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Top-down sustainability transitions in action: How do incumbent actors drive electric mobility diffusion in China, Japan, and California?

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ABSTRACT

In explaining how socio-technical transitions occur, prevailing theories focus on bottom-up processes driven by new entrants, diverse actors and open-ended exploration in small, protected niches. Incumbent firms are frequently portrayed as hampering change, while managerial strategies using traditional public policy instruments remain understudied. Addressing this bias, we examine strategies used by networks of incumbent state and industry actors in China, Japan and California to accelerate the production and diffusion of battery-electric or hydrogen-powered vehicles. We build a comprehensive framework that systematically marries mechanisms of industrial transformation described in developmental-state literature with theories of socio-technical change from transitions scholarship. We then use a vast dataset of secondary documents and interviews to examine the principal strategies employed in each country, identifying variations over two phases of technological diffusion. Findings reveal that the incumbent actor networks in each country have collectively employed multiple but similar strategies. Yet closer inspection of specific policy instruments, such as regulations and performance-based incentives, along with ambitions to phase out vehicles with internal combustion engines, reveals differences across cases. We explain these by considering different motivations for each country's transition and influencing socio-political conditions. Our study contributes to the enrichment of future transitions research in at least two ways. Theoretically, by integrating literature on transitions and developmental states, we deepen understanding of how incumbent state and market actors can attempt to drive socio-technical change. Empirically, our analysis provides important evidence for understanding the strategies driving top-down transitions outside northern Europe, and the conditions affecting instrument choice.

1. Introduction

Scholars are devoting increasing attention to socio-technical transitions driven by incumbent industry and elite state actors, such as government ministries and political leaders [1,2]. With innovation activities by established firms often featuring in literature [3–5], interest is mounting in the role of state actors [6,7] and policy instruments in the pursuit of 'politically accelerated' transitions [8–10]. Scholars highlight the need for state intervention not only for spurring the creation and diffusion of new technologies and industries, but equally for hastening the decline of carbon-intensive energy systems and other environmentally harmful technologies, processes, and substances [11,12]. Thus, in addition to newcomers challenging the status quo, incumbent

government and market actors are potentially powerful drivers of socio-technical transitions [9,10,13,14].

Incumbents in government and industry typically possess vast financial, human, and intellectual capital and direct or strong influence on markets, policies, and politics [15]. This power and resources lead naturally to top-down approaches [10]. These typically involve managerial strategies built around specific objectives and timelines, highly-guided search paths, aggressive intervention in markets through regulation or economic incentives, and large-scale investments in infrastructure [16]. The strength of top-down approaches driven by powerful incumbents lies in the potential to trigger widescale socio-technical change within a short timeframe due to the concentration of resources and agency [17,18]. However, by overlooking local circumstances and

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needs while sidestepping inclusiveness for the sake of scale, speed and efficiency, top-down blueprints for change run the risk of meeting resistance from the interests they underrepresent [19,20].

The idea of top-down, highly coordinated strategies orchestrated by incumbents in government and industry contrasts with the dominant theories. Transitions scholarship has historically viewed socio-technical change as resulting organically from bottom-up approaches [21]. In this paradigm, innovation is driven by newcomer firms and inclusive governance networks linking citizens, scientists and policymakers [22–24]. These diverse actors collaborate in creative visioning and open-ended experimentation in small-scale, protected ‘niches’. Change is purported to occur during windows of opportunity, as the collective influence of ‘regimes’ (established webs of technologies, actors and institutions) is momentarily weakened by the simultaneous emergence of new technologies or business models and ‘landscape’ pressures from markets or society [12,13,16,24]. While bottom-up approaches are attractive by virtue of their inclusiveness and attachment to specific communities and needs [25], their ability to rapidly bring about wide-spread change may be sometimes limited.

Nevertheless, numerous studies by transitions scholars implicitly advocate bottom-up approaches by portraying incumbent actors as hindering innovation [15,26–28] and wedded to unsustainable socio-technical configurations and business practices. Difficulties in breaking with established practices are often seen to result from the lock-in effect of pre-existing assets, institutions, and financial or intellectual resources [29–33]. Several studies [34,35] also describe incumbent firms as actively resisting change via strategies like political lobbying, shared discourse, and renewed investment in current technologies.

Transition scholars have recently highlighted several limitations in the explanatory power of views of change biased towards bottom-up approaches [1,23,28]. First, literature has tended to overlook many instances where incumbent firms drive technological or business innovation and experimentation in protected niches [3,16,26]. Second, accounts of state actors driving transitions [6,8,10,27,36,37] and the influence of conventional policy instruments such as planning, regulation, and public investments [15,21] have received limited attention. Third, some scholars [2,38] claim that literature’s emphasis on niche-driven innovation and participatory governance reflects a normative, Western bias in socio-political conceptualisations of how socio-technical transitions occur. Moreover, not only does the emphasis on bottom-up approaches and newcomers contrast with governance norms in many non-Western settings such as Asia, but established theory is ill-suited to explaining how incumbent government and market actors have collaboratively driven socio-technical change in progressive green economies such as California, Germany, and Sweden [7,39,40].

Insights from developmental-state literature can overcome these tensions between prevailing theories and empirical exceptions. Rejecting the neoliberal idea that economic growth and innovation are best achieved in laissez-faire markets [41,42], literature on so-called ‘developmental states’ seeks to explain the causality between top-down state intervention and industrial, technological, or economic transformations [43,44]. A core goal of the development-state model is to drive economic growth through industrial policy targeted at specific sectors selected for state support [44,45]. Typically used policy instruments include long-term planning and target setting, subsidies for manufacturers, tight government–industry networks for information sharing, state-mediated collaborations across competing industries, public investments in human resources, R&D and infrastructure, and preferential treatment for domestic firms [41,46].

While this field has historically focused on catch-up-style economic development in East Asian nations like Japan, Korea, Singapore and Taiwan during the 1980s–1990s [47,48], recent scholarship has extended this theory of change to explain energy, mobility, and sustainability transitions in various Asian [17,42,49,50], Western [39,51] and developing countries [52]. The emerging field of the green

developmental state [53,54] thus provides an important opportunity to enrich transitions scholars’ understanding of governance strategies that incumbent state and market actors can use to accelerate the supply and diffusion of green technologies, infrastructure, and socio-technical systems [6,36,45].

In this context, this paper aims to build theoretical and empirical understanding into the collaborative actions that networks of incumbent actors in government and industry can play in driving socio-technical transitions. Through a triple case study, our objective is to elucidate and compare the nature of strategies collectively used by communities of incumbents in China, Japan, and California to accelerate the production and diffusion of electric mobility (either plug-in electric or hydrogen) in different socio-political settings. Using primary and secondary data sourced from academic and grey literature along with interviews, we set out to answer: What principal strategies are collectively used by the incumbent actor network in each country? How and why do these strategies change? We also briefly consider outcomes achieved and limitations of strategies in each case.

Our contribution to literature is three-fold. First, we address the growing interest in top-down transitions driven by government intervention [18,55] and discussions about ‘whether transitions can be engineered and planned from above’ [7: 7]. With scholars calling for more studies on this topic [13], our novelty lies in our detailed empirics and comparative approach. Second, we marry two fields of literature: sustainability transitions and the developmental state. While transitions scholars are increasingly interested in the latter [6,51,52], rigorous treatment of the compatible or conflicting theories in each field has lacked until now. By providing an enriched perspective on how socio-technical transitions can occur, this approach addresses calls to cross-fertilise transitions theory with other fields [15,23]. Third, the framework developed to guide our analysis provides a finer-grained picture of a potential toolkit for steering sustainability transitions than previous conceptualisations [56–59]. Incorporating both the creative and destructive dimensions of socio-technical change [12,27,60,61], our framework provides a useful heuristic that other scholars might empirically apply to deepen understanding of what strategies can be used to steer sustainability transitions and how these might vary over different phases of technological development or socio-political contexts.

Henceforth, Section 2 will synthesise literature from sustainability transitions and the developmental state into a framework of governance strategies deemed crucial for accelerating socio-technical change. Section 3 presents our study design and unpacks the methods underpinning our case analysis. Section 4 introduces the cases. Section 5 applies our framework to compare the electric mobility transition strategies of China, Japan, and California. Section 6 summarises key findings and clarifies key characteristics in each case. Finally, Section 7 identifies theoretical implications for scholarship.

2. Analytical framework: governance strategies for accelerating sustainability transitions

2.1. Overview of the literature review

For literature on sustainability transitions, we include empirical and theoretical studies from its four subfields [see 15, 62]: multi-level perspective, strategic niche management, transitions management, and technological innovation systems. Relevant studies were identified by searching Web of Science with keyword combinations¹ and examining their references and citation networks. We also consulted two policymaker reports by transition scholars [63,64]. In selecting papers for analysis, we prioritised those with explicit descriptions of strategies

¹ ‘Socio-technical’, ‘transition’, ‘governance’, ‘strategies’, ‘acceleration’, ‘manage’, ‘success’, ‘drivers’, ‘levers’, ‘conditions’, ‘sustainability’, ‘green’, ‘energy’, ‘mobility’, ‘transport’, ‘technology’, etc.

seen as important for accelerating socio-technical transitions.

For literature on the developmental state, we extracted the quintessential functions of this governance paradigm from classic works of the 1990s [41,43,44,47,48]. We then searched Web of Science with ‘developmental state’ and combinations of ‘sustainability’, ‘green’, ‘low-carbon’, ‘environment’, ‘transition’, and ‘energy’ to identify recent work from an environmental perspective. We also reviewed several studies outside this field that discuss the state’s role in environmental governance [e.g. 39].

2.2. Explanation of the framework

The resulting analytical framework appears in Table 1. This shows generic strategies and specific instruments to implement these (e.g. policies and institutional arrangements). We henceforth follow a two-layered coding system, using C1–8 to denote *categories* of strategies and S1.1–8.4 for *individual* strategies.

The listed strategies were identified both deductively and inductively. We started with articulations provided in specific studies, fine-tuning these to reflect the larger plurality of descriptions identified in both fields of literature. We acknowledge the abundance of existing frameworks that describe various tactics for accelerating socio-technical transitions [56–59,65,66]. Duly integrating this scholarship, our interest in systematically comparing the governance strategies in multiple cases required a comprehensive and higher-resolution framework than found in existent literature.

The framework consists of three broad dimensions: (i) overarching coordination strategies, (ii) targeted strategies for accelerating creation and diffusion, and (iii) targeted strategies for accelerating decline. The first refers to wide-reaching strategies related to governance and management (e.g. overarching policies, technology roadmaps, governance bodies). The other two consist of strategies addressing more specific objectives and challenges in the goal of accelerating either the creation or decline of new technology and industries.

The framework is rooted in multiple literatures. First, it covers four key dimensions of technology policy: production, demand/market creation, infrastructure, and institutions [67–69]. Second, it encompasses both the creation of new sustainable technologies and the abolishment of environmentally harmful precedents [58,60,61,70]. For this, we draw largely on Kivimaa and Kern [57], who extend the basic governance functions suggested in technology innovation systems literature [56,71]. Yet our framework distinguishes itself from previous work. It integrates strategies widely emphasised in transitions or developmental-state literature that have not featured prominently in frameworks to date. These include inclusive governance (S1.2), monitoring and disclosure (S3.2), industry protection (S5.4), removing market barriers (S6.3), and sectoral coupling (S6.4). Third, by integrating insights into industrial-change mechanisms from developmental-state scholars, we explicitly integrate supply-side measures (e.g. S5.2–5.4), which are often under-emphasised in transitions literature. In defining these strategies, we do not explicitly differentiate their suitability for top-down or bottom-up application, since they might be employed in either model [21,72].

Overall, we found that the bulk of strategies identified are seen by both fields of literature as important for accelerating socio-technical and industrial transformation. This is despite different theories of change and contrasting emphasis on variables like top-down vs bottom-up, incumbency vs inclusiveness/newcomers, open-ended experimentation vs managerial-type steering, and supply-side vs demand-side measures. However, since the emphasis placed on each strategy differs somewhat across time or the respective strand of literature, we discuss these variations below.

2.2.1. Knowledge management (C1)

Sustainability transitions and developmental-state scholars widely emphasise the importance of *knowledge dissemination* (S1.1). Frequently stressed is network creation to accelerate the identification and sharing

of technological breakthroughs, promising business and policy models and experiences accumulated by firms, knowledge producers, and government agencies. State actors are expected to play a key role by linking players and mediating across competing firms. Following Hekkert [56] and Meelen and Farla [66], we interpret this strategy as distinct but complementary to *knowledge production* (S5.3), where policy instruments such as R&D grants are more relevant.

2.2.2. Actor networks and collaboration (C2)

Inclusive governance (S2.1) is widely normalised in transitions literature based on views that participation by diverse actors is vital to developing socially relevant change strategies [73,74]. Classic literature on developmental states does not share this emphasis. Recently, however, several scholars problematise this limitation, calling for diverse social inclusion – especially for tackling environmental issues [46,53,75]. In addition, *state–industry collaboration* (S2.2) is heavily prescribed in the developmental-state model. The participatory view historically advocated by many transition scholars underemphasises the need for linking incumbent government and market actors [76]. However, multiple studies have recently shown that incumbent industry involvement has played a major role in driving historical sustainability transitions [10,16,74]. Finally, while both strands voice a need for *industry alliances* (S2.3), each perspective differs. The ‘David vs Goliath’ view in transitions scholarship [77] has heavily emphasised the need for networks of newcomer firms to increase the collective ability to overcome resistance from incumbent opponents [55]. Yet less attention is paid to encouraging collaboration across incumbent firms to increase technological capabilities. In contrast, developmental-state literature heavily emphasises the state’s role in coordinating the formation of alliances across competing incumbent firms [48,51,78].

2.2.3. Planning and commitment (C3)

Early transitions scholarship advocates for change through experimentation with open-ended visions and exploration [24]. Some recent studies, however, stress the importance of *planning and commitment* (S3.1) to influence the direction of innovation by fixing highly specific visions, goals and objectives [16,18,63]. This view concurs strongly with the managerial approach described by developmental-state scholars. Here, government targets for technology production or diffusion along with consistent long-term policy signals are seen as essential for giving confidence to technology producers to invest in new technologies and business models [41,44,49,50]. As stressed in both branches of literature, this ‘blueprint’ approach to transitions creates a need for *monitoring and disclosure* (S3.2) to enable the periodical feedback of results into policy and practice.

2.2.4. Legitimisation and advocacy (C4)

Given that new technologies often battle issues of unfamiliarity [79], transitions scholars frequently advocate the need to *influence public views* (S4.1) through outreach, education, and information dissemination [10,24]. Scholarship also underscores the need for *political lobbying* (S4.2) and advocacy coalitions aimed at boosting political support and favourable institutional arrangements and funding schemes [56]. Yet developmental-state literature places distinctly less emphasis on these strategies, likely for two reasons. First, by nature, the development-state model fosters the emergence of intimate cooperative relationships between policymakers and firms [17,80]. Second, the powerful political and marketing resources of incumbent firms and government agencies are well-suited to influencing public opinion [81].

2.2.5. Industry creation and technology production (C5)

In advocating various strategies to spur the emergence of new industries and technologies, both strands of literature emphasise *cost alteration* (S5.1) through subsidies and pricing schemes [36,41,45,54,57,82]. Primarily concerned with supply-side strategies to boost the competitiveness of technology producers [54], the

Table 1
Framework of strategies for accelerating socio-technical transitions.

Category	Strategy	Definition	Instrument examples	Transitions literature	Developmental state literature	
Overarching coordination strategies						
1. Knowledge management	1.1 Knowledge dissemination	Measures to support the broad dissemination of knowledge about the manufacturing or diffusion of new technologies (and associated policies, markets, business strategies and infrastructure, etc.).	Knowledge sharing networks, workshops and symposiums, R&D and innovation platforms, public-private organisations, technology transfer from universities or scientific institutions to industry, etc.	Hekkert, Suurs, Negro, Kuhlmann and Smits [56] Kivimaa and Kern [57] Jacobsson and Bergek [83] Sovacool and Martiskainen [74] Meelen and Farla [66] Smith, Stirling and Berkhout [65]	Öniş [41] Castells [47] MacNeil [90] Mazzucato [36] Chen and Lees [50] Swilling, Musango and Wakeford [52] Kronsell, Khan and Hildingsson [39]	
	2. Actor networks and collaboration	2.1 Inclusive governance	Measures to include diverse or new actors into decision-making and governance frameworks to ensure that diverse viewpoints and priorities are reflected in technology, business and policy initiatives.	Decision-making frameworks such as advisory or steering committees, public debates etc. that include diverse actors (e.g. new entrants, ventures, NGOs, citizen groups).	Hoogma, Kemp, Schot and Truffer [91] Sovacool and Martiskainen [74] Geels, Turnheim, Asquith, Kern and Kivimaa [63] Johnstone, Rogge, Kivimaa, Fratini, Primmer and Stirling [92] Newell and Simms [7] Fagerberg [93] Roberts, Geels, Lockwood, Newell, Schmitz, Turnheim and Jordan [13] Roberts and Geels [10] Turnheim and Geels [16] Cherp, Vinichenko, Jewell, Suzuki and Antal [14] Sovacool and Martiskainen [74] Harborne and Hendry [97]	Angel and Rock [75] Lang, Wiek, Bergmann, Stauffacher, Martens, Moll, Swilling and Thomas [94] Andrews and Shabani [95] Evans and Heller [96] Vazquez-Brust, Smith and Sarkis [53] Dent [49]
		2.2 State-industry collaboration	Measures to link both government and incumbent industry actors into formal arrangements carrying out collaborative innovation and market development activities.	Public-private organisations, industry-government roadmaps and publications, public-private investments in infrastructure, R&D and market development, etc.	Roberts, Geels, Lockwood, Newell, Schmitz, Turnheim and Jordan [13] Roberts and Geels [10] Turnheim and Geels [16] Cherp, Vinichenko, Jewell, Suzuki and Antal [14] Sovacool and Martiskainen [74] Harborne and Hendry [97]	Öniş [41] Johnson [44] Kronsell, Khan and Hildingsson [39] Lee, Jung and Lee [98] Kim [99] Meckling and Nahm [51] Kalinowski [80] Chien [54]
	2.3 Industry alliances	Measures to link industry actors through formal partnerships or coalitions allowing like-minded firms to align activities and conduct joint technology creation, investments, business development, policy advice etc.	Joint investments in new businesses, R&D or infrastructure, formation of knowledge sharing and joint activity platforms, creation of industry organisations or networks, etc.	Roberts, Geels, Lockwood, Newell, Schmitz, Turnheim and Jordan [13] Lam, Martín-López, Wiek, Bennett, Frantzeskaki, Horcea-Milcu and Lang [100] Tzankova [101] Sovacool and Martiskainen [74] Turnheim and Geels [16] Geels, Turnheim, Asquith, Kern and Kivimaa [63] Hekkert, Suurs, Negro, Kuhlmann and Smits [56] Rotmans, Kemp and van Asselt [24] Frank, Jacob and Quitzow [59] Smith, Stirling and Berkhout [65] Turnheim and Geels [16] Geels, Turnheim, Asquith, Kern and Kivimaa [63]	Öniş [41] Scoones [78] Meckling [45] Meckling and Nahm [51] Andrews and Nwapi [46]	
3. Guidance and planning	3.1 Planning and commitments	Measures to motivate actors, secure long-term commitments to a particular socio-technical trajectory and guide R&D, commercialisation and investments.	Visions, roadmaps and targets (e.g. for diffusion, cost and technical or environmental performance), planning documents, legal or voluntary commitments, etc.	Rotmans, Kemp and van Asselt [24] Frank, Jacob and Quitzow [59] Smith, Stirling and Berkhout [65] Turnheim and Geels [16] Geels, Turnheim, Asquith, Kern and Kivimaa [63]	Öniş [41] Johnson [44] Wong [102] Kim [99] Chen and Lees [50] Mazzucato [36] Meckling and Nahm [51]	

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Table 1 (continued)

Category	Strategy	Definition	Instrument examples	Transitions literature	Developmental state literature
	3.2 Monitoring and disclosure	Measures to track and publicly disclose progress and learning from emerging experiences, to compare to initial goals and expectations, and to facilitate periodical reflection into policy or industry practices.	Progress reports, periodical disclosure of data, workshops, symposiums, etc.	Hekkert, Suurs, Negro, Kuhlmann and Smits [56] Rotmans, Kemp and van Asselt [24] Geels, Turnheim, Asquith, Kern and Kivimaa [63] Markard [60] Sovacool and Martiskainen [74] Altenburg and Pegels [82]	Vazquez-Brust, Smith and Sarkis [53] Scoones [78] Hughes [103]
Targeted strategies for accelerating creation and diffusion					
4. Legitimation and advocacy	4.1 Influencing public views	Measures to positively influence public perceptions and acceptance of the technology (e.g. about benefits/risks, market growth, investment opportunities, etc.).	Public outreach, advertising and education, narratives about the need or desirability of technologies, public demonstrations, expositions, symposiums, etc.	Bergek, Jacobsson and Sandén [71] Rotmans, Kemp and van Asselt [24] Geels, Sovacool, Schwanen and Sorrell [79] Smith, Stirling and Berkhout [65] Nilsson and Nykvist [104] Roberts and Geels [10] Klitkou, Bolwig, Hansen and Wessberg [105]	Han [106]
	4.2 Political lobbying	Measures to influence actions, plans or decisions of government officials or organisations to facilitate the production or diffusion of technologies.	Advocacy or lobbying coalitions, policy proposals, political donations, etc.	Hekkert, Suurs, Negro, Kuhlmann and Smits [56] Bergek, Jacobsson and Sandén [71] Lowe, Woodman and Fitch-Roy [107] Kivimaa, Hyysalo, Boon, Klerkx, Martiskainen and Schot [108] Smith and Raven [85]	Kronsell, Khan and Hildingsson [39]
5. Industry creation and technology production	5.1 Cost alteration	Measures to improve the economic environment affecting the competitiveness of emerging technologies via policies that reduce the cost of production, purchase or use via economic incentives or market rules.	Pricing regulations (e.g. feed-in-tariffs or carbon/fossil-fuel taxes), voluntary price ceilings, tax waivers, performance incentives, etc.	Kivimaa and Kern [57] Roberts and Geels [10] Altenburg and Pegels [82] Nilsson and Nykvist [104] Geels, Turnheim, Asquith, Kern and Kivimaa [63] Jacobsson and Lauber [109]	Öniş [41] Wade [48] Mazzucato [36] Chien [54] Meckling [45] Eckersley [89]
	5.2 Industry nurturing	Measures to support the creation or expansion of new or larger technology producers to increase the supply of technology.	Tax credits, land provision, grants, finance provision, formation of technology parks or regional clusters, local content requirements, etc.	Quitrow [110] Klitkou, Bolwig, Hansen and Wessberg [105] Harborne and Hendry [97] Cooke [111]	Öniş [41] Kim [99] Wong [102] Chien [54] Chen and Lees [112] Meckling [45]
	5.3 Knowledge production	Measures that support the creation of new knowledge (either scientific or business-related) in firms, research institutes or government agencies.	R&D subsidies, fiscal incentives, formation of technology parks, joint knowledge production platforms, etc.	Kanger, Sovacool and Noorköiv [58] Kivimaa and Kern [57] Frank, Jacob and Quitrow [59] Smith, Stirling and Berkhout [65] Hekkert, Suurs, Negro, Kuhlmann and Smits [56] Meelen and Farla [66]	Wade [48] Castells [47] Mazzucato [36] Swilling, Musango and Wakeford [52] Block [113] Meckling [45]

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Table 1 (continued)

Category	Strategy	Definition	Instrument examples	Transitions literature	Developmental state literature
	5.4 Industry protection	Measures to protect domestic industry (especially technology manufacturers) from overseas competition.	Import tariffs, discriminatory subsidy allocation, local procurement requirements, etc.	Mazur, Contestabile, Offer and Brandon [114]	Öniş [41] Wade [48] World Bank [84] Angel and Rock [75] Valentine and Sovacool [115] Andrews and Nwapi [46]
6. Market creation and technology diffusion	6.1 Niche creation and experimentation	Measures to enable or protect the demonstration, testing or upscaling of novel practices (e.g. technologies, policies, social arrangements and business models etc.) that are typically limited geographically or temporally.	Public demonstrations, pilot zones, innovation districts, living labs, etc.	Kivimaa and Kern [57] Geels, Turnheim, Asquith, Kern and Kivimaa [63] Frank, Jacob and Quitzow [59] Hekkert, Suurs, Negro, Kuhlmann and Smits [56] Bergek, Jacobsson and Sandén [71] Hoogma, Kemp, Schot and Truffer [91]	Swilling, Musango and Wakeford [52] Eckersley [89] Scoones [78]
	6.2 Demand creation	Measures that target technology users to increase or stimulate new purchases.	Monetary incentives (e.g. subsidies or tax reductions), non-monetary incentives (e.g. access to car pool lanes), public outreach/marketing, green product labelling, public procurement standards, demonstration projects, etc.	Turnheim and Geels [16] Victor, Geels and Sharpe [64] Nilsson, Hillman and Magnusson [116] Dijk, Iversen, Klitkou, Kemp, Bolwig, Borup and Møllgaard [67] Figenbaum [117]	Mazzucato [36] Meckling [45] Chien [54]
	6.3 Removing market barriers	Measures to modify or remove policies and formal institutions blocking or disincentivising investments in the production or usage of new technologies and businesses.	Establishment of uniform codes and standards for technology design or operation, removal or relaxing of outdated laws and regulations (e.g. safety standards), etc.	Smith and Raven [85] Victor, Geels and Sharpe [64] Geels, Turnheim, Asquith, Kern and Kivimaa [63] Meelen and Farla [66]	Wade [48] Johnson [44] Mathews [118] MacNeil [90]
	6.4 Sectoral coupling	Measures to link the production or usage of common technologies across different markets to accelerate technological improvement and cost reduction via economies of scale.	R&D subsidies, demonstration programs, roadmaps or target setting to stimulate the production or usage of common base technologies (e.g. fuel cells and batteries) or energies across multiple societal sectors.	Geels, Sovacool, Schwanen and Sorrell [79] Geels [23] Markard, Geels and Raven [55] Frank, Jacob and Quitzow [59]	None observed*
7. Resource mobilisation and allocation	7.1 Financial support	Measures that directly supply financial capital or revenue to support the production, demonstration or diffusion of new technologies and associated infrastructure or business models.	Purchase subsidies for consumers, grants and interest free loans or tax credits for industry, revenue generating market instruments (e.g. carbon credit trading), etc.	Smith, Stirling and Berkhout [65] Geels, Turnheim, Asquith, Kern and Kivimaa [63] Kivimaa and Kern [57] Newell and Simms [7] Hekkert, Suurs, Negro, Kuhlmann and Smits [56]	Wade [48] Castells [47] World Bank [84] Mazzucato [36] Block [113] Chien [54] Meckling [45]
	7.2 Infrastructure preparation	Measures to establish the required infrastructure (e.g. smart grids, power storage and charging or refuelling stations) to support technology diffusion.	Infrastructure deployment schedules and targets, financial incentives for installation (e.g. grants, market incentives, tax reductions), building or town planning codes (e.g. mandating PEV chargers in new construction), etc.	Roberts and Geels [10] Nilsson and Nykvist [104] Valentine and Sovacool [119] Dijk, Iversen, Klitkou, Kemp, Bolwig, Borup and Møllgaard [67] Leibowicz [120]	Castells [47] Chien [54] Kim [121] Han [106] Eckersley [89] Block [113]
	7.3 Human resource development	Measures to accelerate the development of human resources to support emerging industries.	Training or employment grants, talent attraction incentives, establishing or investing in	Hekkert, Suurs, Negro, Kuhlmann and Smits [56] Victor, Geels and	Öniş [41] Castells [47] Chen and Lees [50] Vazquez-Brust, Smith

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Table 1 (continued)

Category	Strategy	Definition	Instrument examples	Transitions literature	Developmental state literature
Targeted strategies for accelerating decline	8. Reducing incumbent technology production and use	Measures that explicitly aim to reduce or make the production, sale or usage of incumbent unsustainable technologies difficult, expensive or illegal.	educational/research institutions and technology parks, etc.	Sharpe [64] Kivimaa, Primmer and Lukkarinen [122] Kivimaa and Kern [57] Sovacool and Martiskainen [74]	and Sarkis [53] Block [113] Swilling, Musango and Wakeford [52]
			Technology bans (for producers or users), production quotas, driving restrictions for ICE vehicles, rising environmental standards for emissions/energy efficiency/pollutants, environmental taxes, emissions trading, etc.	Kivimaa and Kern [57] Geels, Sovacool, Schwanen and Sorrell [79] Rosenbloom and Rinscheid [12] Kanger, Sovacool and Noorkoiv [58] Rosenbloom, Markard, Geels and Fuenfschilling [61] Markard [60]	Meckling and Nahm [51] Eckersley [89] Meckling [45] Vazquez-Brust, Smith and Sarkis [53]
			Reduction or removal of subsidies and institutional or economic incentives and privileges (e.g. land provision, permits, contracts, tax benefits), etc.	Kivimaa and Kern [57] Turnheim and Geels [70] Geels, Sovacool, Schwanen and Sorrell [79] Rosenbloom and Rinscheid [12] Brauers, Oei and Walk [123]	Vazquez-Brust, Smith and Sarkis [53]
			Market and regulatory reforms such as market liberalisation, changes to public financing rules (e.g. regarding carbon-intensive investments), introduction of renewable energy portfolio standards or tax increases for technology sale/use (e.g. gasoline or vehicle taxes) etc.	Turnheim and Geels [70] Kivimaa and Kern [57] Geels, Turnheim, Asquith, Kern and Kivimaa [63] Smith and Raven [85]	Eckersley [89] Scoones [78]
			Reform or abolishment of actor composition in decision-making bodies, networks and institutional frameworks in government or industry.	Kivimaa and Kern [57] Normann [88] Cherp, Vinichenko, Jewell, Suzuki and Antal [14] Brauers, Oei and Walk [123] Roberts, Geels, Lockwood, Newell, Schmitz, Turnheim and Jordan [13]	Valentine [17]

developmental-state model actively pursues *industry nurturing* (S5.2) through policies that stimulate the scale and speed of technology production. Emphasis on supply-side strategies is less pronounced in transitions scholarship due to the focus on demand-side measures and technology diffusion. Studies on technological innovation systems are an exception, however. Both fields strongly recognise the need for government support for *knowledge production* (S5.3) [47,48,58,66,83], based on awareness that both newcomer and incumbent firms can lack financial resources to invest in R&D agendas with uncertain near-term reward. The classic developmental state also heavily stresses *industry protection* (S5.4) to shield fledgling industries, by giving local manufacturers preferential treatment (e.g. with subsidies) and discriminating against foreign competitors (e.g. via trade tariffs) [41,48,84]. While recent scholarship on the green developmental state emphasises orthodox measures like *cost alteration* (S5.1), interest in how to protect frail new industries from foreign markets remains high [45,46,50].

2.2.6. Market creation and technology diffusion (C6)

Both fields describe strategies to accelerate market creation and technology adoption. In developmental states, industrial change is driven by picking technological winners. There is thus low emphasis on *niche creation and experimentation* (S6.1) with novel technologies and social arrangements. Recently, however, some scholars integrate insights from sustainability transitions to emphasise open-ended experimentation with competing alternatives under guidance of the state [52]. As mentioned, *demand creation* (S6.2) tends not to feature in classic developmental-state literature due to overwhelming focus on supply-side policy and technology production for export. Yet recent scholarship, discussing the relevance of the developmental-state model for diffusing green technologies, underscores a need for demand-side policies [36,45]. As for *removing market barriers* (S6.3), lack of industry standardisation and outdated institutions such as laws and regulations can slow the diffusion of path-blazing technologies. Strategic niche management [85] and studies on electric mobility transitions [86],

though not widely stressed in transitions scholarship, are vocal about removing such market barriers. Conversely, this strategy is heavily emphasised in classic [48] and green developmental-state literature [87]. Finally, transitions literature often stresses the importance of *sectoral coupling* (S6.4) to stimulate the diffusion of mutually complementary base technologies across multiple industries [23,55]. Developmental-state literature does not prescribe this strategy, presumably due to the focus on sector-specific industrial policy.

2.2.7. Resource mobilisation and allocation (C7)

Both fields recognise the need to mobilise financial, human, and infrastructural resources. Regarding *financial support* (S7.1), in the classic developmental-state model, subsidies to industry are distributed based on performance [48,50]. Both fields emphasise *infrastructure preparation* (S7.2) driven by state funding along with policies and institutional arrangements that stimulate private investments. Lastly, both fields frequently discuss *human resource development* (S7.3), emphasising instruments such as training schemes, employment incentives, and technology parks.

2.2.8. Reducing incumbent technology production and use (C8)

Though neglected in early sustainability transitions literature, recent studies advocate strategies to accelerate the decline of environmentally harmful technologies [57,60,70,88] through *technology control and restriction* (S8.1) and *support removal* (S8.2). Emphasised instruments include bans or restrictions on the production or use of particular technologies, and removal of incentives like subsidies or institutional arrangements that support incumbent industry [12]. Similarly, ‘destructive’ policies, though absent from early developmental-state literature, have received attention in recent work examining state-led governance for climate change and green industrial transformation [45,51,53,89]. For *structural and rule reforms* (S8.3) and *actor changes* (S8.4), the developmental-state literature devotes thin attention to overhauling incumbent governance structures and actor bodies. Still, it is recognised that developmental states tend to foster path dependency and vested interests in the government–industry actor networks sharing allegiance to a particular technology [17].

As demonstrated above, the bulk of strategies for accelerating socio-technical change are widely discussed in both fields of literature. A comprehensive framework has thus emerged to guide our comparison of how each country applies these in practice.

3. Methods

This section briefly outlines key methodological details, focusing on our case selection and the data analysis procedure. The overall study design that guided our research procedure is summarised into Fig. 1.

3.1. Conceptual scope, case selection and temporal focus

In choosing suitable cases for analysis, we set the following criteria, requiring that each feature:

- An ambitious, long-term plan to accelerate a transition to electric mobility;
- A prominent set of incumbent actors from government or industry driving the transition;
- A variety of governance strategies supported by government funding and policies;
- Ongoing and interconnected strategies extending from technological development and testing to market creation and diffusion.

Siding with recent literature [1], our conception of ‘incumbent’ actors in this study focuses mainly on powerful and established organisations in government and industry with a direct stake and influence over the socio-technical regime. By focusing on the collective strategies used

by such actor networks to deliberately accelerate socio-technical change, our view of incumbency differs somewhat from many studies that have by default assumed incumbent actors to possess ‘vested interests in maintaining the status quo’ and be focused on resisting rather than ‘enabling transitions’ [77, 124: 148, 125: 3].

Satisfying the above criteria and featuring such incumbent actors, China, Japan and California were chosen for analysis. Their principal features are summarised in Table 2.

Since this research aims to explore the nature of strategies used in varying contexts, the cases were also chosen to exhibit a contrasting representation of key variables. These include the: (i) prominence of incumbent industry in the main governance bodies and strategies used, (ii) geographical scale of the transition, (iii) political economy styles following variations described in literature [90,126], and (iv) technological focus: fuel-cell electric vehicles (FCEVs) or plug-in electric vehicles (PEVs); with the latter comprised of pure battery electric vehicles and plug-in hybrid variations. The cases vary sharply in these variables, representing diversity rather than typical examples [127].

Also satisfying these conditions, other countries such as Germany and Korea might be considered ripe candidates for analysis. Japan and California, however, were chosen so we could integrate knowledge and data obtained through previous research [68,128]. In addition, inclusion of our three cases is rationalised by China’s global status as the largest PEV market (measured by on-road vehicle numbers) and by California and Japan similarly possessing the world’s largest and second largest FCEV stock respectively [129,130]. Admittedly, the mix of national and sub-national scales poses challenges for comparison across cases. However, the geographical boundaries of our case selection followed the overall focus of market descriptions given in existent literature on each country [68,131–133]. We also focus on the scale where the activities of each country’s incumbent actor network are most prevalent.

To build understanding of how top-down transition strategies evolve, we examine two key phases in the technological lifecycle. As guidance, we adopt the distinction of evolving phases of technological diffusion described in literature. Since these conceptions vary across transitions scholarship [24,134], we began by considering three key phases suggested by Kivimaa et al. [108] and Kanger and Schot [135]: pre-development/start-up, acceleration, and stabilisation. This study examines the first two, given the early nature of the transitions discussed.

The first phase, pre-development and exploration, stretches from initial development, experimentation, testing, and demonstration of technologies to early commercialisation and diffusion. The second phase, acceleration, involves efforts to diffuse technologies, stimulate demand, and accelerate market penetration while continuing to support technological improvement. As Table 2 shows, the duration of phase two is set uniformly across cases, while phase one in California and Japan starts before China’s due to the earlier nature of technological development and testing (see Section 4).

3.2. Data sources and analysis

This study uses data derived from both primary sources (semi-structured interviews) and secondary sources (academic and grey literature). Although interview data helps deepen the analysis, we consider only secondary documents when summarising and comparing the governance strategies used in each country. This increases the replicability and transparency of our conclusions. Documents used as evidence are cited directly in our findings and in online [supplementary material](#) that provides more detailed explanations of strategies, summarised in Tables 3–5.

Details of interviews appear in Appendix A. Respondents for each country include incumbent actors such as government agencies, automakers and fuel suppliers along with experts in universities, private firms, and think tanks. Altogether, we drew on 44 interviews conducted for this and previous research [68,128]. All interviews shared the goal of building understanding of strategies used to spur the production and

<p>1. Literature review and theory building</p> <p>Guiding question:</p> <ul style="list-style-type: none"> • <i>What strategies for accelerating socio-technical change and industrial transformation are emphasised in literature?</i> 	<ul style="list-style-type: none"> • Locate relevant studies in sustainability transitions and developmental state literature • Identify descriptions of transition accelerating strategies • Organise into framework → See Table 1 • Create indicators of weak or strong strategy use → See Appendix B
<p>2. Case selection and data collection</p>	<ul style="list-style-type: none"> • Fix criteria and select relevant cases → See Section 3.1 and Table 2 • Collect evidence of strategy use from secondary documents and interviews → See Appendix A
<p>3. Case analysis</p> <p>Guiding questions:</p> <ul style="list-style-type: none"> • <i>What strategies and instruments were used or underused in each case?</i> • <i>How has the use of strategies evolved across phases?</i> 	<ul style="list-style-type: none"> • Code documents describing strategy use in accord with framework, using software (MAXQDA) → See Tables 3 - 5 and supplementary material • Integrate interview data to enrich explanations
<p>4. Meta analysis</p> <p>Guiding questions</p> <ul style="list-style-type: none"> • <i>What patterns can be seen across cases in each phase?</i> • <i>What contextual factors influenced transition approaches and use of specific instruments?</i> 	<ul style="list-style-type: none"> • Identify trends regarding strategy use across cases → See Section 6.1 and Table 6 • Identify patterns regarding use of specific governance instruments and influencing factors → See Section 6.2 and Table 7

Fig. 1. Summary of research design.

Table 2

Principal attributes of three cases.

Country	China	Japan	California
Principal governance actors	National and sub-national governments (i.e. provincial and city)	State government and incumbent industry	State government and incumbent industry
Scale of transition	Country-wide	Country-wide	State-wide
Type of political economy	Authoritarian and highly coordinated market economy	Corporatist and highly coordinated market economy	Liberal and weakly coordinated market economy
Technological focus	Plug-in electric vehicles (PEVs)	Fuel-cell electric vehicles (FCEVs)	Fuel-cell electric vehicles (FCEVs)
Phase one: Pre-development and exploration	2006 – 2014	1999 – 2014	1999 and 2014
Phase two: Acceleration	2015 – 2020	2015 – 2020	2015 – 2020

diffusion of PEVs or FCEVs in each country, outcomes and challenges, and factors influencing instrument selection.

When summarising each country's transition approach (see Tables 3–5), we assign two values ('strong' and 'weak/not observed') to reflect how strongly a strategy is used. 'Strong' means a strategy is visible in multiple examples (at least two) and used consistently over multiple years (at least two), based on available evidence. Indicators in Appendix B guided our scoring. Values were cross-checked by two authors to minimise subjective interpretation. Though other studies [67,136] use finer-grained evaluations of policy-use intensity (e.g. weak/medium/strong), we adopted the simpler binary system due to the volume and heterogeneity of strategies examined and the difficulties of creating quantitative depictions for which objective evidence could be

collected.

4. Introduction to case studies

To contextualise each country's mobility transition, the following sections outline the timelines of the two phases, key governance actors, and motivating factors. Since civil society is underrepresented in the principal governance body promoting each vehicle technology examined,² we focus actor descriptions on state and market actors.

4.1. Battery electric mobility in China

The Chinese government supports the development and diffusion of battery, fuel cell, and hybrid powertrains under its New Energy Vehicles (NEVs) policy. Following the primary focus of existent literature [133,137] and government policy [138], our case focuses principally on PEVs (comprised of pure battery electric or plug-in hybrids, including passenger vehicles and buses). In line with literature [139], we selected the period 2006–2014³ as phase one (pre-development and exploration) and 2015–2020 as phase two (acceleration). Around the start of phase one, national-government policy support for developing China's NEV industry as a strategic priority was strengthened through five-year plans [140]. Also during phase one, diffusion efforts began, focusing on

² More diverse actor inclusion may occur in other governance frameworks with relevance to electric mobility in each country. This argument is based on the membership of the California Fuel Cell Partnership, Japan's Strategic Hydrogen and Fuel Cell Strategy Council, and literature cited for inclusive governance (S2.1) in Tables 3 and 4 for China and Japan.

³ In setting our temporal periods for analysis, each phase extends from January in the first year to December in the last year.

Table 3
China: Summary of strategies used.

Category	Strategy	Phase 1: Pre-development and exploration (2006–2014)		Phase 2: Acceleration (2015–2020)	
		Use*	Instrument examples	Use*	Instrument examples
Overarching coordination strategies					
1. Knowledge management	1.1 Knowledge dissemination	●	Establishing non-profit China Electric Vehicle Association to promote knowledge sharing across industry and government. Establishing industry alliances of state-owned automakers and part suppliers described in S2.3. Use of this strategy not observed [139,145,167].	●	Instruments from phase one (see S1.1) continued. Establishing industry thinktank China EV100 to diffuse knowledge across industry, government and academia via meetings, publications and forums.
2. Actor networks and collaboration	2.1 Inclusive governance	○	Use of this strategy not observed [139,145,167].	○	Situation unchanged from phase one (see S2.1) [139,144,150].
	2.2 State–industry collaboration	●	Using state-owned enterprises to synchronise government ambitions and industry activity [145,147]. Participation of government actors in industry alliances [145].	●	Instruments from phase one (see S2.2) continued [151].
3. Guidance and planning	2.3 Industry alliances	●	Obliging foreign automakers to partner with domestic firms via joint-ventures when producing vehicles in China [144]. Establishing industry alliances of state-owned automakers and part suppliers (e.g. State-Owned Electric Vehicle Industry Alliance) to promote knowledge sharing, joint research and business ventures [145,173].	●	Instruments from phase one continued (see S2.3). Promoting and establishing mergers (e.g. between FAW, Dongfeng and Changan) and joint-ventures (e.g. T3 Mobility) between state-owned enterprises and private firms [174].
	3.1 Planning and commitments	●	Periodically signalling long-term government commitments to the NEV industry and priority areas via multi-year plans [132]. Setting numerical targets for NEV sales, infrastructure deployment and technical performance [172].	●	Instruments from phase one continued (see S3.1) [163].
	3.2 Monitoring and disclosure	○	Weak use of this strategy [175,176].	○	Situation unchanged from phase one (see S3.2) [150]. Data on PEV sales and infrastructure deployment is published disparately by various industry associations. Yet government data is not published in an integrated, consistent and annual format.
Targeted strategies for accelerating creation and diffusion					
4. Legitimisation	4.1 Influencing public views	●	Demonstrating NEVs at high-profile international events (e.g. Beijing Summer Olympics in 2008). Introducing PEVs into public bus and taxi fleets via national pilot project programme (Ten Cities Thousand Vehicles) [138]. Establishing public demonstration, marketing and business development zones (e.g. NEV testing zones in Shanghai International Automobile City) [177].	●	Instruments from phase one (see S4.1) continued, namely the Shanghai International Automobile City via demonstrations of PEVs and intelligent connected vehicles [178].
	4.2 Political lobbying	○	Weak use of this strategy. No dedicated coalition for political lobbying observed.	○	Situation unchanged from phase one (see S4.2).
5. Industry creation and technology production	5.1 Cost alteration	●	Providing government subsidies to automakers to reduce production and sales costs [144,163]. Providing government subsidies to pilot cities to reduce burden of PEV fleet purchases and installing charging infrastructure [132].	●	Instruments from phase one (see S5.1) continued [163,165]. Setting national price ceiling for recharging rates in public and private stations [179,180].
	5.2 Industry nurturing	●	Providing R&D funds to support development of new or existing firms [181]. Requiring foreign firms to transfer NEV-related knowledge to domestic partner when forming joint-ventures [144]. Providing land, tax breaks and low-interest loans to support establishment of PEV factories [146,148].	●	Instruments from phase one (see S5.2) continued [146,148,163,165]. Mandating minimum shares of NEVs in public fleets to support production through increased demand [166].
	5.3 Knowledge production	●	Providing R&D funds (via '863' plan) to support development of core PEV technologies [143,182]. Establishing innovation clusters and research institutes [139,181]. Requiring foreign firms to transfer NEV-related knowledge to domestic partner when forming joint-ventures [144].	●	Instruments from phase one (see S5.3) continued, notably through R&D fund provision via 'National Key Research & Development Program' plan [183].
	5.4 Industry protection	●	Setting import tariffs to increase sales price of imported vehicles [184]. Preferentially allocating government subsidies to domestic auto/battery makers [172].	●	Instruments from phase one (see S5.4) continued, but weakened towards end of phase two [144,172].
6. Market creation and technology diffusion	6.1 Niche creation and experimentation	●	Establishing pilot cities programme to facilitate experimentation with PEVs in public fleets and novel policies or business models (e.g. battery swapping) [141,167,171].	●	Instruments from phase one (see S6.1) continued [142,163].
	6.2 Demand creation	●	Setting mandatory procurement targets for government fleets [132,144].	●	

(continued on next page)

Table 3 (continued)

Category	Strategy	Phase 1: Pre-development and exploration (2006–2014)		Phase 2: Acceleration (2015–2020)		
		Use*	Instrument examples	Use*	Instrument examples	
7. Resource mobilisation and allocation	6.3 Removing market barriers	○	Reducing purchase prices via subsidies to manufacturers [180]. Providing driving privileges to PEV purchasers (e.g. exception from driving or licence plate restrictions) [139]. Weak use of this strategy. Limited evidence of efforts to set national standards for PEV components and recharging infrastructure [140,171].	●	Instruments from phase one (see S6.2) continued [150,165]. Setting national standards for charging interfaces, piles, data communication protocols and safety standards for batteries [179]. Streamlining or removing permitting procedures to accelerate the speed of installing charging infrastructure.	
	6.4 Sectoral coupling	○	Weak use of this strategy. Limited evidence of national efforts to couple PEV deployment with complementary technologies (e.g. smart grids or renewable energies) despite political statements and small-scale experimentation.	●	Coupling IT and PEV industry by promoting and establishing partnerships and joint-ventures to realise development of shared, connected and autonomous vehicles [146,151].	
	7.1 Financial support	●	See examples in cost alteration (S5.1), industry nurturing (S5.2), knowledge production (S5.3) and infrastructure preparation (S7.2). Providing public loans and grants for R&D to automakers [165].	●	Instruments from phase one (see S5.1–5.3 and S7.2) continued.	
	7.2 Infrastructure preparation	●	Providing government subsidies for establishing public or private charging infrastructure [180]. Directing national power utilities to install charging stations [173].	●	Instruments from phase one (see S7.2) continued. Mandating the installation of charging infrastructure in town planning and building codes [180].	
	7.3 Human resource fostering	●	Allocating R&D funds to industry and research institutes [140]. Establishing new research institutes and innovation parks [150].	●	Instruments from phase one (see S7.3) continued [183].	
	Targeted strategies for accelerating decline of incumbent technologies					
	8. Reducing incumbent technology production and use	8.1 Technology control and restriction	●	Restricting the purchase/usage of ICE vehicles while incentivising the purchase and usage of NEVs via driving day bans and reduced allocation of licence plates to ICE vehicles [169].	●	Instruments from phase one (see S8.1) continued. Setting mandatory ZEV production targets to suppress the volume of new ICE passenger vehicle sales [133,163].
	8.2 Support removal	○	Use of this strategy not observed.	●	Halting the issuance of permits to proposed constructions of new ICE vehicle factories [11,146]. Abolishing diesel subsidies for public bus fleets [132].	
	8.3 Structural reforms	○	Use of this strategy not observed.	●	Promoting the market entry of foreign firms by weakening protection measures (see S5.4) to stimulate competition and technological learning for domestic firms [144,146].	
	8.4 Actor changes	○	Weak use of this strategy. Political statements made about merging redundant vehicle makers and reorganising state-owned enterprises to boost NEV development and production. Yet no evidence of implementation.	●	Implementing mergers and changing leadership of several state-owned vehicle makers (e.g. FAW, Dongfeng and Changan) to accelerate PEV production, innovation and cost-cutting via economies of scale [174].	

○ indicates use of a strategy is 'weak' or 'not observed'. ● indicates use of a strategy is 'strong'. See Section 3.2 for further explanation.

government vehicles in pilot cities [141]. Since 2015, phase two marks a shift towards mass-market adoption and the widespread rollout of charging infrastructure [142,143].

Though dominated by the state, the network driving China's transition to electric mobility also includes actors from industry, academia, and research institutes [144,145]. Incumbent government actors include political elites (e.g., President Xi Jinping, electric mobility advocates like Wan Gang), national agencies (e.g., the National Development and Reform Commission, the Ministry of Science and Technology, the Ministry of Industry and Information Technology), and sub-national authorities at provincial or city level (e.g., Beijing, Shanghai, Shenzhen) [146,147]. Sub-national agencies actively experiment with new policies, but their mandate is strongly dictated by the national government [148]. Industry comprises incumbent state-owned automakers (e.g., FAW, Dongfeng), newcomer private automakers and battery makers (e.g., BYD, Geely, CATL), and industry alliances and associations (e.g., EV100). While newcomers are gaining business and political power, incumbent state-owned enterprises have much more influence over policymaking, thanks to government links [145]. Finally, research institutes include R&D centres in elite government universities (e.g., Tsinghua University, Tongji University). Government dominates this

web of actors due to the one-party system and control over state-owned enterprises and industry associations [145,149] (int. 3,5). Accordingly, our analysis focuses on transition strategies formulated by national government and, to a lesser extent, sub-national governments.

Three motivations underpin China's transition strategy. The first is environmental, linked to desires to reduce air pollution and carbon emissions from increasing automobile usage in major cities (int. 4,6) [137,150]. Concerns over civil uprising against government policy due to chronic and severe air pollution strengthen this ambition [38]. The second motivation concerns industrial upgrading and the government's desire to boost the international competitiveness of the domestic auto-industry [11] (int. 4). With China's mastery of internal combustion engines (ICE) lagging behind foreign automakers [144], the lower complexity of building PEVs provides a precious opportunity for technological leapfrogging [147,151]. Electrification also serves ambitions to foster China's global dominance of connected and autonomous vehicle technologies [146]. The third motivation is energy security. This arises from the need to curb China's growing consumption of imported oil for transport and reduce economic vulnerability to price increases and supply disturbances [152] (int. 5).

Table 4
Japan: Summary of strategies used.

Category	Strategy	Phase 1: Pre-development and exploration (1999–2014)		Phase 2: Acceleration (2015–2020)	
		Use*	Instrument examples	Use*	Instrument examples
Overarching coordination strategies					
1. Knowledge management	1.1 <i>Knowledge dissemination</i>	●	Establishing industry alliances for knowledge sharing and joint R&D (e.g. Fuel Cell Commercialization Conference of Japan) [194]. Diffusing knowledge from government supported innovation activities via public forums [193].	●	Instruments from phase one (see S1.1) continued [128,194].
2. Actor networks and collaboration	2.1 <i>Inclusive governance</i>	○	Weak use of this strategy. The principal governance framework for hydrogen mobility (Strategic Hydrogen and Fuel Cell Strategy Council) was dominated by large industry [158].	○	Situation unchanged from phase one (see S2.1) [157,158].
	2.2 <i>State–industry collaboration</i>	●	Establishing joint industry-government platforms (e.g. Japan Hydrogen and Fuel Cell Project) to support the development and commercialisation of hydrogen mobility and refuelling infrastructure [131]. Producing joint roadmaps and identifying areas for collaboration via government-industry committees [156].	●	Producing joint roadmaps and identifying areas for collaboration via government-industry committees [154]. Establishing international hydrogen supply chains with public and private investment and collaboration [185].
	2.3 <i>Industry alliances</i>	●	Establishing alliances of oil/gas, engineering, electronics and automotive firms along with research institutions to accelerate knowledge sharing, innovation and fuel cell commercialisation (e.g. Research Association of Hydrogen Supply/Utilization Technology and the Fuel Cell Commercialization Conference of Japan) [156,194,195].	●	Instruments from phase one (see S2.3) continued. Mobilising oil/gas companies, automakers and investors to accelerate deployment of refuelling infrastructure via Japan H2 Mobility (JHyM) platform [187].
3. Guidance and planning	3.1 <i>Planning and commitments</i>	●	Publishing government-industry roadmaps to spur long-term commitments to developing and commercialising FCEVs and fix quantitative targets for deployment, performance and cost [155,156,158,196].	●	Instruments from phase one (see S3.1) continued [154]. Publishing the multi-decade vision of a ‘hydrogen society’ to motivate stakeholders and spur innovation and investments [20,153].
	3.2 <i>Monitoring and disclosure</i>	○	Use of this strategy not observed.	●	Monitoring and annually reporting progress towards government targets for vehicle and refuelling infrastructure development, R&D agendas and cost/performance targets [197].
Targeted strategies for accelerating creation and diffusion					
4. Legitimation	4.1 <i>Influencing public views</i>	●	Conducting public demonstrations of FCEVs and fuel cell buses to raise public awareness, especially at high profile international events [198]. Conducting public forums, trade shows and information provision to motivate and educate politicians, industry and the public.	●	Instruments from phase one (see S4.1) continued [154].
	4.2 <i>Political lobbying</i>	○	Weak use of this strategy. No dedicated coalition for political advocacy was observed.	○	Situation unchanged from phase one (see S4.2).
5. Industry creation and technology production	5.1 <i>Cost alteration</i>	●	Providing public subsidies to reduce construction costs of hydrogen refuelling stations [199].	●	Instruments from phase one (see S5.1) continued [186]. Setting voluntary price ceiling for hydrogen fuel for transport (1,000 yen/kg) [128]. Providing public subsidies and stamp duty waivers to reduce purchase price of FCEVs and fuel cell buses [128,189].
	5.2 <i>Industry nurturing</i>	●	Establishing university-industry knowledge clusters (e.g. Fukuoka Hydrogen Strategy and the Yamanashi Fuel Cell Valley). Providing government funding for R&D and demonstrations to support industry creation [193].	●	Instruments from phase one (see S5.2) continued.
	5.3 <i>Knowledge production</i>	●	Supporting basic and applied research via R&D and demonstration subsidies to industry and research institutions [156]. Establishing industry-academic research centres and knowledge clusters (e.g. Fuel Cell Nanomaterials Centre at the University of Yamanashi) [200].	●	Instruments from phase one (see S5.3) continued for R&D and demonstration subsidies [186,189,201] and knowledge clusters (e.g. Yamanashi Fuel Cell Valley) [186].
	5.4 <i>Industry protection</i>	○	Use of this strategy was not observed.	○	Situation unchanged from phase one (see S5.4).
6. Market creation and technology diffusion	6.1 <i>Niche creation and experimentation</i>	●	Establishing demonstration or pilot projects to test and showcase hydrogen mobility (FCEVs, buses, trucks), hydrogen production and business models [155].	●	Instruments from phase one (see S6.1) continued [186,202].
	6.2 <i>Demand creation</i>	○	Weak use of this strategy. Limited evidence of explicit measures like subsidies to stimulate vehicle demand.	●	Providing public subsidies and stamp duty waivers to reduce purchase price of FCEVs and fuel cell buses [128,189].
	6.3 <i>Removing market barriers</i>	●	Identifying and reforming laws and regulations hampering the development of hydrogen mobility [156].	●	Instruments from phase one (see S6.3) continued [189].

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Table 4 (continued)

Category	Strategy	Phase 1: Pre-development and exploration (1999–2014)		Phase 2: Acceleration (2015–2020)	
		Use*	Instrument examples	Use*	Instrument examples
7. Resource mobilisation and allocation	6.4 Sectoral coupling	●	Establishing international standards for key technologies and processes (i.e. refuelling) [155,156]. Promoting the simultaneous development and commercialisation of fuel cells for mobile and stationary applications (i.e. mobility and heat/power co-generation) through roadmaps and industry innovation platforms [156,194].	●	Instruments from phase one (see S6.4) continued, notably by simultaneously providing subsidies and setting diffusion targets for mobility and co-generation [154]. Promoting consumption of hydrogen in the transport and electricity sector to achieve economies of scale [128,154].
	7.1 Financial support	●	Providing public subsidies to reduce construction costs of hydrogen refuelling stations [199].	●	Instruments from phase one (see S7.1) continued [186]. Providing operating revenue to refuelling stations via the H2 Mobility platform [128].
	7.2 Infrastructure preparation	●	Establishing an industry partnership (HySUT) to prepare a national network of refuelling infrastructure by testing and developing technology ahead of vehicle deployment [156,199].	●	Fixing multi-year deployment targets for refuelling stations [128,154]. Establishing an industry alliance (Japan H2 Mobility) to mobilise public-private funding for construction and operation of refuelling stations and plan network development [128,186].
	7.3 Human resource fostering	●	Establishing research institutes and training programmes at prefectural level (e.g. the Hy-Life Project in Fukuoka) [186,189].	●	Instruments from phase one (see S7.3) continued.
Targeted strategies for accelerating decline of incumbent technologies					
8. Reducing incumbent technology production and use	8.1 Technology control and restriction	○	Use of this strategy not observed.	○	Weak use of this strategy. The government intention to ban sales of ICE vehicles by mid-2030 was only announced in December 2020 [203].
	8.2 Support removal	○	Use of this strategy not observed.	○	Use of this strategy not observed.
	8.3 Structural reforms	○	Use of this strategy not observed.	○	Use of this strategy not observed.
	8.4 Actor changes	○	Use of this strategy not observed.	○	Use of this strategy not observed.

○ indicates use of a strategy is 'weak' or 'not observed'. ● indicates use of a strategy is 'strong'. See Section 3.2.

4.2. Hydrogen mobility in Japan

Japan, like China, actively supports the production and diffusion of hybrid, battery, and hydrogen drivetrains. We focus on FCEVs due to the heavy emphasis on hydrogen in national energy and transport policies [20,153,154]. Matching the Californian case, phase one is set to 1999–2014⁴ to coincide with a period of intensive technological development, testing and market preparation [155,156]. Phase two is set to 2015–2020. Not only do efforts by government and industry to commercialise FCEVs accelerate significantly during this phase, 2015 marks the start of commercial FCEV sales and serial production (notably the Toyota *Mirai*) and the national rollout of refuelling infrastructure.

A distinct network of domestically-based incumbent actors is driving the transition [157,158]. Government actors at national level include the Ministry of Economy, Trade and Industry; the Prime Minister and his Cabinet; and multiple agencies like the New Energy and Industrial Technology Development Organisation and the Ministry of Environment. Sub-national governments such as Tokyo Metropolitan, Yokohama, and Aichi Prefecture are also highly active. Incumbent firms include vehicle manufacturers (Toyota, Honda), engineering or electronic firms (e.g. Mitsubishi Heavy Industry, Kawasaki Heavy Industry, Toshiba, Panasonic), oil and gas suppliers (e.g. Iwatani, ENEOS), and industry alliances (e.g. Japan H2 Mobility). Multiple universities and research institutes also participate through technology development and policy advisories. Our case focuses on strategies used by government agencies (mainly national but also prefectural) and incumbent industry.

Three sets of motivations propel Japan's transition towards hydrogen mobility. First is climate change and energy security. With the majority of Japan's energy needs imported as hydrocarbons, large-scale deployment of renewable energy has historically been hampered by

geographical, political, technological, and economic factors [31,159]. Thus, state actors are looking to hydrogen to spur the decarbonisation of transport, electricity generation, and industry while opening up new energy import pathways (int. 14,16,19). The second motivation is economic. Not only is the production and export of hydrogen and fuel-cell technologies perceived as an important growth market, Japanese firms and research institutes have gained decades of expertise under state support [160]. The third motivation concerns industrial development. State actors and incumbent automakers are concerned by the global shift towards battery vehicles. With fewer technological hurdles to hamper new entrants, the growing PEV market could destroy the international competitiveness of Japanese automakers, attained from mastering high-efficiency hybrid or ICE vehicles (int. 14,20). Also, when produced at scale, PEVs will eliminate the need for part suppliers and derivative businesses underpinning the incumbent vehicle industry's vertically integrated business model [146]. Moreover, the automotive industry is a major contributor to employment, GDP, and exports. Thus, industry and government alike are looking to the complexity of fuel-cell technology to protect against encroachment by new entrants [156] and preserve the basic structure of existing part supply chains (int. 14,16,19).

4.3. Hydrogen mobility in California

With state policy focused on supporting zero-emission drivetrains (i.e. both PEVs and FCEVs), our analysis focuses on the latter, including passenger vehicles, buses, and trucks. Since similar forces shape Japan's and California's hydrogen-mobility markets, phase one (1999–2014) and phase two (2015–2020) are set uniformly for each case.

The principal incumbents from state-level government agencies whose actions we examine consist of the California Energy Commission, the California Air Resources Board, and the Office of Governor. For incumbent industry, we focus on collective strategies employed by foreign and domestic firms headquartered out-of-state, such as

⁴ Per footnote 3, this phase goes from January 1999 to December 2014.

Table 5
California: Summary of strategies used.

Category	Strategy	Phase 1: Pre-development and exploration (1999–2014)		Phase 2: Acceleration (2015–2020)	
		Use*	Instrument examples	Use*	Instrument examples
Overarching coordination strategies					
1. Knowledge management	1.1 Knowledge dissemination	●	Holding annual symposiums (e.g. California Hydrogen and Fuel Cell Summit) and webinars as well as publishing reports (e.g. by California Fuel Cell Partnership and the California Hydrogen Business Council) to diffuse market and policy trends.	●	Instruments from phase one (see S1.1) continued.
2. Actor networks and collaboration	2.1 Inclusive governance	○	Limited use of this strategy. Steering groups in the principal governance framework for hydrogen mobility (California Fuel Cell Partnership) dominated by incumbent industry [161].	○	Situation unchanged from phase one (see S-2.1) [215].
	2.2 State–industry collaboration	●	Establishing public–private partnership (California Fuel Cell Partnership) to align government and industry activities and accelerate development of hydrogen mobility market [161].	●	Instruments from phase one (see S2.2) continued [216].
	2.3 Industry alliances	●	Establishing industry alliances (e.g. California Fuel Cell Partnership and the California Hydrogen Business Council) to align industry activities and accelerate market development [217].	●	Instruments from phase one (see S2.3) continued [218].
3. Guidance and planning	3.1 Planning and commitments	●	Setting mid-term and long-term targets for vehicle and refuelling station deployment via government–industry roadmaps and legally binding government policy (executive orders) [219].	●	Instruments from phase one (see S-3.1) continued.
	3.2 Monitoring and disclosure	○	Weak use of this strategy. Instruments described in phase two (see S3.2) began in 2014.	●	Publishing an integrated annual report to disclose progress towards government/industry targets for vehicle and refuelling infrastructure development and policy outcomes [220].
Targeted strategies for accelerating creation and diffusion					
4. Legitimation	4.1 Influencing public views	●	Implementing vehicle demonstrations aimed at the public and politicians via the California Fuel Cell Partnership and California Hydrogen Business Council. Introducing fuel cell buses into public transit fleets [221,222].	●	Instruments from phase one (see S4.1) continued.
	4.2 Political lobbying	●	Establishing a dedicated industry alliance (California Hydrogen Business Council) to carry out political advocacy for fuel cell mobility and hydrogen [217].	●	Instruments from phase one (see S4.2) continued [218], with a new alliance (California Hydrogen Coalition) established in 2020 [68].
5. Industry creation and technology production	5.1 Cost alteration	●	Establishing a co-funding scheme to cover portion of construction costs for hydrogen refuelling stations [223]. Establishing a market instrument (Low Carbon Fuel Standard) to generate credit-based revenue for refuelling stations for sales of low-carbon fuels including hydrogen [223].	●	Instruments from phase one (see S5.1) continued. Expanding the Low Carbon Fuel Standard to also provide revenue for hydrogen refuelling stations based on capacity [68,205].
	5.2 Industry nurturing	●	Establishing government grants to support the expansion of new and existing companies building zero-emission vehicles, parts or infrastructure [207].	●	Instruments from phase one (see S5.2) continued.
	5.3 Knowledge production	○	Weak use of this strategy. Knowledge production support focused on applied rather than basic research (e.g. government funding for vehicles and refuelling station demonstrations) [222].	○	Situation from phase one (see S5.3) unchanged.
	5.4 Industry protection	○	Use of this strategy not observed.	○	Situation from phase one (see S5.4) unchanged.
6. Market creation and technology diffusion	6.1 Niche creation and experimentation	●	Testing and demonstrating FCEVs, fuel cell buses and refuelling stations in university campuses and public vehicle fleets [221,222].	●	Testing and demonstrating fuel cell trucks and refuelling stations in commercial fleets (e.g. Project Portal and Shore-to-Store project in Los Angeles ports) [224].
	6.2 Demand creation	●	Setting minimum ZEV procurement targets for public bus agencies [225]. Providing subsidies to reduce purchase costs of zero emission buses.	●	Instruments from phase one (see S6.2) continued. ZEV procurement targets tightened to 100% by 2030 via the Innovative Clean Transit regulation [226]. Incentivising FCEV purchases with free fuel provision, access to car pool lanes and state subsidies [68].
	6.3 Removing market barriers	●	Identifying problematic policies (e.g. regulations, laws and formal rules etc.) and proposing modifications via publications and industry–government dialogues [217]. Developing common standards and protocols for vehicle refuelling, hydrogen storage and refuelling station safety through industry–government collaboration [227,228].	●	Instruments from phase one (see S6.3) continued [229], with the development of standards and protocols expanding to heavy-duty trucks [230].
	6.4 Sectoral coupling	●	Promoting the use of hydrogen and fuel cells in non-transport areas such as renewable energy, energy storage and co-generation via industry alliances (California Hydrogen Business Council) and public	●	Instruments from phase one (see S6.4) continued.

(continued on next page)

Table 5 (continued)

Category	Strategy	Phase 1: Pre-development and exploration (1999–2014)		Phase 2: Acceleration (2015–2020)	
		Use*	Instrument examples	Use*	Instrument examples
7. Resource mobilisation and allocation	7.1 Financial support	●	symposiums (e.g. the California Hydrogen and Fuel Cell Summit) [217]. Providing government funding to reduce the construction costs for refuelling stations [231]. Establishing a market instrument (Low Carbon Fuel Standard) to generate credit-based revenue for refuelling stations for sales of low-carbon fuels including hydrogen [223].	●	Instruments from phase one (see S7.1) continued [232], with the Low Carbon Fuel Standard expanded to also provide revenue for hydrogen refuelling stations based on capacity [68,205]. Providing government funding to support fuel cell truck demonstrations. Automakers (Toyota and Honda) directly acquiring equity in refuelling station companies (e.g. First Element) [233].
	7.2 Infrastructure preparation	●	Setting targets for refuelling station deployment [219]. Supporting the planning of refuelling station deployment via government agencies and government-industry collaboration (California Fuel Cell Partnership) [219,227].	●	Instruments from phase one (see S7.2) continued [68,205].
	7.3 Human resource fostering	●	Providing grants (via the California Energy Commission's Clean Transportation Program) to support ZEV-related workforce training and education in industry and colleges [234].	●	Instruments from phase one (see S7.3) continued [235].
Targeted strategies for accelerating decline of incumbent technologies					
8. Reducing incumbent technology production and use	8.1 Technology control and restriction	●	Setting mandatory ZEV production targets to suppress the volume of new ICE passenger vehicle sales. [162,209] Setting minimum ZEV purchase requirements for vehicle fleets (10% by 2015) in public agencies [207].	●	Instruments from phase one (see S8.1) continued [209]. ZEV production targets were widened to target heavy-duty trucks via the Advanced Clean Trucks Regulation [211] while ZEV procurement targets for government agencies were raised to 25% by 2020. Setting a mandatory phase-out schedule for non-zero emission buses serving public fleets via the Innovative Clean Transit Regulation [236].
	8.2 Support removal	○	Use of this strategy not observed.	●	Reducing then abolishing subsidies for the purchase of low-emission internal combustion engines in trucks and buses and redirecting to zero-emission technologies [214].
	8.3 Structural reforms	●	Setting maximum carbon intensity limits for gasoline via the Low Carbon Fuel Standard to incentivize low-carbon transportation, including hydrogen [237].	●	Instruments from phase one (see S8.3) continued.
	8.4 Actor changes	○	Use of this strategy not observed.	○	Use of this strategy not observed.

○ indicates use of a strategy is 'weak' or 'not observed'. ● indicates use of a strategy is 'strong'. See Section 3.2.

automakers (e.g. Toyota, Honda, Hyundai, Nikola, Mercedes, GM, Cummins), fuel suppliers (e.g. Shell, Air Liquide and recently Chevron), and industry consortiums such as the California Hydrogen Business Council. A particularly influential entity is the public-private California Fuel Cell Partnership [161]. This mobilises industry and government around the shared goal of growing the FCEV market through vehicle demonstrations, infrastructure investment, collaborative planning, and outreach.

Like in China, government actors are chiefly motivated by environmental factors; namely air pollution and climate change [162] (int. 27,29,38,44). Los Angeles has historically suffered from some of the worst air quality in the U.S. Being the primary cause of this pollution, transport is also California's principal source of GHG emissions (around 40%). Mobility electrification is thus essential to achieve the ambitious goal of reducing emissions 40% by 2030 from 1990 levels [40] and improving air quality. Unlike Japan or China, California lacks a strong economic rationale to promote hydrogen mobility since automakers currently manufacturing FCEVs are based in Asia. Instead, state actors have historically promoted hydrogen mobility due to advantages like long driving ranges, suitability for large vehicles, and short refuelling times (int. 43).

5. Findings

We now apply the analytical framework to identify the main strategies used by the incumbent actor network in each jurisdiction to spur the transition towards electric mobility. To facilitate comparison, each

case follows the same structure. After summarising prominent areas of application and typifying approaches, we consider variations over the two phases, notable outcomes, and challenges. Summaries of strategies used appear in Tables 3–5. We also provide more detailed descriptions and supporting evidence in online supplementary material.

5.1. Strategies used in China's electric mobility transition

As Table 3 shows, the Chinese state is employing all possible means to pursue its transition to electric mobility. Indeed, in phase two, only three strategies remain underused: inclusive governance (S2.1), monitoring and disclosure (S3.2), and political lobbying (S4.2). Several strategies emerged in phase two, such as sectoral coupling (S6.4) and accelerating the decline of ICE vehicles (C8). The mix has thus evolved in volume, complexity, and stringency.

Beginning with overarching coordination strategies, planning and commitment (S3.1) plays a crucial role, given the top-down nature of the transition and the need to mobilise scores of cities and provinces around the pursuit of common goals. Throughout both phases, multiple national government agencies have consistently issued multi-year development plans and statements of policy commitments [132,133]. These signal at regular intervals, for sub-national governments and industry, the specific and evolving areas of national priority (e.g., preparing charging infrastructure, establishing standards, accelerating the development and commercialisation of next-generation batteries and autonomous driving) and principles to guide these (e.g., market-led approaches). Development plans also fix numerical targets and roadmap-like

milestones. Examples include vehicle or charging pile deployment targets (e.g., 1 million NEV sales by 2020 and 3 million by 2025 under the *Made in China 2025* plan set in 2015 [163]) and technological performance targets (e.g. reducing average power consumption in pure PEVs to 12 kWh/100 km from the current 15 kWh, outlined in the *New Energy Vehicle Industry Development Plan 2021–2035*) [164].

Moving to targeted strategies for accelerating creation and diffusion, those in the industry-creation and technology-production category (C5) play a key role. First, mirroring tactics used to nurture industries like solar PVs [148], government actors have consistently exploited cost alteration (S5.1) to reduce manufacturing and purchasing costs for PEVs. Government subsidies are widely discussed in literature [163,165]. Awarded after a vehicle purchase, subsidies artificially suppress the cost of production and sale – benefitting both manufacturers and consumers. A noteworthy feature of subsidy instruments in phase two is the increasing stipulation that qualifying automakers reach minimum performance specifications (e.g. mileage per charge). This approach, which mitigates cost barriers, also nurtures industry (S5.2) by incentivising faster technological learning [146]. Second, many industry-protection instruments (S5.4) are employed. Scholars often discuss ‘local protectionism’, whereby sub-national governments have preferentially allocated subsidies to local automakers [132,137,139]. Yet discriminatory tactics have also been used nationally to protect the domestic NEV market from foreign automakers with cheaper or superior technologies [144,146,152,166]. Notably, foreign firms were disqualified from receiving public subsidies via a so-called ‘whitelist’ of eligible vehicle and battery manufacturers.⁵ Tariffs on imported vehicles (25% in phase one, 15% in phase two) and the joint-venture requirement have also protected domestic industry. The latter policy mandated that foreign automakers wishing to produce vehicles within China to avoid import tariffs must partner with a domestic firm and transfer key NEV technologies.

Strategies for market creation and technology diffusion (C6) also feature prominently. The national and sub-national governments have widely used public procurement instruments to stimulate vehicle demand (S6.2), which also serves industry-nurturing objectives (S5.2). Specifically, the national government mandated minimum ratios of ZEVs when procuring new vehicles in government fleets, especially buses and taxis [132]. Next, despite abundant top-down managerial approaches, strategies to foster experimentation with novel technology, business, or policy arrangements (S6.1) also feature strongly. Most notably, the pilot city programme [141,167] supports the trialling of unique approaches based on local needs, from which promising outcomes are reflected into national policy [139]. Also noteworthy is that sectoral coupling measures (S6.4) intensified in phase two. Beyond mere electrification *per se*, the ultimate objective for mobility in China is to become the dominating global market for shared, interconnected, autonomous vehicles [146,168]. To this end, the government has promoted links between IT firms (e.g., Alibaba, Baidu, Tencent) and state-owned automakers (e.g., FAW, Dongfen) to drive cross-sector synergies and innovation [151].

China’s case demonstrates an expanding and increasingly stringent suite of strategies to suppress and eventually abolish the production and use of ICE vehicles. Technology control and restriction (S8.1) began in phase one with instruments to curb demand for ICE vehicles. In 2011, governments in Beijing and other cities started reducing the number of licence plates issued to new vehicles via lottery systems while increasing the share for NEV counterparts [169]. In parallel, restrictions were introduced to curb ICE vehicle usage on particular weekdays or during periods of heavy smog. With such demand-side measures continuing

⁵ Introduced in 2015 then abandoned in 2019, this listed battery makers whose products could be eligible for government NEV subsidies. Japanese and Korean makers were initially excluded. See Schwabe (2020) and Kennedy (2020).

into phase two, stricter instruments such as no-go zones for ICE vehicles are currently being developed [170]. Since phase two, instruments to phase out ICE vehicles also began targeting production. First, automakers wishing to expand production capacity could only receive government permits if the scale of NEV production over the previous two years exceeded the national industry average [146]. Second, since 2019, quotas oblige automakers to produce a minimum and rising share of NEVs annually (starting at 10% and rising 2% yearly) [133,163]. Support removal (S8.2) has also occurred. After 2016, national and sub-national governments stopped issuing permits for construction of new ICE vehicle factories [11,146]. Additionally, fuel subsidies for diesel bus fleets were abolished to encourage replacement with battery alternatives [132]. Finally, structural reforms (S8.3) and actor changes (S8.4) took place. Beginning in 2019, reforms have weakened protection instruments such as the abovementioned joint-venture requirement.⁶ By allowing foreign vehicle and battery makers to establish independently owned factories [144], this aims to stimulate faster technological learning and cost reduction by exposing domestic automakers to overseas competition [146,164].

Some strategies have been neglected or underexploited. Scholars critique the absence of instruments to remove market barriers (S6.3), such as national standards for vehicle and charging infrastructure during phase one [140,171]. Monitoring and disclosure (S3.2) is also weak. Although the Chinese state collects data to measure progress towards key targets such as vehicle and infrastructure diffusion, results are not publicly shared in a consistent, periodic fashion [137,140,150,167]. Political lobbying (S4.2) via dedicated industry platforms was not observed. In explaining this, interviewees emphasised the power of the political apparatus and cooperative relationships between state and industry in NEV development (int. 4,5).

These transition strategies have generated impressive results. From just 30,000 sales in 2013, China’s on-road fleet of PEVs reached 2.58 million in 2020, more than double the size of all other countries combined [129]. In cities such as Shenzhen, public bus and taxi fleets have transitioned fully to batteries. Demand creation (S6.2) and cost alteration (S5.1) measures have contributed substantially to this market growth [163]. The number of domestic PEV and battery makers has exploded due to government subsidies to automakers (S5.1) and knowledge production support (S5.3) [150]. Automakers like BYD now export buses to Western markets; NIO produces long-range, high-performance vehicles rivalling Tesla [146]; and the driving range of batteries from newcomer manufactures like CATL exceeds that of incumbent Korean makers.

Despite these achievements, multiple challenges have emerged [144]. The pursuit of aggressive targets for vehicle sales sacrificed quality for quantity. This resulted in battery-safety problems like spontaneous fires or explosions, and low-performance vehicles whereby subsidies paid per unit of output reduced the incentive for firms to invest in R&D and technological improvement [147] (int. 1,2,5). Subsidies also triggered overproduction and excessive entry of new firms with similar technologies and poor economic competitiveness [148,163]. Some manufacturers cheated by over-reporting sales when applying for public subsidies [139]. Also, although protectionist instruments (S5.4) such as the joint-venture requirement have allowed domestic automakers to flourish, many over-rely on technology transferred from foreign partners [172]. This situation explains several tactical changes in phase two. For example, structural reforms (S8.3) aim to weed out weaker automakers by opening the market to foreign firms (int. 5). Additionally, the shift to a credit-based market trading system (inspired by California) seeks to reduce automakers’ dependence on per-unit-based subsidies [146].

⁶ Reform of the joint-venture requirement is reported to apply only to new factories; see Schwabe (2020). Since trade tariffs remain in place, we consider industry-protection measures (S5.4) to be still ‘strong’ in phase two.

5.2. Strategies used in Japan's hydrogen mobility transition

Table 4 summarises strategies collectively used by state and industry actors in Japan. The relative absence of instruments to suppress production and use of ICE vehicles is noteworthy (C8). In the other seven categories (C1–7), diverse strategies are used consistently, changing little over the two phases. The only two additions observed are monitoring and disclosure (S3.2) and demand creation (S6.2).

Beginning with overarching coordination strategies (C13), most involve tight collaborations between government and incumbent industry (S1.2). Collaborative actions include government–industry roadmap creation and committees advising government about key technological developments and market trends [154,156]. Tight government–industry links are also visible in publicly funded research and demonstration platforms. These include the Japan Hydrogen and Fuel Cell Project (implemented over 2002–2010), established to support the development of hydrogen transport and refuelling infrastructure [131], and projects seeking to establish international supply chains importing mass-produced hydrogen [185,186]. State actors also coordinated the formation of industry alliances (S2.3) that link competing firms and otherwise isolated knowledge producers to enable joint R&D, demonstrations and knowledge exchange. The ongoing Japan H2 Mobility (JHyM) platform [187], for example, mobilises energy vendors, automakers, and investors to spearhead the national rollout of refuelling infrastructure [186]. Government actors also leverage industry links to diffuse knowledge (S1.1) through forums and consortium-driven projects.

State actors use planning and commitments (S3.1) to muster long-term engagements and investments from key private, academic, and sub-national-government stakeholders. Notable instruments include national policy documents and roadmaps [153] that articulate priority areas for innovation agendas, policy, and investments. These also set numerical targets and milestones for technology deployment, costs, and technical performance [154]. For example, ambitious FCEV deployment targets set by the state in phase one (50,000 cumulative sales by 2010, 5 million by 2020) were renewed in phase two (40,000 sales by 2020, 800,000 by 2030). Targets were also set for refuelling station numbers (160 by 2020, 320 by 2025), power density of fuel cells, platinum usage, costs of key vehicle components (e.g. fuel tanks, fuel cell stacks) and the economics and volume of hydrogen production [20,128]. In this suite of targets, state policymakers stressed those for vehicle deployment due to their expected role in motivating industry to upscale production and investments (int. 20).

Among planning and commitment instruments (S3.1), visions play a prominent role in championing hydrogen and fuel cells, as they have for other state-supported technology-development programmes like solar PVs [97]. In phase two, government and industry actors jointly formulated an aspiration to attain a ‘hydrogen society’ [20]. This envisions using hydrogen not just in vehicles but broadly across heavy industry, chemical production, heat and power generation, and other transportation like boats, trains, ships, and aeroplanes [153,154,188]. Three distinct but interconnected phases leading beyond 2040 were fixed, each signalling the evolving priority areas for R&D, policy, and business development. Japan's vision of a hydrogen society helps to guide sustained, long-term commitments towards materialising these phases.

Regarding strategies for accelerating creation and diffusion, the state's guiding hand also features prominently in knowledge production (S5.3). Particularly in phase two, government actors tried to accelerate innovation by encouraging competing automakers (e.g. Toyota, Honda) to openly share the technological problems hampering mass production of FCEVs. Thematic R&D grants support basic and applied research to spur corresponding solutions [128]. As in China and California, Japan's incumbents have manipulated market conditions to alter the costs of using technology (S5.1). Notable strategies include government subsidies for refuelling stations and vehicle purchases and an industry-wide price ceiling to reduce hydrogen-refuelling costs for motorists.

Government and industry also collaboratively provide financial support (S7.1) through the H2 Mobility platform. This subsidises operational expenses until on-road FCEV numbers have increased to the point where refuelling stations attain financial self-sufficiency. In this money-intensive approach, around one third of Japan's hydrogen-related budget of 70 billion yen⁷ in 2020 was devoted to subsidies [189,190].

Three strategies for market creation and technology diffusion (C6) are heavily exploited in both phases. First, niche creation and experimentation (S6.1) is actively used through demonstration projects. Implemented mostly by incumbent firms [158], these have involved public testing and showcasing of passenger vehicle, bus, and truck prototypes [155,191], refuelling stations, and mass production of hydrogen from fossil-fuel [185] or renewable energy [186,192]. Government agencies support this experimentation through funding and providing collaboration opportunities to otherwise competing firms. Second, state and industry actors have consistently underlined the need to remove market barriers (6.3) during both phases (int. 14,15,21). This two-fold approach involves establishing common standards and protocols for industry while simultaneously removing or reforming regulations that hamper market investments in hydrogen mobility (e.g. hydrogen safety laws) [128,155,156]. Third, sectoral coupling (6.4) strategies are actively leveraged. This is visible in efforts to establish a common supply of mass-produced, low-carbon hydrogen [128,188] bridging the mobility and power-generation markets. Specifically, the gigantic fuel requirements of gas-fired power plants are anticipated to benefit transport by lowering fuel-production costs through economies of scale (int. 18,19).

Throughout both phases, three strategies remain weakly used. First, unlike in California, Japanese incumbent industry promoting hydrogen mobility has not established a dedicated platform for political lobbying (S4.2). Although lobbying might occur through existing industry organisations representing the entire automotive industry, according to one respondent (int. 19), the cooperative and intimate nature of state–industry relations reduces the need for a dedicated lobbying entity. Second, protectionist measures (S5.4) were not observed. The same respondent explained that the economic importance of exporting automobiles has reduced the political feasibility of discriminating against foreign firms entering Japan's market. Third, as mentioned, strategies for accelerating the decline of incumbent ICE vehicle technologies (C8) are absent.⁸ Explaining this gap, multiple interviews (int. 14,19,22) cited resistance from incumbent industry and the political fear of triggering economic stress in one of Japan's most important industries.

This minutely orchestrated and planning-intensive transition strategy, though ambitious and comprehensive, has produced only mediocre results. For example, state policymakers have not achieved vehicle-deployment aspirations fixed in both phases [131,193]. While phase two targets aimed for 40,000 cumulative FCEV sales by the end of March 2021, less than 10% of this was achieved by late 2020 [128]. The strategy of preparing infrastructure (S7.2) ahead of vehicles has been more successful. Some 135 refuelling stations were in operation in late 2020 (the government target is 160 by end of March 2021). This is undoubtedly due to generous government subsidies (S5.1, S7.1) and the success of industry alliance measures (S2.3) – whereby H2 Mobility is mobilising joint investments and overseeing network development. Yet refuelling companies see miserable prospects for profitability due to the low fuel requirements of the nascent vehicle population [190]. As one station operator lamented: ‘We are doing this as a societal contribution’ rather than for profit (int. 21).

This situation is the direct result of a lower-than-anticipated vehicle supply. Only two automakers (Toyota and Honda) mass-produced

⁷ Equivalent to around US\$ 661 million in February 2021.

⁸ In December 2020, Japan announced ambitions to ban the sale of gasoline engines after the mid-2030s, but this was not considered a ‘consistent’ measure for phase two.

vehicles during phase two. With their production volumes limited [128], the state's efforts to motivate other domestic automakers previously testing prototypes to enter mass production are yet to bear fruit [156]. This is largely explainable by supply-side barriers. These include the expense and technological complexity of mass-producing FCEVs and establishing production lines and part supply networks in addition to preferences for battery or hybrid powertrains in clean vehicle portfolios (int. 16,19,22).

5.3. Strategies used in California's hydrogen mobility transition

Table 5 summarises strategies used by state and market actors in California. The approach is comprehensive and largely consistent over both phases. Only four strategies were underused in phase two. Of these, measures for knowledge production (S5.3) were deemed weak due to negligible support for science and early-stage R&D. Notably, California exhibits an expanding and increasingly stringent suite of strategies to accelerate the decline of vehicles with ICE engines (C8).

Beginning with actor networks and collaboration (C2), formalised interactions between state and incumbent industry (S2.2) feature strongly. The California Fuel Cell Partnership is a key enabler here. Established in 1999, this public-private organisation unites incumbent automakers, oil/gas suppliers, and manufacturers with government agencies to align policymaking with market-development efforts while enabling joint activities like planning vehicle and infrastructure deployment and carrying out research and outreach [161]. Viewed from the guidance and planning perspective (S3.1), California's approach, like China's and Japan's, is both focused on long-term objectives and highly managerial. For instance, state and industry actors have collaboratively fixed numerous milestones (S3.1) for vehicle and infrastructure deployment during both phases [68]. In phase two, targets include achieving 1,000 refuelling stations and 1 million on-road FCEVs by 2030 [204,205]. These form part of a suite of higher-level ZEV diffusion targets set as legally binding executive orders from successive governors (e.g. 1.5 million on-road ZEVs by 2025, set in 2012; then 5 million by 2030, set in 2018). These signalling instruments provide common objectives for industry and government, offering long-term stability in a dynamic democracy where the fate of technologies is often affected by changing preferences of political leaders at state and federal levels. California is the most proactive of the three cases at disclosing progress towards industry-government targets and other policy objectives (S3.2), with the California Air Resources Board publishing this annually [205] in a consistent, comparison-friendly format. Its commitment to data disclosure and transparency allows stakeholders to monitor and adapt activities to changes in the hydrogen-mobility market.

For industry creation and technology production (C5), the state introduced multiple instruments to improve the cost competitiveness of hydrogen mobility (S5.1). These mainly target refuelling stations, serving the goal of accelerating infrastructure deployment (S7.2). State actors have reduced the financial burden for refuelling-station developers by subsidising up to half of construction costs [206] and supporting income generation through regulation-backed and incentive-based market mechanisms [68]. To this end, the Low Carbon Fuel Standard generates credit-based payments in accord with hydrogen fuel sales and station capacity [205]. Finally, as in the Asian cases, state intervention extends to support industry nurturing (S5.2) and human resource development (S7.3), through grants for training programmes and for the expansion of ZEV-manufacturing capabilities. Although California does not possess a local FCEV manufacturing industry, this support appears driven by expectations of attracting new industries and creating ZEV-related employment opportunities as a political tactic [207,208].

In the category of market creation and technology diffusion (C6), niche creation and experimentation (S6.1) features heavily in both phases. Activities have mainly involved collaborations between government agencies and incumbent firms to test and showcase the market

readiness of vehicles (including buses and trucks) and refuelling infrastructure. Demonstrations and experiments also seek to generate applied knowledge about technological performance, user behaviour, vehicle compatibility with infrastructure, and business feasibility [68]. Thus, public demonstrations help support knowledge production (S5.3) and efforts to influence public views (S4.1). This said, knowledge production activities are focused overwhelmingly on applied research and market creation rather than early-stage R&D or basic science, which is supported by federal funding (int. 40,45). In explaining the applied focus of fuel-cell truck demonstrations, one bureaucrat (int. 29) stressed ambitions to 'scale up these projects to really prove their capabilities to the eventual market. Because, again, what we're trying to do is move that market faster than it would already do [without state intervention]'. Since demonstrations of fuel-cell trucks in the logistics chains serving Los Angeles ports also involve decarbonisation of storage and heating/cooling, niche experimentation is a key lever for promoting sectoral coupling (S6.4) between mobile and stationary applications of hydrogen.

California's transition approach includes strategies to phase out ICE vehicles (C8). Two pioneering instruments were introduced by the state in phase one. First, the ZEV mandate was formulated as a technology-control and restriction measure (S8.1). Adopted in 1990 and activated in 2005, this regulation suppresses the production of ICE vehicles by imposing a minimum and rising quota for annual ZEV sales while incentivising efforts beyond this through credit-trading [162,209,210]. At the end of phase two, this regulation expanded to target heavy-duty truck manufacturers [211]. Second, structural reforms (S8.3) have reduced institutional support for ICE vehicles. One instrument, the Low Carbon Fuel Standard, destabilises the institutional environment supporting the gasoline-station industry. By setting a declining maximum carbon-intensity standard for transportation fuels, it stimulates the supply of alternative low-carbon fuels such as hydrogen while increasing the cost of hydrocarbons [212].

Efforts to phase out ICE vehicles increased in volume and intensity during phase two. From around 2018, support removal (S8.2) actions began as state actors dismantled subsidies that previously incentivised the purchase of low-emission ICE buses and trucks, redirecting these to ZEV technologies [213,214]. Explaining this, one policymaker highlighted the influence of the aforementioned ZEV-diffusion targets set by state governors (S3.1), in particular their 'scale' and 'compressed timeframe' (int. 35). In parallel, control and restriction measures (S8.1) were tightened. Not only are the minimum quotas for ZEV sales rising each year, the minimum share of ZEV purchases required for government vehicle fleets was also raised, and a phase-out of non-electric vehicles was mandated.

These strategies have produced mixed outcomes. With more than 7,000 FCEVs in circulation by mid-2020 [205], California boasts the world's largest on-road fleet. With no locally based FCEV manufacturing, vehicles have been coaxed to California from Asia through proactive demand creation (6.2) and supply-side measures suppressing the production of ICE vehicles (S8.1). Through its sustained demonstration programmes (S6.1), California has established a reputation as an attractive test bed for emerging fuel-cell technologies for domestic and overseas automakers (int. 40). As for limitations, the speed of vehicle and refuelling-station deployment is below historical expectations, with planning targets consistently missed (S3.1). Slow growth of the vehicle population can be explained firstly by the limited size of the refuelling network (currently around 43 stations in early 2020) and its inability to support a larger fleet of FCEVs, secondly by the limited production volumes of Asian automakers (see Section 5.2), and thirdly by the shift of electrification strategies towards batteries by domestic and overseas automakers previously developing FCEVs [68,205] (int. 35,38,39,41,43).

6. Discussion

6.1. Comparing strategies and phases

We now identify common trends across the three cases and two transition phases. Table 6 compiles the strategies employed, to enable a bird's-eye comparison.

One striking observation is that, aside from a few variations discussed below, most strategies are commonly employed in each case – despite highly diverse socio-political and cultural contexts. The main temporal trend is that strategies are *added* rather than removed during the acceleration phase.

Among overarching coordination strategies, commonly used are those reflecting top-down, managerial approaches and tight links between state and incumbent firms such as state–industry collaboration (S2.2) and planning and commitments (S3.1). The absence of measures to involve diverse actors in the principal governance structures for each mobility technology was expected, but in phase two, only China lacks explicit strategies to publicly disclose progress towards government targets.⁹

Considering targeted strategies for accelerating technological decline (C8) reveals sharp variations. Absent in Japan, they are used extensively in California and China. If viewed temporally, a ratcheting approach becomes visible, with the volume and stringency of strategies and associated instruments increasing in phase two. In China, this occurred notably through addition of structural reforms (S8.3) and actor changes (S8.4) by the state to stimulate mergers and increased ZEV production while removing institutional support for ICE vehicles. In California, government regulations for technology control and restriction (S8.1) and structural reforms (S8.3) were tightened or expanded (e.g. from passenger vehicles to trucks). Additionally, phase two saw an explicit strategy introduced to remove public subsidies (S8.2) for ICE trucks and buses.

Two findings merit emphasis given their slight deviation from transition approaches accentuated in literature. First, although legitimisation and advocacy (C4) occur in each country, strategies by industry in Japan and China are limited to influencing public views (S4.1). Political lobbying (S4.2) through dedicated industry entities was not observed. Interviewees in China and Japan echoed a view that close state–industry cooperation reduces the imperative for lobbying. A respondent in Japan (int. 19) stated: ‘Because the state and industry are promoting hydrogen energy together, I don’t see how the current situation requires political lobbying’. Similar observations were made for China (int. 1,3). It is possible that lobbying occurs via subtle or invisible channels. But evidence from China and Japan along with accounts in literature suggest that in developmental states, incumbent industry’s influence on policy likely occurs through ‘tight direct links that have formed over decades based on politics, bureaucracy and business’ [80] rather than dedicated lobbying *per se*.

The second noteworthy finding concerns industry protection (S5.4), used exclusively in China. Undoubtedly, imitating strategies in other countries such as import tariffs and discrimination against foreign firms would lack political feasibility. But their importance in nurturing the technological capabilities of Chinese firms suggests that different approaches to protecting new supply-side industries merit more attention from transitions scholars. This is especially apparent given the emphasis on ‘shielding niches’ in transitions literature [85] and the prevalent use of industry-protection tactics in developmental states [41,75,84].

⁹ Various industry trade associations (e.g. China EV100 and China Association of Automobile Manufacturers) along with private think tanks disparately release data on vehicle sales or charging pile installations. Yet we were unable to find an integrated and annually published report from a government affiliated organisation with comprehensive data permitting year-to-year comparisons on progress towards state targets or policy outcomes. See Pelkonen (2018).

6.2. Comparing contextual factors and instruments

Overall, our analysis has revealed similar patterns in strategy use across cases. Yet distinctions can be teased out by considering the contextual conditions influencing each transition approach and specific instruments used (e.g. regulatory or incentive-based), as Table 7 shows.

We begin with contextual details. With their incumbent vehicle industries, the transition to electric mobility in China and Japan was triggered by industrial development ambitions and the need to maintain automakers’ technological competitiveness in an increasingly carbon-sensitive and electrified global market. Lacking a local automotive industry, California’s transition strategy was triggered by environmental aspirations, and specifically the need to mitigate chronic air pollution while reducing the state’s largest source of climate emissions. Thus, the urgent environmental imperative to tackle poor air quality and reduce associated impacts on public health is exclusive to China and California.

Several sharper distinctions emerge if we consider the degree to which specific policy instruments are used to implement acceleration strategies. Here we consider two: regulation and market incentives. Other instruments like planning and public investments are also relevant to sustainability transitions [10,21]. Since these are widely used across all cases, we disregard them here.

The most notable difference lies in the use of stringent regulation. In California and China, command-and-control instruments were the driving force behind strategies aimed at cost alteration (S5.1), demand creation (S6.2), and technology control and restriction (S8.1). Here, environmental regulations were tightened or added to influence supply-side and demand-side behaviour. Examples include minimum ZEV-production quotas and procurement rules for public fleets mandating a minimum share of zero-emission powertrains and a phase-out of fossil-fuel counterparts. Regulation in China, seeking to increase public demand for ZEVs while curbing the growing ICE vehicle stock, even extended to affect individual behaviour through driving bans and restrictions on licence-plate allocation. No comparable regulations exist in Japan.¹⁰ Not only does demand creation (S6.2) rely solely on subsidy instruments, Japan’s general approach to regulation involves *removing* legal barriers, as visible for instance in efforts to dismantle market obstacles affecting refuelling stations (S6.3).

Further distinct variations emerge when considering the use of market incentives linked to environmental regulation. Critically, instruments distributing financial rewards based on environmental performance – as opposed to uniformly distributing fixed-subsidy amounts or ratios – are widespread in China and California. Here, environmental regulations mandate conformance to minimum standards (e.g. ZEV production ratios or the carbon intensity of transport fuel), then incentivise performance beyond this via opportunities for credit trading. China and California also encourage efforts to raise vehicles’ technical performance by allocating ZEV credits or subsidies to manufacturers in accord with driving range. Again, Japan’s transition approach differs. Instead of regulatory whips, Japanese state actors seek to influence the behaviour of incumbent industry through incentives such as subsidies and information provision.

The use of particular policy instruments can be explained by reconsidering the contextual conditions and ambitions to accelerate the decline of ICE vehicles (C8). Regarding regulation, chronic air pollution in China and California has historically provided a rationale for strict environmental regulation to accelerate the electrification of road transport (int. 4,6,27,29,38,44). The grave consequences for public health have also justified introducing supply-side and demand-side strategies to weaken the market share of ICE vehicles and their supporting institutions (C8). In California, the absence of an incumbent automotive industry lowers the political barriers to introducing rigorous

¹⁰ In late 2020, the Japanese government announced the intention to ban ICE vehicle sales – too late to count as ‘strong’ usage in phase two. See footnote 8.

Table 6
Comparison of strategy use across cases.

Category	Strategy	Phase 1: Pre-development & exploration			Phase 2: Acceleration		
		China	Japan	California	China	Japan	California
Overarching coordination strategies							
1. Knowledge management	1.1 Knowledge dissemination	●	●	●	●	●	●
2. Actor networks and collaboration	2.2 Inclusive governance	○	○	○	○	○	○
	2.2 State–industry collaboration	●	●	●	●	●	●
	2.3 Industry alliances	●	●	●	●	●	●
3. Guidance and planning	3.1 Planning and commitment	●	●	●	●	●	●
	3.2 Monitoring and disclosure	○	○	○	○	●	●
4. Legitimation and advocacy	4.1 Influencing public views	●	●	●	●	●	●
	4.2 Political lobbying	○	○	●	○	○	●
5. Industry creation and technology production	5.1 Cost alteration	●	●	●	●	●	●
	5.2 Industry nurturing	●	●	●	●	●	●
	5.3 Knowledge production	●	●	○	●	●	○
	5.4 Industry protection	●	○	○	●	○	○
6. Market creation and technology diffusion	6.1 Niche creation and experimentation	●	●	●	●	●	●
	6.2 Demand creation	●	○	●	●	●	●
	6.3 Removing market barriers	○	●	●	●	●	●
	6.4 Sectoral coupling	○	●	●	●	●	●
7. Resource mobilisation and allocation	7.1 Financial support	●	●	●	●	●	●
	7.2 Infrastructure preparation	●	●	●	●	●	●
	7.3 Human resource development	●	●	●	●	●	●
8. Reducing incumbent technology production and use	8.1 Technology control and restriction	●	○	●	●	○	●
	8.2 Support removal	○	○	○	●	○	●
	8.3 Structural reforms	○	○	●	●	○	●
	8.4 Actor changes	○	○	○	●	○	○

○ indicates use of a strategy is ‘weak’ or ‘not observed’. ● indicates use of a strategy is ‘strong’. See Section 3.2.

controls. Moreover, its attractive status as America’s largest vehicle market gives policymakers formidable negotiating power over automakers. As one state official remarked: ‘If they want to sell cars here, they have to figure out how to play [by our rules]’ (int. 38).

Also heavily influencing each country’s transition approach are broader and historical governance norms. Chinese policymakers’ ability to apply an iron fist can be explained by the vertical, single-party nature of the political apparatus and control over sub-national governments, state-owned enterprises, even private firms (int. 3,5,6). Commenting on this unique power, one respondent (int. 1) stated: ‘In other countries, these policies are not easily introduced. Can you imagine in Japan if they [the state] said, “You cannot drive your car on Thursday? Or you have to go through a lottery to get car plates?”’ Beyond automobiles, California has a long history of introducing aggressive environmental mandates to ‘push the envelope and set the regulations just a little beyond what is currently available [on the market]’, as one stakeholder observed (int. 27). Policymakers are thus skilled at dealing with industry resistance and, most importantly, are backed by environmentally progressive voters (int. 44). These enabling conditions are lacking in Japan, where voluntary industry frameworks and roadmaps rather than stringent regulation are the historical norm for environmental governance [159]. Japan’s absence of stringent regulations and decline strategies can also be explained by resistance from the automotive and gasoline industries [238] and the political difficulty of disrupting the economically important business models of incumbent automakers specialised in producing high-efficiency gasoline and hybrid engines (int. 14,19,22).

7. Conclusions

This paper aimed to deepen knowledge of the nature of top-down strategies used by networks of incumbent state and market actors to accelerate socio-technical transitions towards sustainability. Our comparison of strategies used in China, Japan, and California to spur the production and diffusion of battery and hydrogen mobility made two concrete contributions to scholarship. First, we married knowledge from sustainability transitions and the developmental state to identify mechanisms that drive socio-technical and industrial transformation, combining these into a comprehensive framework. This approach provides an important opportunity to overcome the limited ability of transitions scholarship to theorise the role of incumbents and top-down, managerial approaches. Second, in applying this framework to learn how such strategies work in three geographies underrepresented in scholarship, we built a rich repository of data on contemporary governance practices used in three countries at the forefront of electric mobility transitions, also identifying conditions affecting the choice of particular instruments.

What did our study reveal about the nature of top-down transitions? First, and not surprisingly, the main transition agents in each country are distinct communities of incumbents from government (both national and sub-national) and powerful firms such as automakers, fuel providers, and technology manufacturers. While elite knowledge producing institutions contribute to these transitions, civil society actors play a negligible role. Next, the incumbent actors use meticulously coordinated managerial strategies to guide markets, spur innovation, and influence supply-side and demand-side behaviour. Regarding the use of specific instruments, we observed active use of traditional policies (e.g.

Table 7
Defining attributes of each mobility transition.

	China	Japan	California
Contextual factors			
<i>Agency of industry in governance</i>	Limited	High	High
<i>Motivations (for state actors)</i>	Environmental amelioration (air pollution) Climate change mitigation Energy security Development of domestic automotive industry	Climate change mitigation Energy security Development of domestic automotive industry	Environmental amelioration (air pollution) Climate change mitigation
<i>Enabling or limiting factors</i>	Authoritative power of central and local government over industry and society Proliferation of state-owned enterprises under government control	Historical preference for industry-led voluntary frameworks in environmental governance Presence of incumbent ICE vehicle industry	Historical acceptance of state-led regulation in environmental governance Absence of incumbent ICE vehicle industry
Transition objective			
<i>Objective</i>	Creation and destruction	Creation only	Creation and destruction
Specific instruments			
<i>Use of stringent regulation</i>	Strong Used to influence supply-side and demand-side behaviour (S8.1, S8.3)	Weak Reformed to remove market barriers (S6.3)	Strong Used to influence supply-side and demand-side behaviour (S8.1)
<i>Use of market incentives</i>	Strong Performance-based subsidies to automakers (S5.1) Credit-based ZEV production quotas (S8.1)	Weak Absence of performance-based incentives Reliance on uniform subsidy amounts/ratios and public investment (S5.1, S6.2)	Strong Credit-based financial support to refuelling stations (S5.1) Credit-based ZEV production quotas (S8.1)

regulation, planning, subsidies, public investment and information) emphasised by developmental-state and governance scholars. Yet cases also revealed use of instruments championed by transition scholars (e.g. network building, visioning, niche-experimentation, and market-based incentives). Thus, as stated elsewhere [10,18], effective top-down transitions may involve a mix of contrasting governance paradigms (e.g. command-and-control, market-driven, network-driven). Scholars exploring incumbent-led transitions in other settings should therefore heed overlaps and conceptual blurriness when applying category-based theories to the messy reality of real-world cases.

Despite different political and social circumstances, findings revealed much resemblance in the core strategies driving each country's electric-mobility transition. Beneath the surface of generic strategies, however, we observed strong variation in the specific instruments used.

Appendix A. Summary of interview details

Period conducted	No. of interviews (respondents)*	Representative affiliations of respondents**
California		

(continued on next page)

These were particularly accentuated by comparing the use of regulation and performance-based market incentives, and ambitions to phase out ICE vehicles. As observed elsewhere [11], these variations are shaped by contextual factors, such as motivations in environmental amelioration and industrial development, incumbent industry's influence on policy, and the degree of regulatory authority wielded by state actors. We thus found that a politically feasible transitions approach in one country might not be in another.

By highlighting the strong agency exercised by incumbents in pursuing the transition to electric mobility, our study can enrich future scholarship. It reaffirms a stated need [16,125] to move past theoretical tendencies – whether implicit or explicit – to view newcomers and bottom-up approaches positively, while negatively portraying elites and policy-heavy, managerial strategies. Examining alternative governance approaches in regions thinly represented in literature might therefore deepen our understanding of the diverse tools available for accelerating socio-technical transitions. Along with other research [6,36,45,52], our study explicitly sought to cross-fertilise theories of socio-technical transitions with causal explanations of state-led industrial transformation. Yet the developmental state is just one of many fields with abundant knowledge on various mechanisms that state actors might use when pursuing socio-technical change, and conditions that can affect strategy formulation.

Finally, methodological limitations provide cues for future scholarship. First, when measuring the degree to which strategies were used in each case, we adopted broad definitions and a coarse binary evaluation that resulted in mostly 'strong' rather than 'weak/not observed' outcomes. Future studies could fix more stringent criteria or a wider spectrum of values [136] to generate finer-grained understanding of the relative importance of different strategies. Second, we did not systematically measure interactions between strategies [67,239]. Future work could tackle this by drawing on policy-mix literature and paying attention to synergistic and antagonistic relations [67,239,240]. Third, our choice to study ongoing, still-evolving cases has limitations. If full market penetration for each technology is taken as the desired end point, our cases provide insights into relevant strategies only during the market-formation phases of 'pre-development and exploration' and 'acceleration'. Finally, given the interlinked nature and spill-over effects of individual strategies, we refrained from speculating about their impacts. Future studies could focus more on this topic.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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(continued)

Period conducted	No. of interviews (respondents)*	Representative affiliations of respondents**
Mar – May 2020	20 (26)	Government: California Air Resources Board; California Energy Commission; California Governor's Office of Business & Economic Development; Port of Los Angeles Public-private: California Fuel Cell Partnership Private firms: Air Liquide USA; Honda (American Honda Motor Inc.); Hyundai-Kia (America Technical Center Inc.) Shell New Energies; True Zero (First Element Fuel Brand); Toyota (Toyota Motor North America) Universities: University of California, Berkeley (Institute of Transportation Studies); University of California, Davis (Institute of Transportation Studies) Non-profit: Center for Transportation and the Environment; International Council on Clean Transportation
China Nov 2019	6 (9)	Universities: Shenzhen University (College of Management); Tsinghua University, Shenzhen Graduate School (Research Center for Modern Logistics), University of California, Davis (China Center for Energy and Transportation) Private firms: WeBank Non-profit: Rock Environment and Energy Institute
Japan Jan 2019 – Mar 2020	18 (26)	Government: Ministry of Trade, Economy and Industry; New Energy Development Organisation; Tokyo Metropolitan Government Private firms and research institutes: Honda and Honda Central Laboratories; Iwatani; Japan H2 Mobility; Japan Research Institute; Kawasaki Heavy Industries; Mizuho Research Institute; Toyota Central Laboratories; Toyota Universities: Kyushu University (International Institute for Carbon Neutral Research); Musashino University; Tama University
Total	44 (61)	

Notes: * Four interviews, included here, were conducted outside this period as follows: Japan (March 2018), China (March 2020 and January 2021) and California (February 2021). ** Not all affiliations are listed.

Appendix B Indicators for evaluating strategy use in each country

Category	Strategy	Indicator*	
Overarching coordination strategies			
1. Knowledge management	<i>1.1 Knowledge dissemination</i>	“Strong” if there are multiple, explicit and consistent** measures to foster knowledge exchange and dissemination across government and industry such as information sharing networks, symposiums, publications, collaborations etc.	
	2. Actor networks and collaboration	<i>2.1 Inclusive governance</i>	“Strong” if there are multiple, explicit and consistent measures to balance the participation of incumbent actors with diverse social actors (e.g. NGOs, citizen groups) in the principal governance framework or decision-making body.
		<i>2.2 State–industry collaboration</i>	“Strong” if there are multiple, explicit and consistent collaborations between government and incumbent industry such as public–private partnerships/projects, foundation of public–private organisations or production of joint outputs like roadmaps, etc.
3. Guidance and planning	<i>2.3 Industry alliances</i>	“Strong” if there are multiple, explicit and consistent measures to foster the development of joint actions across industry such as partnerships, coalitions, foundations or joint projects/investments etc.	
	<i>3.1 Planning and commitment</i>	“Strong” if explicit goals/targets for production/diffusion etc. or formalised commitments to support the technology and associated socio-technical arrangements and encourage investments have been issued.	
	<i>3.2 Monitoring and disclosure</i>	“Strong” if progress towards key targets for vehicle and infrastructure deployment are monitored and disclosed annually to the public in an integrated format (e.g. report) allowing year-to-year comparisons.	
Targeted strategies for accelerating creation and diffusion			
4. Legitimisation and advocacy	<i>4.1 Influencing public views</i>	“Strong” if there are multiple, explicit and consistent measures to create a positive image or reputation of the new technology through marketing, public-relation campaigns (in conventional and social media), and showcase events etc.	
	<i>4.2 Political lobbying</i>	“Strong” if there are multiple, explicit and consistent measures by firms to influence government policy or support through dedicated advocacy coalitions.	
	5. Industry creation and technology production	<i>5.1 Cost alteration</i>	“Strong” if there are multiple, explicit and consistent measures to assist firms to reduce the cost of producing, purchasing or using the targeted technology or to generate extra income or reward good behaviour (e.g. subsidies, pricing schemes, carbon pricing schemes etc.).
<i>5.2 Industry nurturing</i>		“Strong” if there are multiple, explicit and consistent measures to support the creation or expansion of new or larger technology producers to increase the supply of technology (e.g. subsidies for R&D or production, tax credits, land provision, formation of technology parks or regional clusters, local content requirements, etc.).	
<i>5.3 Knowledge production</i>		“Strong” if there are multiple, explicit and consistent measures that support the creation of both basic and applied knowledge (i.e. both scientific and practical in nature) such as funding for R&D, technology parks, research centres and demonstration projects etc.	
<i>5.4 Industry protection</i>		“Strong” if there are multiple, explicit and consistent policies or institutions in place to protect domestic industry (especially technology manufacturers) from external/overseas competition such as discriminatory subsidies, rules/laws, import tariffs etc.	
6. Market creation and technology diffusion	<i>6.1 Niche creation and experimentation</i>	“Strong” if there are multiple, explicit and consistent efforts and support mechanisms for experimentation and the testing of novel technologies, policies, business models and social arrangements such as funding schemes, public demonstrations, pilot projects, innovation districts etc.	
	<i>6.2 Demand creation</i>	“Strong” if there are multiple, explicit and consistent measures that target technology users to increase or stimulate purchases for new technology such as economic incentives (e.g. purchase subsidies or tax waivers), non-economic incentives (e.g. priority use of car pool lanes) or public procurement initiatives.	
	<i>6.3 Removing market barriers</i>	“Strong” if there are multiple, explicit and consistent measures to both (i) reform policies or formal institutions (e.g. standards and laws) and (ii) establish technical standards, in the goal of reducing market obstacles for new technologies or investments.	
	<i>6.4 Sectoral coupling</i>		

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Category	Strategy	Indicator*
7. Resource mobilisation and allocation	7.1 Financial support	“Strong” if there are multiple, explicit and consistent measures to link the production or usage of electric mobility or related technologies across different markets to accelerate overall technological advancement, synergies or cost reduction via economies of scale etc.
	7.2 Infrastructure preparation	“Strong” if there are multiple, explicit and consistent measures that directly supply financial capital or revenue to support the production, demonstration or diffusion of new technologies and associated infrastructure or business models such as subsidies, grants, loan programs, market incentives etc.
	7.3 Human resource development	“Strong” if there are multiple, explicit and consistent support schemes or investments by government or industry for refuelling or recharging stations such as funding schemes, policy targets, regulatory changes, industry platforms etc.
8. Reducing incumbent technology production and use	8.1 Technology control and restriction	“Strong” if there are explicit measures to accelerate the development of human resources such as training programs or financial or institutional support for industry and research/educational institutions.
	8.2 Support removal	“Strong” if there are explicit and mandatory government policies to restrict the production, sale or use of ICE vehicles such as environmental standards (e.g. emissions regulations) or control policies (e.g. driving or production bans, production quotas, etc.) in the goal of accelerating the transition to electric mobility.
	8.3 Structural reforms	“Strong” if there are explicit government policies that reduce or remove existing support or incentives for ICE vehicles such as reductions in subsidies, R&D schemes, institutional incentives (e.g. tax reductions) etc. in the goal of accelerating the transition to electric mobility.
	8.4 Actor changes	“Strong” if there are explicit policies that alter the wider market or regulatory environment to promote new entrants, accelerate production/adoption of ZEVs or weaken the institutional arrangements supporting the incumbent ICE vehicle industry (e.g. carbon standards or increased taxes for the production/sale of fossil-fuel for transport or the sale/use of ICE vehicles, etc.).

Notes:

* A value of ‘weak or not observed’ was allocated when the degree of utilisation was inferior to descriptions in the listed indicator or if no corresponding strategies were observed.

** We take ‘consistent’ to mean the continuation of the same measure over multiple years (at least two) consecutively.

Appendix C. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.erss.2021.102184>.

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