A framework for electric vehicle power supply chain development

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ABSTRACT:

One anticipated pathway in society's decarbonization is the electrification of the transportation sector. From a power system perspective, transitioning to electric vehicles (EVs) presages many impacts, both positive and negative. This study utilizes the theoretical framework of business model theory and a review of the existing literature to portray a rational development path for the electric vehicle power supply chain (EVPSC). Three phases of development were identified in which EVs transition from the present day's low utilization, to rapid development, to a mature technology dominating the transportation sector. Within these phases, the business content, business structure, and corresponding coordination modes were analyzed and discussed. The three phases of development are shown to dynamically interact, between development phases and the business models, providing insight into the content of the EVPSC. Such insight is necessary for developing coherent policies and institutional supports to foster efficient development of the EVPSC. This study provides a new perspective about EVPSC development, answers the core question on how to realize the coordinated development between EVs and the electric power system chain (EPSC) based on the model of EVPSC, and provides recommendations on the establishment of business models for the future EVPSC.

KEYWORDS: Electric vehicle; Charging services; Discharging services; Power supply chain; Business model

Abbreviation

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ACF	Affiliated charging facility
CCF	Commercial charging facility
CFO	Charging facility operator
CSSC	Charging service supply chain
DER	Distributed energy resource
DSSC	Discharging service supply chain
EPSC	Electric power supply chain
EV	Electric vehicle
EVPSC	Electric vehicle power supply chain
HCF	Home charging facility
ICVs	Internal combustion vehicles
M2M	Machine-to-machine
P2P	Peer-to-peer
PCF	Public charging facility
V2B	Vehicle-to-building
V2G	Vehicle-to-grid
V2H	Vehicle-to-home
V2M	Vehicle-to-microgrid

1. Introduction

The global energy crisis and related environmental issues, in addition to the progress of a number of key technologies, such as battery technology, are spurring electrification of the transportation sector and a transition to the electrification era [1][2]. During the process, incumbent internal combustion vehicles (ICVs) will be progressively substituted by electric vehicles (EVs). This transition not only portends a remodeling of vehicle powertrain, but it will also have far-reaching influences on the entire electric power supply chain (EPSC). For instance, to satisfy the increasing electricity demand due to EV charging, more charging facilities with their corresponding supporting infrastructures will be needed and built [3]. To cope with the potential impact on power systems due to increasing EV loads, numerous equipment protection and management devices need to be added or upgraded [4][5]. All these changes will create a power supply chain capable of providing charging services to EVs, one that will be subject to and affected by the existing, conventional EPSC. This new aspect of the power supply chain will be designated here as the electric vehicle power supply chain (EVPSC) in order to distinguish it from the EPSC for the entire power grid.

As a derived supply chain, along with the development of EVs, the EVPSC will encounter challenges but will also experience a number of benign opportunities. In terms of opportunities, the increase in the number of EVs will result in an increase in the electricity demand, meaning that relevant entities in the EVPSC will enjoy an increasing sale space of electricity [6]. If managed properly, EVs could even bring extra benefits to the EVPSC, e.g., through persuading and aggregating EVs to provide ancillary services to the electricity distribution networks. Conversely, without suitable management, the proliferation of EVs could lead to a set of negative impact in the operation of the power supply and distribution systems such as power quality problems, steady-state voltage increase, overloading of cables and transformer, steeper ramps and higher peak loads [7][8][9]. In order to avoid the impacts and exploit the benefits, many researchers have suggested solutions involving charging network planning [10], EV charging load management [11], and EV discharging control [12]. After examining the relevant studies, it is evident that the majority of them are based on special technical scenarios of EV market-penetrating, from which it is difficult to compose an integral picture of EVPSC development. This limitation makes it difficult to direct the holistic perspective development of the EVPSC.

To examine the EVPSC development process in order to portray a reasonable and instructive path for EVPSC development, a systematic analysis is conducted within the framework of the business model theory, in the following sections of this article. Section 2 introduces basic knowledge about business model theory as the theoretical framework of analyzing the EVPSC business model, based upon which model theory, the EVPSC is categorized into either charging service supply chain (CSSC), discharging service supply chain (DSSC), or both. In Section 3, the EVPSC development process is broken into three phases according to differences in the external environments in which the EVPSC is implemented. The business models in each of the three phases are analyzed in terms of their business content, business structure, and coordination mode. On the basis of these analyses, Section 4 presents a rational evolutionary path for the development of the EVPSC, showing the dynamic interaction between the phases. In Sections 5 and 6, relevant discussion and conclusion are presented. Through the above systematic analysis, this research makes the following three contributions: 1) identifying the development phases of EVPSC; 2) identifying EVPSC business models for the different implementing phases; and, 3) portraying a holistic evolutionary path for the EVPSC.

2. Basic business model of the EVPSC

2.1 Basic business model

The core objective of an organization's business model is to fulfill its customers' needs while generating profits for its stakeholders. The process of establishing a business model can be viewed as an organic combination of human, physical and capital resources for satisfying a specific business purpose, while taking into consideration the internal and external environments in which it will be implemented [13]. Generally, the implementing environments include all the uncontrollable factors related to the business model (e.g., the scientific and technological levels and social cognition level related to the EVPSC) [14]. Based upon the environments, the main body of a business model, i.e., the business content, business structure, and business coordination mode, are designed and constructed [15]. Here, business content refers to the main services provided to consumers; the business structure refers to the interactive relationship among the relevant stakeholders, and; the business coordination mode is the way of making all stakeholders' interest compatible [13].

Because of the dependent relationship between business models and implementing environments, a business model usually changes with its external implementing environments [16][17][18]. In a relatively static implementing environment, a business model tends to stay in a locked-in state, in which its relevant stakeholders have little motivation to innovate the business model [19][20]. However, when a significant change of the environments occurs, especially when there is an opportunity to gain new benefits for stakeholders through adaptation, the business model will be changed [21], as demonstrated in Figure 1. From a dynamic point of view, altering the business model's implementing environment will lead to changing of the original interest balance of the business model. In this circumstance, a new value opportunity could surface. In order to capture the opportunity, the business content redesigned is required, which usually gives rise to a series of related investments, particularly for the core resources in the future business model [22]. When this occurs, those that hold the core resource possess the advantage in the relationship-remodeling process. This process occurs regularly in businesses driven by technological change, for example during the current revolution of the 5G business model [23][24].

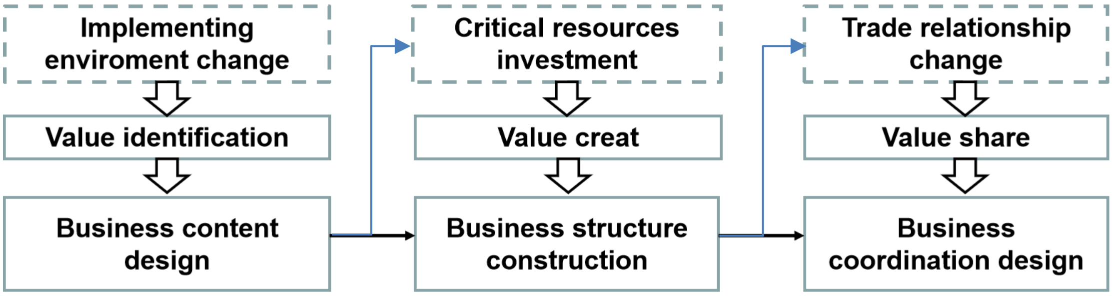


Figure 1. Process of business model adaptation motivated by changing environmental conditions

2.2 EV charging and discharging: CSSC and DSSC

The EVPSC, the power supply chain connecting EVs with EPSC, can be classified as the charging service supply chain (CSSC) or the discharging service supply chain (DSSC). Table 1 summarizes the business content, consumer, core resources, and coordination mode for both CSCC and DSSC. As shown in Table 1, the business content of CSSC is satisfying the charging demand of EVs through the construction of charging points and the selection of proper charging modes (e.g., fast charging mode or slow charging mode), while the business content of DSSC is aimed at dispatching electricity from EVs back to the gird in order to improve the operational state of EPSC. In terms of the core resources, the charging points and charging service capacity of the EVPSC are the core resources for CSSC, while for the DSSC, its core resources are the EVs willing to participate in the discharging service and the available control schemes and equipment [25].

Table 1. Main components of EVPSC business model

Features	CSSC	DSSC
Consumer	EVs	EPSC
Business service content	Fast Charging	Load management

	Slow charging	Power quality improvement
		Power regulation
Core resource	Charging point	EVs as service providers
	Power capacity	Relevant control equipment
Coordination mode	Charging price	Charging/discharging price
	Charging contract	Charging/discharging contract

The primary difference between CSSC and DSSC lies in their business structures. As shown in Figure 2, in the CSSC model, EVs are the objects of charging services, but in the DSSC model, they turn into the providers of ancillary services through discharging of EVs to EPSC [26][27]. Within both supply chains, the EV charging facility operators (CFOs) play an important intermediary role. In the CSSC model, CFOs are responsible for charging EVs, while in the DSSC model their duty transits to controlling the charging and discharging of EVs. In terms of coordination, as shown in Table 1, the main duty of CFOs in the CSSC is creating charging price tactics to affect the EV users' charging choices. In the DSSC, the CFOs duty becomes creating and implementing suitable management schemes that encourage the EV users to actively participate [28]. Otherwise, many features overlap between CSSC and DSSC. For example, the upper-stream supply chains of the two modes are both EPSC, and their operations are both directly influenced by the operational status of EPSC, and in particular by the operational state of the distribution grid. However, when comparing CSSC and DSSC, the EPSC fulfills distinctly different roles: it serves as the supplier of power in the CSSC but becomes the receiver of EV discharging services in DSSC.

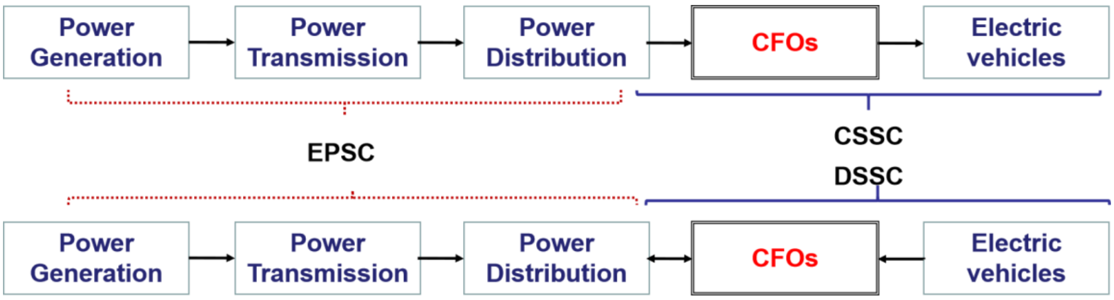


Figure 2. Business structure of CSSC and DSSC

3.Business model evolution of the EVPSC

3.1 Phases of development of the EVPSC

In terms of the order of occurrence of EVPSC services, CSSC emerges earlier than DSSC because charging EVs by the CSSC is the first requirement of EVPSC when EVs are introduced. The formation of the DSSC depends on the scale of EV uptake and the continued development of the whole power system (i.e., the EPSC). Thus, to some degree, along with the development of EVs and the EPSC, the business model of the EVPSC will evolve from CSSC to DSSC. As illustrated in Figure 3, EVs′ social uptake rate and the degree of intelligence of the EPSC constitute the external environment for the development of EVPSC. In this study, we assume that the development track of EVs, like other new high-tech products, follows an s-shaped development curve [29][30], during which the intelligence degree of the EPSC develops in response to the increasing impact of EV charging, thereby the EVPSC evolves [31][32]. Based on the uptake rate of EVs and the development level of EPSC, the EVPSC development trajectory can be divided into three phases as presented in Figure 3. The three phases are detailed as follows.

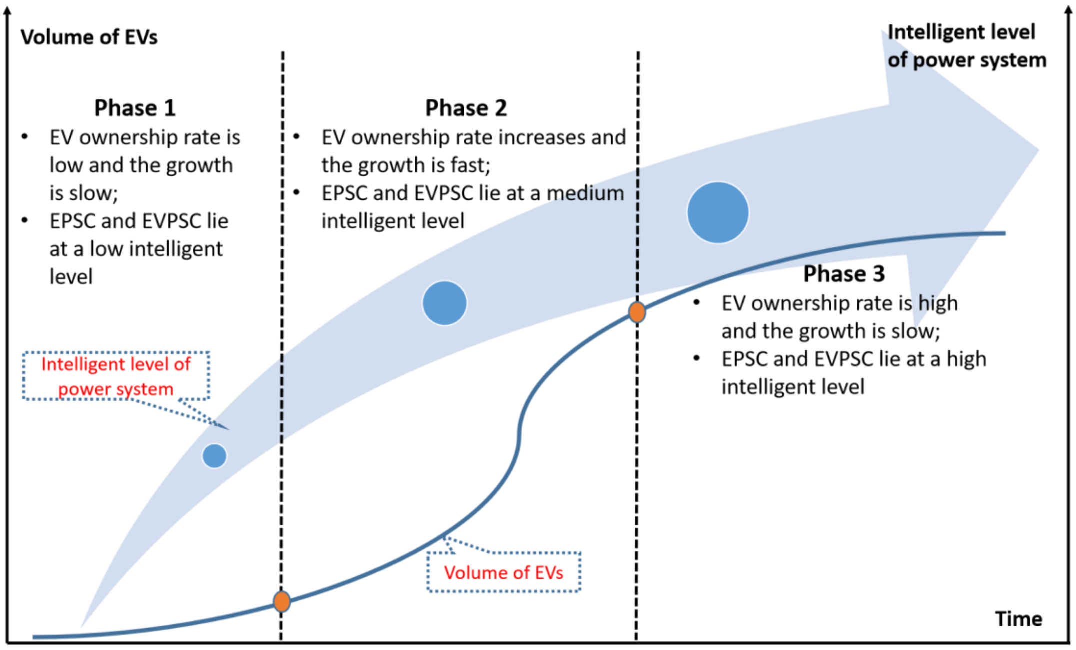


Figure 3. Co-evolution of discharging services and the electric power grid

Phase 1: In the early period of EV development, due to the technological barriers (e.g., EV battery technology) and the lack of relevant social cognition, the uptake rate of EVs is small, leading to little impact of EV charging on the EPSC [5]. Also, since a low penetration of EVs, it is hard to aggregate enough EVs to provide discharging services. Therefore, in this period, the main mode of the EVPSC is CSSC, and the business content is to provide charging services for limited numbers of EVs and to cultivate the EV market.

Phase 2: Thanks to the breakthrough of key EV technologies and ongoing government support, EVs transition into a fast-development phase [33]. In this phase, there are two tasks for the EVPSC: building more charging points to deal with the surging EV charging demand, and designing proper management schemes to mitigate the pressure of EV charging on the EPSC. One additional task is upgrading the intelligent control of the EVPSC that considers the operational condition of the EPSC [34]. Controlling EV charging and discharging is perceived as the main approach in this phase, thus it is characterized by both CSSC and DSSC [35].

Phase 3: When the ownership rate of EVs is high and the EPSC enters a higher level of intelligence, more complex EVPSC services can be realized [36] where providing EVPSC services would become a social norm for EV users [37]. Meanwhile, the interactions among EVs, the EVPSC, and the EPSC would become more frequent, flexible, and seamless. The vision for this phase is the ideal situation in the smart grid era [38][39].

3.2 Business model of EVPSC in Phase 1

3.2.1 Phase 1 business content

The state of EV development across the world is currently in its primitive stage, where the majority of countries push ahead EV development, ambitiously hoping to decarbonize their road transportation and guaranteeing the worldwide energy security [40]. During this process, as the key supporting resource for EVs, enough charging points are necessary for wide social acceptance of EVs [41][42]. In alignment with social goals, the main business content of the EVPSC in Phase 1 is to provide charging services for EVs. Therefore, in this phase, the core resource is charging facilities.

3.2.2 Phase 1 business structure

Due to the core resource status of charging facilities in Phase 1, stakeholders with investments in charging facilities, especially owners of parking lots, will have a critical influence on the establishment of the business model of the EVPSC [43]. Different parking lot owners will build different EVPSC models, becoming charging facilities operators (CFOs). As illustrated in Figure 4, according to the property-right characteristics of charging places, the charging facilities owned by different CFOs can be classified into four types: commercial charging facilities (CCFs), affiliated charging facilities (ACFs), public charging facilities (PCFs), and home charging facilities (HCFs) [44][45][46][47]. CCFs refer to dedicated charging facilities that are invested for profit. ACFs are the chargers built into commercial centers and office buildings so as to enhance their clients' charging convenience. PCFs refer to the public charging facilities invested by the government or utilities. HCFs refer to the charging facilities equipped in the home of EV users. All these charging facilities constitute a charging network.

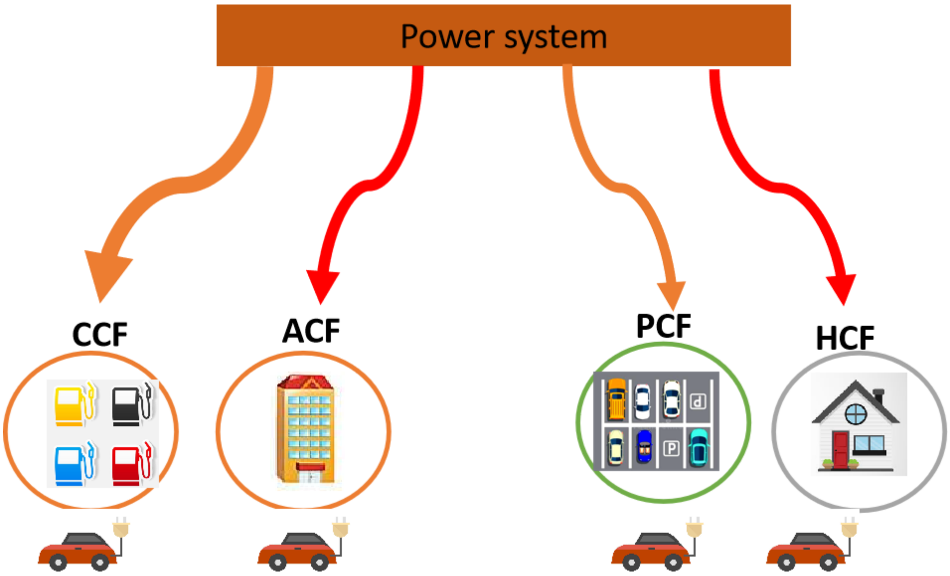


Figure 4. Business structure charging services in Phase 1

Because the investment motivation for different charging facilities is different, the operational goals of their CFOs are different as well. As summarized in Table 2, (i) the goal of CCFs' CFOs is to make profits only; (ii) the ACFs' goal is to provide charging services to enhance the welfare of their clients who own EVs, thereby promoting the attraction of the whole commercial area; (iii) the PCFs' goal, in line with the goal of the government, is to increase the charging convenience and then advance the social take-up of EVs; and (iv) HCFs' goal is to satisfy the EV owners' charging need.

Table 2. Comparison of CSSC and DSSC

Charging facility type	Goal
CCF	Profit from the EV charging business
ACF	Increase the overall value of the areas or buildings
PCF	Promote the EV charging convenience
HCF	Charging private EVs

3.2.3 Phase 1 coordination mode

Supplying sufficient charging facilities is a key issue in Phase 1. However, in view of the current state of charging facility deployment, due to the limited scale of EVs and the corresponding investment risk for charging facilities, many investors are not motivated to invest in charging facilities, except for EV users and relevant governments [48]. To this end, Haustein and Jensen [49] noted that in the early stages of EV development, it will be difficult for investors to make a profit from investing charging infrastructures because of the high initial investment, low utilization rate and the lower-than-expected recovery rate, which discourages the investors from engaging in the construction of charging infrastructures. On the other hand, the direct outcome of inadequate EV charging facilities is the diminishing of the market acceptance rate of EVs.

To overcome this dilemma, researchers have suggested that establishing a charging network in advance is important for increasing the confidence of EV buyers and reducing the "range anxiety" of the EV owners [50][51]. Indeed, it has been observed that an adequate number of charging facilities is a prerequisite for EV development [52][53]. At this stage, incentives from the government, particularly for charging facilities, are viewed as pivotal in overcoming the substantial cost gap that exists between EVs and ICVs, as well as to conquer the early-adopter disadvantage that characterized the development of alternative fuel infrastructures [54][55][56]. Narassimhan E and Johnson C found that after quantifying the relationship between supporting the public charging infrastructures and EV adoption in the United States, that early investment in charging infrastructure was likely to increase EV adoption [57]. A similar conclusion was reached in Canada [58] and Europe [59], and other areas as summarized in Table 3.

Table 3. Example policies supporting EV charging facilities in several countries.

China	It is mandated that 100% of parking spaces of new commercial buildings, 10% of residential communities and 10% of public parking places should be built with EV charging facilities; at least one public charging station should be built for every 2,000 EVs [60]. Additionally, encourage social sectors to participate public-private partnership (PPP) projects of EV charging facilities [61].

Germany	From 2007 to 2020, the government plans to invest 300 million euros to build 15,000 charging piles to meet its EV development goal [62].
France	The French government plans to construct 100,000 charging stations by 2020 [63], and invest 1.5 billion mainly in EV charging infrastructure [64].
United Kingdom	A total of £1billion is invested in a pilot project to build a solar-powered car charging network [65]. Besides, the government has set up a £400 million investment fund for charging infrastructure to deploy charging stations independently [66].
Sweden	In 2015, the government introduced two investment support schemes (Climate Leap and Urban Environment Agreements) aiming to facilitate charging infrastructure, which in 2016 was influential to the development. Additionally, Sweden is also experimenting with the world's first electrified road for charging EVs [67].
Finland	The Finnish government invested 5 million euros in 2017 to build at least 800 public charging points for EVs [68].
USA	The federal government provides tax credits of up to $2,000 for each home charging pile built (half the cost of buying and installing a home charging pile) and up to $50,000 for each commercial charging facility. In addition, some states have developed additional tax exemptions or subsidies based on local levels of EV development [69].
Japan	Japan plans to build 5,000 quick-charging stations and 2 million home charging devices for EVs by 2020 [70]. To attain the goal, a fiscal subsidy of 100.5 billion yen will be provided for electric vehicle charging facilities [71].
Korea	EV Charging facilities in public locations such as apartment complexes, restaurants, and cafés, have been supported by the government [72].

3.3 Business model of EVPSC in Phase 2

3.3.1 Phase 2 business content

With the progress of the key EV technologies like battery packs [73][74], the development of EVPSC will enter the second phase. In this phase, the market volume of EVs will grow rapidly, and the high penetration of EVs into the network will bring a series of challenges to the EPSC such as power shortage, transformer, and cable thermal impacts, voltage violation of statutory steady-state limits, and increase in the losses, particularly at the time of peak demand [75][76][77]. In order to avoid the risks coming from the surge of EVs charging load, appropriate optimal planning and management strategies are suggested. For example, to control the charging or discharging power of EVs, the use of intelligent power-controlling units is suggested by many studies. Some of these studies contended that with charging and discharging control, not only can EV charging requirements be satisfied, but the stable operation of the local power grid can also be satisfied. Discharging to the gird to support the EPSC is central to the DSSC model. Controllable energy storage, whether mobile in EVs or non-moblie in buildings can be discharged to the grid, i.e., vehicle-to-grid (V2G) models and vehicle-to-building (V2B) models [78][79]. Thus, in Phase 2, the managed EVs charging and discharging services like V2G or V2B constitute the main business content of the EVPSC, as summarized in Table 4

Table 4. Business content of Phase 2

Services	**Service contents**	**Coordination mode**
Common charging service	Uncontrolled charging	Charging price
Controlled charging service	Controlling the EV charging power	Controlled charging service contract
V2B (vehicle-to-building) services	Controlling the EV charging/discharging power to the building	V2B service contract
V2G (vehicle-to-grid) services	Controlling the EV charging/discharging power-to-grid	V2G service contract

3.3.2 Phase 2 business structure

In this phase, EVs play dual roles, i.e., power consumers when being charged in an uncontrolled way, and power service suppliers when being charged/discharged in a controlled manner to provide ancillary services for local EPSC. Some researchers have tested the effectiveness and economy of the implementing scenarios where EVs act as ancillary services providers. For example, Després J et al. concluded that compared to other electricity storage options such as standalone batteries, compressed air energy storage, or pumped hydro, using EVs as storage equipment will be more economical and efficient if controlled properly [80]. Moreover, a study focused on the United States concluded that ancillary services from EVs could provide economic benefits up to $12 billion per year [81]. Similarly, a study focused on ancillary service markets trading was conducted for validating the feasibility of V2G services in the United Kingdom context, arguing that there would be an individual vehicle net present value of ~£8400 [82].

For realizing the expected development in Phase 2, some adjustments will be undertaken by CFOs [83][84][85]. However, for different CFOs, their business adjustments are different, especially for CCFs and ACFs. For CCFs, to cope with the surging charging demand of EVs and to avoid the high electricity prices coming from the grid in some periods, installing a storage system is usually suggested [86][87]. Local storage would permit the CCF operators to continue to provide charging services at a moderate price by avoiding the need to purchase electricity when the price is high. Furthermore, extra benefits could be obtained through exporting the excess electricity back into the EPSC [11][88]. To ACF operators, because their main business is not providing charging services for EVs but guaranteeing the power supply of their buildings or areas to be stable and economic, making EV charging subject to the local power system control through installing charging control devices will be a logical choice [89][90][91]. Taking V2B as an example. Odkhuu N et al. indicated the negative impact of EV charging on the operation of a building energy system could be minimized [92]. A similar concept, vehicle-to-home (V2H) is put forward to coordinate EV charging and household power consumption, which is possible when using upgraded HCFs [93][94][95]. In addition, as shown in Figure 5, by virtue of their large car parking lots, PCF operators could work with or act as an aggregator of EV loads to earn profits in providing ancillary service through aggregating and controlling charging of parked EVs [96][97].

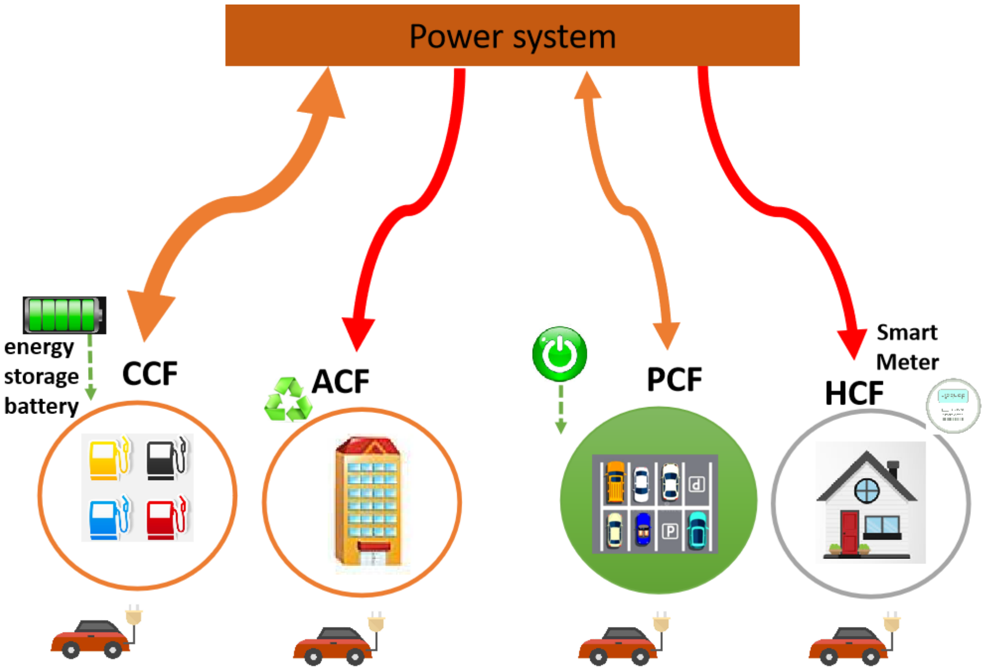


Figure 5. Business structure of Phase 2

3.3.3 Phase 2 coordination mode

The coordination mode of the EVPSC business structure in Phase 2 is categorized into two types: price coordination mode and contract coordination mode. As illustrated in Table 4 and Figure 6, in price coordination mode some of the charging service providers, such as CCF operators, may adopt different electricity pricing strategies to shift the charging choices of EV users to the periods of low electricity prices, thereby reducing their operating cost [98][99]. Other charging service providers such as ACF operators could contract with EV users for control rights of their EV charging/discharging so as to participate in the ancillary services trade to obtain benefits, or to minimize their operation cost [100][101]. PCF operators who have the capacity to offer V2G/V2B services could choose a combination coordination strategy to obtain a high-quality charging/discharging performance and larger profit space, in which the charging/discharging service prices and service times are set in advance [102]. HCF operators are usually the EV users per se, so their charging behaviors are related to the electricity prices and to what is convenient [103].

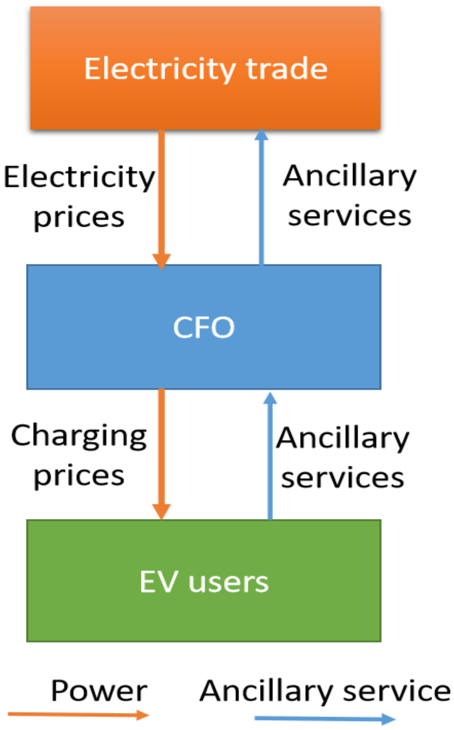


Figure 6. Business structure and coordination mode of Phase 3

3.4 Business model of EVPSC in Phase 3

3.4.1 Phase 3 business content

The salient characteristics of the Phase 3 EVPSC are the overall intellectualization in terms of technology [104][105], and the decentralization in terms of the organization [106], along with the maximization of EV penetration. For this phase, many researchers think that due to the optimal integration of EVs with other distributed energy resources (DERs), EVPSC would consist of many microgrids [107][108], in which each microgrid is independent and responsible for managing or coordinating its various DERs or CFOs, and meanwhile interacting with other entities of EPSC based on peer-to-peer (P2P) trading platforms [109][110][111], as illustrated in Figure 7. In the vision of Figure 7, microgrid operators are in charge of managing the power production and demand within the microgrid while interacting with the EPSC. EVs become one of the basic elements to be managed in the microgrid ecosystem [112][113][114]. Thus, in Phase 3, the business content of EVPSC will transform into a vehicle-to-microgrid (V2M) model.

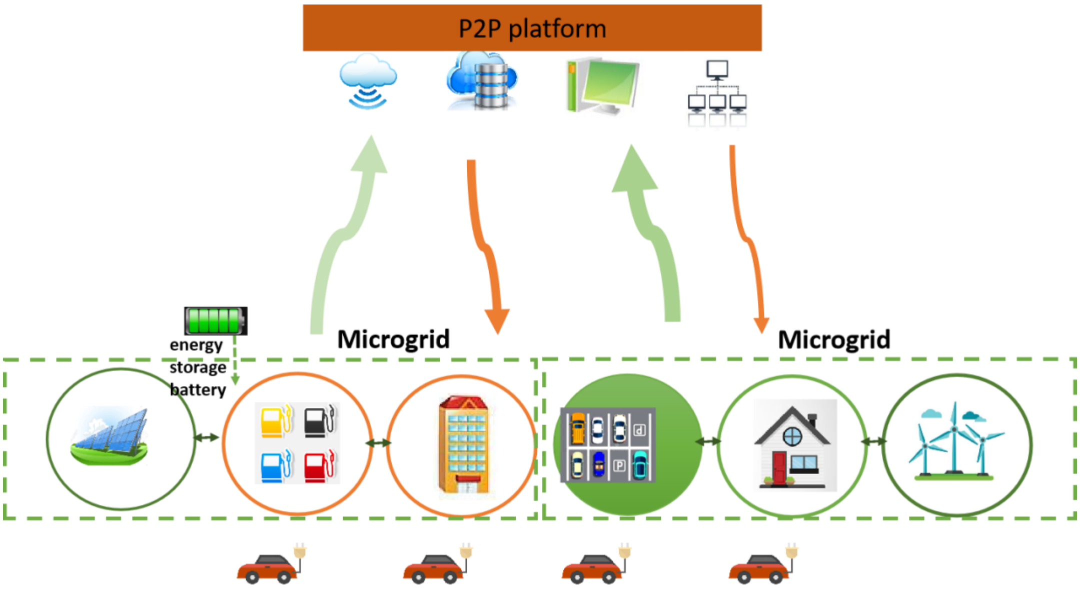


Figure 7. Business structure of Phase 3

3.4.2 Phase 3 business structure

As discussed in Section 3.4.1, compared with Phases 1 and 2, in Phase 3 EVPSC will be integrated into the V2M model, in which the ultimate goal of a microgrid will rest in the operational benefit maximization through managing the electricity units (including DERs, various types of consumers, EVs) [115]. Although as demonstrated in Figure 7 the whole EVPSC includes diverse microgrids with different entities within them, the core function of EVPSCs is to minimize its operational cost and maximize the benefits from trading with other counterparts or upper-level EPSC. In all types of microgrids, EVs will play an important role because of the characteristic of mobile storage. However, due to the full penetration of intelligent devices, in this phase management of EVs will be much more autonomous, flexible and smarter. For example, as illustrated in Figure 8, with the assistance of intelligent technologies utilizing big data and cloud computing, management of EV charging/discharging would be more economical and efficient via online monitoring and control. In this phase, EVs are envisioned to be much more autonomous due to the maturation of related technologies and the full deployment of assistant infrastructures. Thus, management and coordination of EVs within the EVPSC structure will become more convenient and seamless [116]. Based on the comprehensive intellectualization of both EVPSC and transport system, capabilities such as plug-and-play services for EVs, not possible in Phases 1 and 2, can be realized [117][118][119].

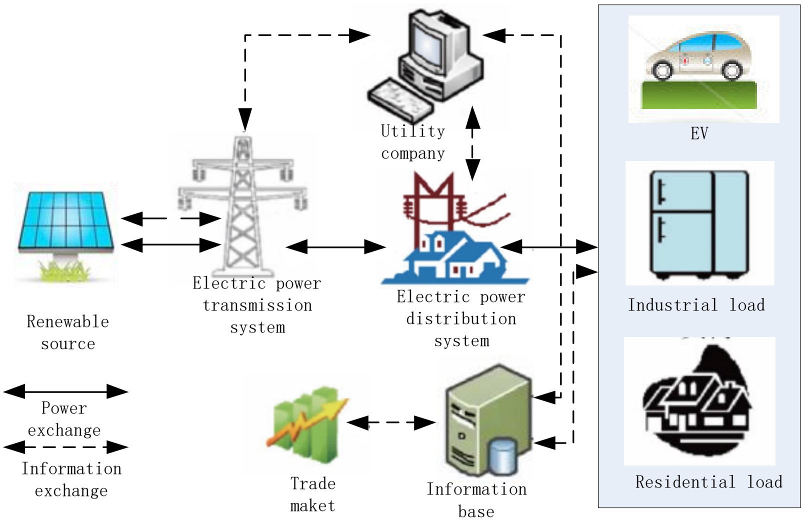


Figure 8. Management of microgrid in Phase 3

3.4.3 Phase 3 coordination mode

Thanks to the high level of intelligence and automatization, in this phase, the cost of both communicating and controlling EVs would be lower than that in other phases. Smart devices and sensors are installed and ubiquitous throughout the power system. In this smart operation environment, the interactions between all the parties are becoming very convenient. EV users are familiar with V2G services and more consumers are actively taking part in demand-side management services or other service programs due to less investment risk. All these positive conditions support efficient coordination between EV users, microgrid operators, and the EPSC. For example, using blockchain technology, EV users could trade with microgrid operators directly without any mediators such as aggregators [120][121].

As illustrated in Figure 9, in the Phase 3 coordination mode, microgrid operators interact with select EV users, or aggregators that act on their behalf, who bid for charging/discharging services based upon their biding information and historical performance [5][26][27]. Once contracts are made, the energy management system of a microgrid will control the EVs according to the operational state of the microgrid. This trading process will be fully automated, depending on machine-to-machine (M2M) communication [122][123]. Microgrid operators could trade with other microgrids or generators in the wholesale electricity market [124]. The process of microgrid operation could be divided into tri-level optimization problems normally: internal operation optimization, external operation optimization, and overall operation optimization. The tri-level optimization problems could be solved by developing optimization functions for market participants' payoff or cost with respect to their technical constraints and concomitant uncertainties [125].

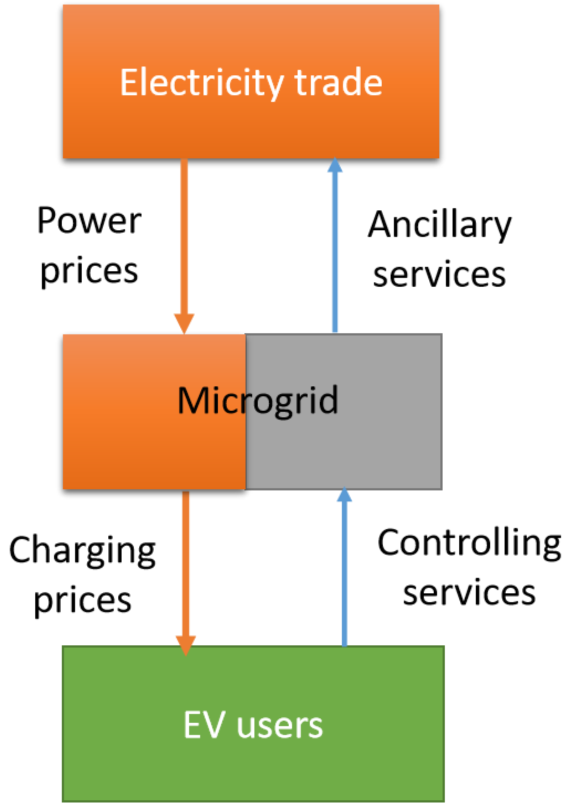


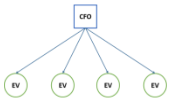
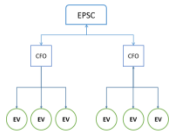
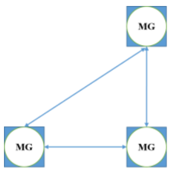
Figure 9. Business structure and coordination mode of Phase 3

4. EVPSC development roadmap

The development of the EVPSC was envisioned herein to occur in three phases. In the first phase, with a relatively small number of EVs and charging stations, the business content is the provision of EV charging services using existing power system infrastructure and business mechanisms. As EVs become more cost-effective and charging stations more readily available, the adoption of EVs will increase dramatically, following the "s-curve" observed in the development of other new technologies. This rapid increase in the adoption of EVs is considered in the second phase, where EVs will interact in the power system both through charging and discharging, allowing both EV owners and the electric grid to benefit from the charging needs and capabilities of EVs. New business models will arise to take advantage of emergent communications technologies and data analytics. For example, "aggregators" contracting with large numbers of EV owners will minimize charging costs by optimizing charging times to coincide with low electricity prices, and by scheduling charging and discharging of EVs in order to provide grid ancillary services. In the third phase, EVs are assumed to be the dominant mode of transportation with an established EVPSC. In this phase, the grid is assumed to have further evolved into intelligent microgrids enabled with advanced communications and data technologies. These technologies will allow microgrid operators to optimize their electrical service and economic use of EVs, as well as contribute toward the optimization and reliability of the overall electrical grid. This will be possible because new business models enabled by the implementation of advanced technologies will permit vehicles, homes, and companies to be interactive in the microgrids, and for the microgrids to be interactive between themselves. Because of the interdependent relationships between business models and implementing environments, business models will change as external implementing environments change. When changes occur, especially as new opportunities for gaining benefits arise, business models will change. Thus, there will be a dynamic interaction between the three phases of development.

Starting with the perspective that transitioning to EVs from ICVs is crucial for addressing environmental and energy concerns, and with the acknowledgment that EVs are more energy-efficient and will in the near future become more cost-effective, it is necessary to chart a path for the development of the EVPSC for this transition to EVs. The EVPSC is nascent and in its preliminary phase, thus to devise appropriate policies in support of this transition it is necessary to understand its development path, which can be projected based upon the previous discussion. Table 5 summarizes the business content structure and coordination mode for each of the three phases described, along with the key participants, internal and external factors. As illustrated in Figure 10, the dynamic interaction between EVs and the EVPSC forms the whole development process of the EVPSC. In the initial phase (Phase 1), to promote the diffusion of EVs and initiate the market potential of EV charging, EVs are actively promoted by many countries and cities. In this phase, a primary factor is whether or not to construct a convenient and economic EV charging network. To achieve this, governments can provide incentive measures to guarantee benefits to charging-facility owners, investors, and operators, to encourage their participation in charging network construction. As a consequence, the social acceptance rate of EVs will progressively increase. Incentives should be focused on all categories of charging facilities: CCFs, ACFs, PCFs, and HCFs, because these are the starting points for the evolution of the EVPSC into the future.

Table 5. Summary of the EVPSC phases of development

	Business content	Business structure	Coordination mode	Key participant	External factors	Internal factors
Phase 1	Provision of charging services		Charging network construction	CFOs	Environmental and resource crisis	Satisfying EVs charging demand
Phase 2	Provision of controllable charging/ discharging services		Charging prices and discharging services contract design	CFOs (Aggregators)	EVs booming development	Mitigating the pressure of EVs' charging
Phase 3	Provision of automatic charging/ discharging services		Sophisticated trading measures	Microgrid operators	Realization of smart grid	Exploiting the potential value of EVs for both EV owners and the microgrid

EV represents EV; CFO represents CFO; EPSC represents EPSC; MG represents microgrid.

With the breakout of key EV technologies, EVs will move into the fast development phase (Phase 2 in Figure 10), in which the uncoordinated charging load will impact power system operations, potentially causing serious problems such as power shortages, increased peak loads, increased ramping, and instability of grid operation. To cope with these issues, EPSC costs can be managed with price and/or contract coordination, such as time-of-use electricity rates, that would be transferred to its downstream stakeholders and ultimately to its EV users. Based upon the cost or potential benefits, some CFOs (e.g., operators of CCFs, ACFs, and PCFs), will enhance their EV charging and discharging capabilities through upgrading relevant charging devices and implementing corresponding price tactics. These adjustments will transform their business models from the original CSSC model to the DSSC model, and the CFOs will not only manage the EV charging demand but also interact with the EPSC, reshaping their business structures. For EV users, Phase 2 will provide opportunities to share the management rights of their vehicles with CFOs for obtaining revenues or avoiding high charging costs during certain periods.

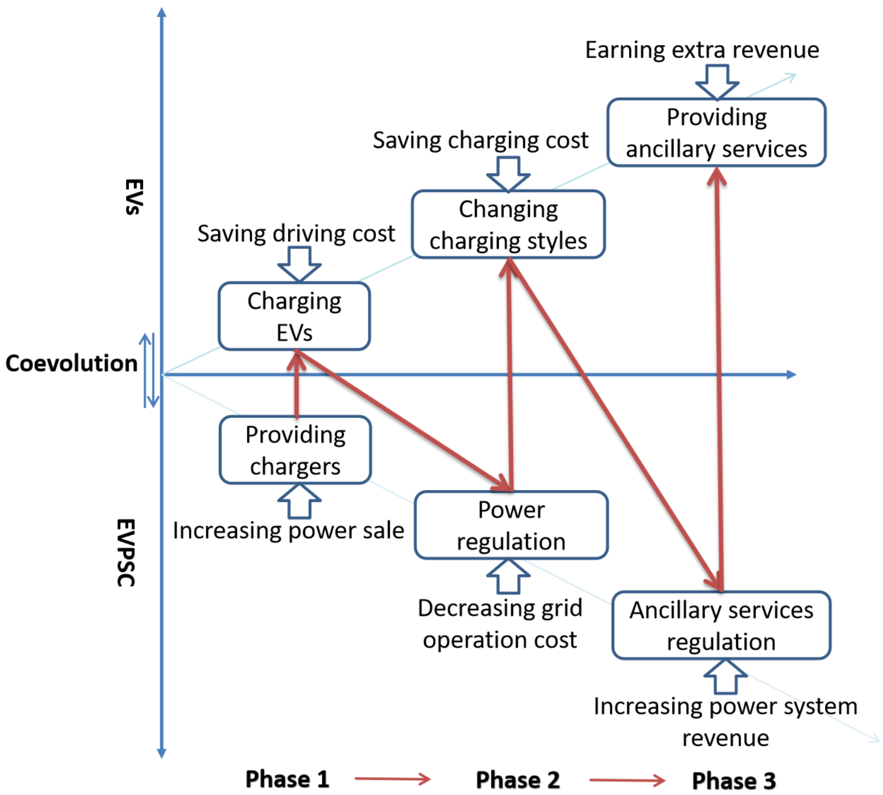


Figure 10. Development path of the EVPSC

With high adoption of EVs during Phase 2, continuous development of EV technology, infrastructure and intelligent upgrading of the EPSC, the EVPSC would move into Phase 3. The core characteristic of the EVPSC in Phase 3 is the intellectualization of the whole service supply chain and the decentralization of its organization, as shown in Table 5. In this phase, the traditional power system would be segmented and restructured by the microgrids, which become basic operational units in the EPSC along with the high-voltage transmission system and large power stations, integrating the relatively independent entities of the previous two phases such as DERs and CFOs. Advances in communications and informatics, controlling equipment, demand-side management, and supporting management schemes will enable the transition to Phase 3 [126]. Advanced technologies such as blockchain, big data analytics, and secure and fast communications will permit microgrid operators to interact with all entities in their jurisdictions, allowing for the efficient and cost-effective use of resources, extending beyond any single microgrid to the entire EPSC. For example, a microgrid operator could profit from controlling EV charging/discharging to absorb excess electricity from DERs or to provide services for other microgrids. Moreover, many actors in the market will lead to competition, innovation, and more efficient use of resources. As for EV users, the vision of plug-and-play services would be realized, making it convenient for EV users to participate in charging/discharging services, unlike during Phase 2.

5. Discussion

The business model framework for the development of the EVPSC outlined in this study is valuable to stakeholders in EV charging services, and to all people interested in society's decarbonization of transportation. To create coherent policies leading to a sensible transition away from ICVs and to EVs, a clear roadmap of the evolution of the EVSPC is needed. The information presented here provides such a roadmap, but there are limitations due to the complexity of the businesses and organizations involved in both the transportation and the electric power sectors, their governance, and their roles in evolving the EVPSC. For example, although the development of the EVPSC can be divided into three phases according to their external and internal features, this does not mean that the EVPSC development would be carried out synchronously. In practice, the promotion rate of EVs and the actual situation of the EPSC in each country or area is distinct [127][128], and this will lead to differences in detailed EVPSC development plans in different areas. These differences are evident in recent pilot projects carried out in different countries. For instance, starting in 2019, the state of Maryland in the United States initiated a five-year pilot project that attempts to promote charging station network development in support of EVs adoption [129]. Otherwise, as the leader of the U.S. in EV adoption, California launched a set of pilot projects in 2018, which are more niche-targeted than in Maryland due to their different development levels of EVs. California targeted school buses, heavy-duty fleets, and private cars with their projects [130]. Also in California, the U.S. Department of Defense is currently (as of 2013) testing the use of 20 personal vehicles to provide discharging services, in support of renewable energy integration and to provide ancillary services at a Los Angeles Air Force Base [131].

As a key component relevant to EV development, not only will the EVPSC directly impact the social penetration of EVs, but it will, in turn, be influenced by the EVs. In this study, the effect of future vehicle ownership models is not considered, e.g., the potential impact of sharing EVs is not considered. However, sharing EVs, as one evolving transport model, has shown strong momentum in some regions [40][132][133]. The reasons for its successes is business model innovation, such as the one-stop solution for those difficulties that hinder the current EVs adoption like high purchase cost and charging inconvenience. This change may partially affect the development model of EVPSC. For example, considering uniform management of sharing EVs, Biondi et al. [134] suggested that since charging of shared EVs differs from private EVs, a suitable charging station layout may need to be designed. Freund et al. [135] proposed an agent-based scheduling and energy management system suitable for a shared EV fleet, in which distributed energy storage systems can coordinate the generation of DERs and charging of EVs. Iacobucci and Bruno [136] considered the autonomous sharing of EVs in the context of a smart grid and put forth a methodology for the joint optimization of vehicle charging, V2G services, and fleet rebalancing in mobility systems. Nevertheless, as the model of sharing EVs is still in an embryonic stage, the discussion on its impacts on EVPSC is limited. This issue will be one of our future research directions.

Due to the dependence of the EVPSC development on its external implementing environments, some changes in the environment will alter the whole development trajectory of the EVPSC as described in Section 4, even leading leap-frogging some business models. For example, the vision of Phase 3 might come true earlier when the internet of things (IoT) and other related technologies such as big data technology are deployed before the full penetration of EVs [137]. By contrast, the development of the EVPSC may slow down or even stop if some negative factors appear. For example, King and Webber [138] noted that the increasing electricity consumption due to the transition from ICVs to EVs could cause negative impacts on water availability, especially for fossil fuel and nuclear power plants, which dominate the electricity generation sector and require large amounts of water for the production of steam and for cooling processes although it is mostly nonconsumptive water use. Furthermore, the

EV manufacturing process can be polluting, and it also involves the mining of rare earth minerals and other elements (for batteries, drivetrains, and components) that do have environmental costs [139]. These ripple effects might make some regions, especially arid regions, reconsider their transport electrification strategies. Therefore, a set of comprehensive solutions should be addressed in future studies, not only to take into account the positive effects associated with EVs and EVPSC, but also to consider the possible negative effects.

6. Conclusion

One anticipated pathway in society's decarbonization is the electrification of the transportation sector. From a power system perspective, transitioning to EVs presages many impacts, both positive and negative. To avoid the negative impacts and exploit the potential benefits, it is necessary to examine the development process of the EVPSC in order to portray a reasonable and instructive path for its development. This study utilized business model theory and a review of the existing literature to portray a development path for the EVPSC, in which the business models of the EVPSC were analyzed and discussed for the three phases identified. Relating the dynamic interaction between business models and development phases provides insight into the content of the EVPSC. Such insight is necessary for developing coherent policies and institutional supports to foster efficient development of the EVPSC. This research provides a new perspective on EVPSC development, answers the core question on how to realize the coordinated development between EVs and the EPSC based on the model of EVPSC, and provides recommendations on the establishment of business models for the future EVPSC.

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