells: A path toward high performance metal-supported cells for vehicular applications. *J. Power Sources* **2020**, *449*, 227598. [CrossRef]
86. Fujimoto, T. The long tail of the auto industry life cycle. *J. Prod. Innov. Manag.* **2014**, *31*, 8–16. [CrossRef]
87. Midler, C.; Beaume, R. Project-based learning patterns for dominant design renewal: The case of Electric Vehicle. *Int. J. Proj. Manag.* **2010**, *28*, 142–150. [CrossRef]

88. Sovacool, B.K.; Axsen, J. Functional, symbolic and societal frames for automobility: Implications for sustainability transitions. *Transp. Res. A Policy Pract.* **2018**, *118*, 730–746. [CrossRef]
89. Noel, L.; Sovacool, B.K.; Kester, J.; de Rubens, G.Z. Conspicuous diffusion: Theorizing how status drives innovation in electric mobility. *Environ. Innov. Soc. Transit.* **2019**, *31*, 154–169. [CrossRef]
90. Arora, A.; Niese, N.; Dreyer, E.; Waas, A.; Xie, A. *Why Electric Cars Can't Come Fast Enough*; Boston Consulting Group: Boston, MA, USA, 2021. Available online: https://www.bcg.com/pt-br/publications/2021/why-evs-need-to-accelerate-their-market-penetration (accessed on 22 December 2021).
91. Peugeot. New Peugeot 208. 2022. Available online: https://carros.peugeot.com.br/compre/tenha-um-peugeot/ofertas/ofertas-peugeot-208.html?gclid=Cj0KCQjw3IqSBhCoARIsAMBkTb1LeoNfPVu90uvViLVJl0puSlc9ndtWzj4wwxKUbESWTxKXW31kHT0aAub8EALw_wcB (accessed on 16 March 2022).