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Exploring the fuel-cell technological innovation system: Technology interactions in the mobility sector

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ABSTRACT

With the rise of alternative sustainable powertrain technologies, the mobility paradigm has undergone fundamental changes in recent years. In the wake of the ongoing transition of the road-vehicle sector, fuel-cell vehicles (FCVs) have received increased political attention. However, they constitute only a tiny fraction of total road vehicles nowadays and still face competition from other powertrain technologies. Therefore, this study specifically focuses on how the focal technological innovation system of FCVs is influenced by the emerging electric vehicles (EVs) and established internal combustion engine vehicles (ICEVs) as its context structures. To this end, our time-series vector error correction models analyze the short- and long-run causalities between our focal TIS and its context structures. Using publications, patents, and standards as quantitative TIS indicators, we analyze the modes of technology interaction between FCVs and EVs and FCVs and ICEVs to determine the life-cycle phase of our focal FCV-TIS in more depth. Our results demonstrate that the FCV-TIS is in its formative phase based on the dominance of the EV and ICEV context structures. As policy implications, we derive application-sensitive technology policies that combine the benefits of each mobility technology toward the sustainable transition of the mobility sector.

1. Introduction

Hydrogen technologies offer the potential to tackle global challenges related to the clean energy transition[1] and energy security. Various governments worldwide have acknowledged this potential and codified it in the form of national hydrogen strategies (Albrecht et al., 2020; IEA, 2021). Among these hydrogen strategies, several countries have formulated the transition of mobility as one of the target sectors (IEA, 2021). Accordingly, hydrogen technologies, including hydrogen fuel-cell vehicles (FCVs), have received increased R&D funding ever since (Behling, 2013; Li et al., 2020). FCVs present a promising option for decarbonizing road transport characterized by short refilling times and the ability to operate over longer distances (Aminudin et al., 2023; Xu et al., 2022). However, they face competition from other mobility technologies. Electric vehicles (EVs), as an emerging technology, and established internal combustion engine vehicles (ICEVs), along with hybrid vehicles, are currently the dominant technology designs in road transport (Pohl & Yarime, 2012; Sinigaglia et al., 2022a; Weiss & Scherer, 2021, 2023). Due to the lack of infrastructure, issues with the sustainability of hydrogen production, safety concerns, and their currently high price (Hardman et al., 2017; Keles et al., 2008; Morrison et al., 2018), FCVs make up only a tiny share of vehicle sales worldwide (IEA, 2022; Manoharan et al., 2019). Nevertheless, FCVs are expected to gain a greater role in the global vehicle market, especially because hydrogen combustion produces zero emissions (Acar et al., 2022).

Previous research has addressed the relationship between FCVs and EVs in terms of their chemical and physical features, vehicle mileage, fueling or charging times, vehicle costs, energy use, greenhouse gas emissions, and patenting activities (Morrison et al., 2018; Sinigaglia et al., 2022b; Thomas, 2009; Wong et al., 2021; Yang et al., 2020). For the FCV-ICEV relationship, previous research compares both powertrain technologies in terms of their technology life cycle, energy use, greenhouse gas emissions, vehicle range, and R&D funding (Liu et al., 2020; Pohl & Yarime, 2012; Yang et al., 2020). Despite these theoretical and

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[1] Note: Only if the hydrogen is produced from renewable energy, it can be considered as green.

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empirical attempts, little is known about the causal relationship between research and innovation in FCVs compared to EVs and ICEVs. Therefore, this study aims to comparatively analyze research and innovation in FCVs, EVs, and ICEVs as mobility technologies with different degrees of maturity.

To this end, we apply the *technological innovation system* (TIS) approach (Bergek et al., 2015; Markard, 2020; Wieczorek & Hekkert, 2012) and the modes of technology interaction (Sandén & Hillman, 2011) using scientific publications, patents, and standards (PPS) as indicators. These indicators are closely linked to the R&D profiles of firms and institutions and disseminate their R&D output (Asna Ashari et al., 2023; Asna Ashari & Blind, 2024; OECD & Eurostat, 2018; Watts & Porter, 1997).

We focus on how our focal TIS of interest in mobility, FCVs, interacts with EVs and ICEVs as context structures to derive implications for the life-cycle phase of the FCV-TIS (Markard, 2020). In doing so, we delve into the recent trend of quantitative research exploring various dimensions of TIS-TIS interactions, including knowledge exchange, expectations, and firm cooperation (e.g., Noailly & Shestalova, 2017; Mirzadeh Phirouzabadi et al., 2020a, 2020b, 2020c, 2020d). Specifically, we build on the latest research by Mirzadeh Phirouzabadi et al. (2022), exploring various dimensions of TIS-TIS interactions through multiple indicators. We extend their previous insights into powertrain technologies with a focused analysis of FCVs. Moreover, we complement their system dynamics approach to functional TIS-TIS interactions with our TIS life-cycle perspective, offering a dedicated structural understanding of the nature of technology interactions. Following this work by Mirzadeh Phirouzabadi et al., as well as Weiss and Scherer (2021, 2023), and Weiss and Nemeczek (2022), we delineate our TIS with a focus on road vehicle applications.[2] The above-described research gap guides us in addressing the following research questions:

RQ1: How can the modes of technology interaction be integrated empirically into the TIS life-cycle analysis?

RQ2: Do changes in the research and innovation progress of EV and ICEV technological context structures influence the focal FCV-TIS in the short and long run?

RQ3: How does the FCV-TIS life-cycle phase compare to EVs and ICEVs in terms of research and innovation progress and impact?

We answer these research questions based on a combination of both descriptive and time-series analyses investigating the causal relationships between these mobility technologies and their impact on the focal FCV-TIS. For publications and patents, we cover the period 1980–2019, while the period 2000–2019 is relevant for the analysis of standards across the three technologies. With this study, we contribute to previous research at multiple levels: At a theoretical level, we contribute to previous TIS research by considering competing TISs in the mobility sector as context structures, using PPS as indicators. Furthermore, we empirically relate the TIS approach to the modes of technology interaction introduced by Sandén and Hillman (2011). We thus better grasp TIS-context relations and transition pathways in mobility. At a methodological level, we conduct, to the best of our knowledge, the first time-series analysis to explore the causal relationships between a focal TIS and its context structures. As policy implications, we formulate the need for application-sensitive technology policies that better exploit the benefits of each mobility technology based on their past interactions.

The remainder of this research paper is structured as follows: Section 2 presents the conceptual framework. Section 3 introduces the descriptive analysis. Section 4 is the joint methods and results section of our time-series analysis. In Section 5, we discuss the results with respect to the conceptual background. The final Section contains concluding remarks, policy implications, limitations of our study, and pathways for future research.

2. Conceptual background

2.1. Life cycle of technological innovation systems

We apply the *life cycle of technological innovation systems* (TIS) as a framework for analysis. A TIS is defined as “a set of elements, including technologies, actors, networks and institutions, which actively contribute to the development of a particular technology field” (Bergek et al., 2015). Following this definition, previous TIS literature distinguishes functional TIS analyses, focusing on the seven system functions (e.g., Bergek et al., 2008; De Oliveira & Negro, 2019; Hekkert et al., 2007), including in the context of transportation (Bach et al., 2020), and structural TIS analyses (e.g., Markard, 2020; Markard et al., 2020; Wieczorek & Hekkert, 2012), focusing on the analysis of the above-mentioned TIS elements. Recently, Markard (2020) introduced the TIS life-cycle framework, which offers an adequate framework for analyzing the emergence of new technologies, the decline of incumbent technologies, and the interaction between them. This study explores the interaction of the FCV-TIS with the emerging EV-TIS and the declining ICEV-TIS. To this end, we analyze the life-cycle phase and development of our focal FCV-TIS along the four dimensions of the TIS framework: size and actor base, e.g., related manufacturers, suppliers, or research institutes; institutional structure and networks, such as regulations, standards, or informal ones such as social norms; technology performance and variation, i.e., rising or declining technology development; and the context and TIS-context relations (Markard, 2020; Markard et al., 2020). To assess the life cycle of the focal FCV-TIS, we explain the characteristics of the four life-cycle phases along the TIS dimensions proposed by Markard (2020): the formative, growth, maturity, and decline phases. The four phases differ in terms of TIS size and actor base, i.e., market size, the number of actors’ entries and exits from the TIS; the degree of institutional structuration and network development; technology performance and variation; and the degree of interaction between the focal TIS and its context structures.

In the formative phase, TIS-context relations are characterized by the context structures shaping the focal TIS, and not vice versa. In the growth phase, TIS-context relations develop toward an increasingly dominant impact of the focal TIS on the context, causing conflicts or co-dependence with its context structures. In the maturity phase, TIS-context relations are characterized by more established interactions, resulting in the co-dependence of competing technologies. In the decline phase, the focal TIS is increasingly challenged by other emerging technologies, thereby losing influence. Despite the importance of the context structures in shaping the focal TIS, only Markard et al. (2020) have analyzed the TIS-context relations to determine the life-cycle phase of the focal TIS. Especially, the impact of competing TISs on the focal TIS from this life cycle perspective is barely explored. Therefore, our approach offers a complementary structural perspective to existing research on TIS-TIS interactions from a functional standpoint, as explored in extensive studies by Mirzadeh Phirouzabadi et al., (2020a,2020b,2020c, 2020d, 2022). Notably, we will revisit the complementarity of these perspectives in the discussion section.

2.2. Publications, patents, and standards as empirical TIS indicators

To operationalize the relationship between the focal FCV-TIS and its context structures, we use publications, patents, and standards (PPS) as empirical TIS indicators following Asna Ashari et al. (2023). PPS are knowledge and technology transfer channels and indicators that disseminate research and innovation progress (Blind & Fenton, 2022; Blind et al., 2018; Dziallas & Blind, 2019), including standards accompanying and supporting innovation (Blind & Gauch, 2009; Featherston et al., 2016). PPS codify knowledge and technology flows (OECD & Eurostat, 2018) and constitute sources and objectives of research and

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[2] We do not consider hybrid vehicles as a separate TIS because they are dominated by the prevailing ICE technology design (Suarez et al., 2018; Weiss & Scherer, 2021, 2023).

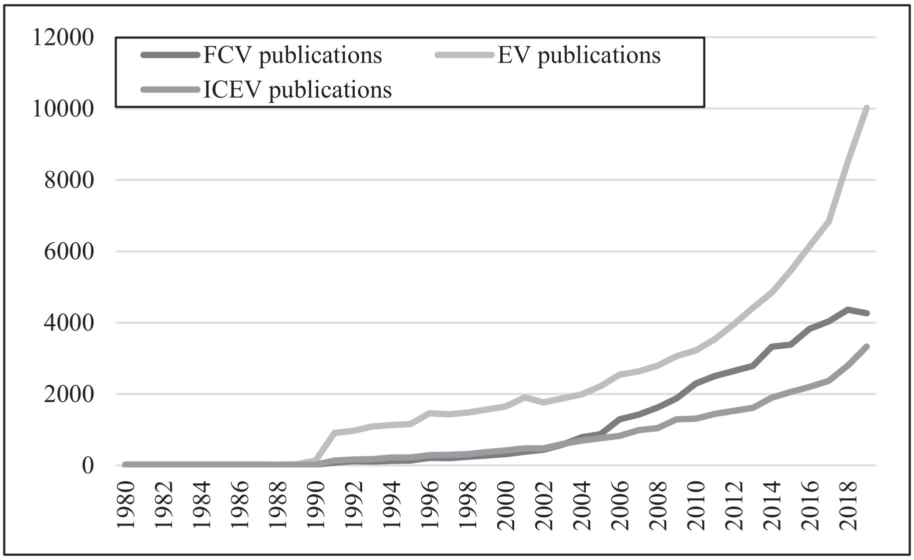

Fig. 1. Publications per year compared by technology.

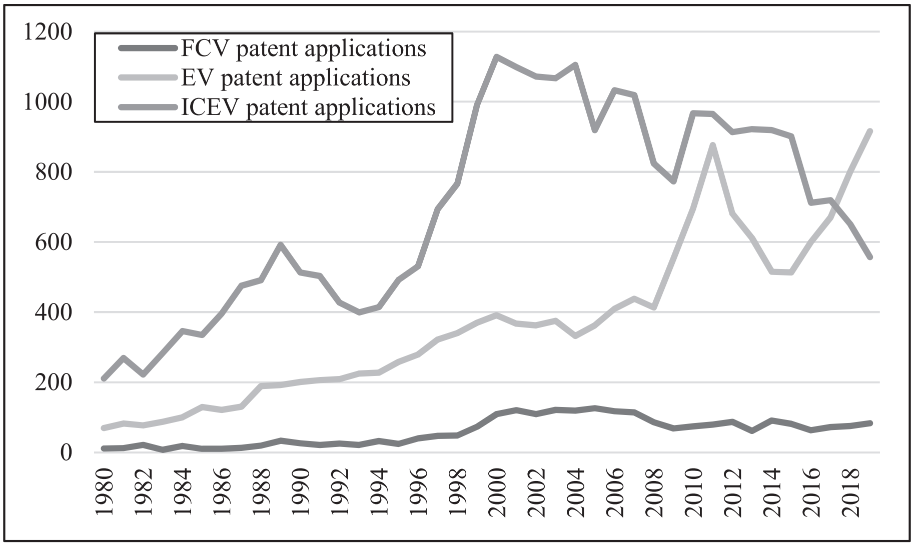

Fig. 2. Patent applications (earliest priority date) compared by technology (1980–2019).

innovation. As postulated, e.g., by Markard (2020) and Asna Ashari et al. (2023), publications and patents can serve as indicators of the size and actor base. They represent the evolution of TIS actors based on the participation of research and industrial actors and point out the TIS size based on patents as an indicator of innovation linked to market formation. Within the institutional structure of a TIS, innovation-specific institutions, including standards, laws, and regulations, are important elements that provide guidance for stakeholders toward the development and diffusion of innovations (Ghazinoory et al., 2020; Ortt & Kamp, 2022). Therefore, we refer to standards as representing the TIS's institutional structure. More specifically, standards represent the self-regulatory part of the institutional structure of a TIS but might explicitly complement the regulatory framework, such as in the EU (Blind et al., 2017).

In addition to quantitatively operationalizing the size and actor base and institutional structure, PPS can also proxy technology variation and performance by capturing research and technological trends, including the performance and variation in technological designs (Asna Ashari et al., 2023). However, we are aware that PPS do not capture the TIS dynamics and developments in their entirety. Instead, PPS provide an R&D-based perspective on the TIS. Since our objective is to determine the life cycle of the focal FCV-TIS in relation to the EV-TIS and ICEV-TIS, our quantitative analysis creates better comparability of technology interactions, bearing in mind the complexity of the TIS. Herewith, our analysis adds to previous TIS research that is primarily based on qualitative designs (Ko et al., 2021; Konrad et al., 2012), literature reviews (Bauer et al., 2017; Markard et al., 2020; Nevzorova & Karakaya, 2020), or quantitative analyses with limited representativeness of knowledge and technology indicators, e.g., when only publication or patent data are used as TIS indicators (Kushnir et al., 2020; Li et al., 2022; Mirzadeh Phirouzabadi et al., 2020a; Weiss & Scherer, 2021, 2023).

2.3. Modes of TIS-TIS interaction

In this study, we extend the use of PPS to the context and TIS-context relations. Context structures refer to the elements outside a focal TIS that influence the latter and vice versa (Bergek et al., 2015; Markard, 2020). Bergek et al. (2015) distinguish four types of context structures: 1.) Interactions between a focal TIS and other TISs; 2.) interactions between a focal TIS and sectors in which the TIS is embedded; 3.) interactions between a focal TIS and geographic context structures; and 4.) interactions between a focal TIS and its political context. Empirical TIS research focuses on analyses of sectoral (e.g., De Oliveira & Negro, 2019; Stephan et al., 2017) and spatial (e.g., Binz et al., 2014; Murphy, 2015; Weiss & Scherer, 2021, 2023) TIS-context relations, while largely neglecting political (Markard et al., 2015; Reichardt et al., 2017) and TIS-TIS ones (Mirzadeh Phirouzabadi et al., 2020a).

However, the TIS framework does not fully conceptualize and operationalize the TIS-context relations for quantitative research. Previous TIS studies (e.g., Markard, 2020; Markard et al., 2020) have focused on complementarity or competing technology interactions (Bergek et al., 2015) using qualitative approaches and associated indicators. In contrast, we deploy the framework by Sandén and Hillman (2011), which can be operationalized quantitatively (see Mirzadeh Phirouzabadi et al., 2020a). Herewith, we contribute to the limited but growing number of quantitative analyses of TIS-context relations (e.g., Binz et al., 2014; Li et al., 2022; Mirzadeh Phirouzabadi et al., 2020a). In doing so, we focus specifically on TIS-TIS interactions (Kieft et al., 2021; Sandén & Hillman, 2011) and determine the FCV-TIS life-cycle phase more comprehensively than previous studies (Markard, 2020; Markard et al., 2020) based on PPS as TIS indicators (Asna Ashari et al., 2023; Mirzadeh Phirouzabadi et al., 2020a; Noailly & Shestalova, 2017; Sandén & Hillman, 2011).

The model of technology interaction proposed by Sandén and Hillman (2011) revolves around three dimensions, describing how different TISs overlap with each other: 1.) The material dimension captures physical artifacts like production lines, infrastructure, or resources; 2.) The organizational dimension considers actors such as individuals, companies, research institutes, and governmental bodies as well as associated networks; 3.) The conceptional dimension involves 'schemata' that include (technological) knowledge, expectations, and normative and regulative rules, i.e., laws, norms, and conventions. Considering these dimensions, two TISs can influence each other through knowledge spillovers created by patents or publications, expectations toward a common goal, e.g., sustainable mobility, or regulations and standards pertaining to multiple technologies, and through shared value chains and associated manufacturers or suppliers. Thereupon, Sandén and Hillman (2011) define the six modes of technology interaction: competition for markets and resources; symbiosis, i.e., technologies along the same value chain or complementarity; neutralism, i.e., no technological or geographic overlap; parasitism, e.g., a new or emerging technology benefiting from a more established technology while simultaneously displacing it; commensalism, i.e., "the resource that is developed by one technology and made available for a second technology" (Sandén & Hillman, 2011); amensalism, where the new technology is typically blocked from entering the established innovation system of the old technology (Table 1).

3. Descriptive data analysis

This section presents the descriptive results of the analysis of FCVs, EVs, and ICEVs compared by scientific publications, patent applications, and international standards. A detailed overview of the data collection approach is given in Appendix A.

Scientific publications

Fig. 1 compares the development of the annual number of published research articles and proceeding papers related to FCVs, EVs, and ICEVs between 1980 and 2019. Across all technologies, we observe a general rise in the research amount. However, the total amount of research per technology varies widely. FCV-related publications amount to 44,669, while those related to EVs and ICEVs amount to 91,041 and 30,467, respectively (Table A.1). Thus, there appears to be more research-based knowledge on EVs than on FCVs and ICEVs. While the growth in new FCV publications has stagnated since 2018, EV publications, in particular, have increased exponentially since 1991. Relating this finding to Markard's (2020) TIS life cycle, the FCV-TIS has received less attention in academia than the EV one but more than the incumbent ICEV-TIS. Therefore, from the perspective of publications, the FCV-TIS has experienced growth beyond the formative phase.

Patents

In contrast to scientific publications, the pattern in patenting shows that most patent applications are linked to ICEVs (27,615), followed by EVs (14,694) and FCVs (2,366) (Table A.2). This pattern points to a greater market relevance of ICEVs and EVs compared with FCVs. However, the trend in patenting reveals that ICEV patenting growth has stagnated and declined since 2000, while EV patenting has increased steadily since 2008, except for the 2011–2014 period, and even surpassed ICEV patenting in 2018 and 2019 (Fig. 2). FCV patenting remained at the lowest level overall, with a peak in 2005. Apart from the increase in the early 2000 s, which corresponds to the hype cycle of hydrogen technologies (Bakker, 2010), FCV patenting has remained at a consistently low and stagnant level. Thus, FCV patenting appears to be in its formative TIS life-cycle phase (Asna Ashari et al., 2023; Markard, 2020), as the overall number of filed patents is lower compared with EVs

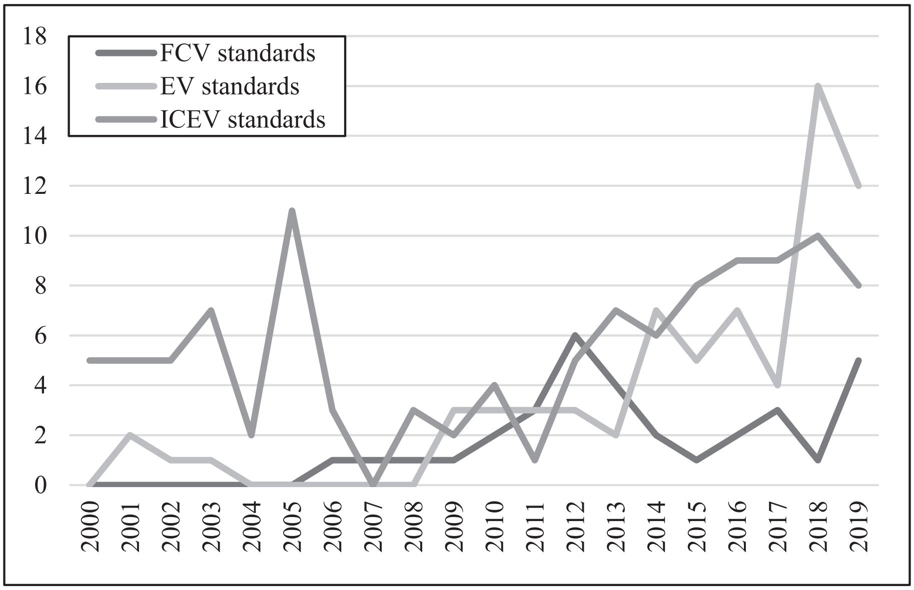

Fig. 3. Published standards compared by technology (2000–2019).

and ICEVs.

Standards

Standardization in the international standards bodies ISO (*International Organization for Standardization*) and IEC (*International Electrochemical Commission*) has been dominated by the development of ICEV-related standards. Between 2000 and 2019, 110 ICEV-related standards were published, compared with 69 EV-related and 33 FCV-related standards (Table A.3). Furthermore, 92 ICEV standards were published between 1980 and 1999, compared with zero standards for FCVs and EVs in the same period. Therefore, we truncated the period for the standards to 2000–2019 because we cannot assume any meaningful interplay between the three technologies before 2000. In 2009, 2014, 2018, and 2019, the number of EV standards equaled or exceeded ICEV standards, thus pointing to increased standardization in EVs compared with the mature ICEV, which has been going through standardization for many decades. The revision of old standard documents and the emergence of more hybrid-vehicle standards applicable to both ICEVs and EVs explain the increasing number of published ICEV standards in recent years. In contrast to EVs and ICEVs, FCV standards have been published since 2006 and have remained at a comparatively low level despite exceeding EV and ICEV standardization in the early 2010 s. Overall, EVs and ICEVs seem to compete and influence each other in international standardization, while FCVs have not yet played a substantial role. Despite individual growth phases compared with EVs and ICEVs, the standard-based FCV-TIS is still in its formative phase (Asna Ashari et al., 2023; Markard, 2020) due to the overall low number of published FCV standards.

4. Methods and results

Previous quantitative approaches capturing the TIS-TIS relations are based on regression analyses of patent citation data for knowledge spillovers and geographic distance (Li et al., 2022; Mirzadeh Phirouzabadi et al., 2020a). Besides the well-known drawbacks of using citation data (Jaffe et al., 2019), these previous approaches required an ex-ante structural specification of the regression model, potentially predetermining the direction of influence (Streb et al., 2007). Moreover, they lack the differentiation between short- and long-run relations, as described by Sandén and Hillman (2011).

Therefore, we use a *vector error correction model* (VECM) as a method applied in previous publication and patent analyses (Streb et al., 2007; Wang et al., 2012). A VECM is particularly suitable for identifying short- and long-run interactions between endogenous variables without any apriori assumptions about the direction of causality (Streb et al., 2007; Wang et al., 2012). A VECM is a special case of a vector autoregression (VAR) model in which non-stationary variables are combined to obtain a long-run stationary linear cointegration relation. Herewith, the model derives both short- and long-term coefficients. The former refers to the contemporaneous relationship between the included variables. The latter, long-term coefficients, or error correction terms (ECT), measure the speed of adjustment of the variables towards their long-run development path given by their cointegration relation. To estimate the VECM for each of the variables, publications, patents, and standards (PPS) per technology, we first conducted unit root tests to verify if all variables are stationary in the first difference, I(1).

Second, we tested for the presence of a cointegration relationship. Finally, we estimated the three respective VECMs using the Johansen normalization restriction (Johansen, 1995; Lütkepohl, 2005). These two conditions must be met for a VECM to be an applicable estimation model for the underlying data. For the model selection and validation, we apply a combination of ex-ante lag order selection criteria, i.e., Akaike's information criterion (AIC), Schwarz's Bayesian information criterion (SBIC), the Hannan and Quinn information criterion (HQIC), and post-estimation diagnostics, including testing for autocorrelation in the residuals and checking the stationarity of the cointegration equations. In doing so, we aim for a parsimonious model with the smallest optimal/valid lag order and add additional lags if the autocorrelation or stability conditions of the VECM are not met (Lütkepohl, 2005).

Similar to Li et al. (2022) and Mirzadeh Phirouzabadi et al., (2020a), we operationalize our analysis of technology relations based on the significance levels and signs of the estimated regression coefficients. In particular, the VECM coefficients capture how a positive change in one variable affects another variable in the short and long run, considering both the direction and magnitude of the effects (Wang et al., 2012). Following Sandén and Hillman (2011), this allows us to capture the six modes of technology interaction between the focal FCV-TIS and the EV-TIS and the ICEV-TIS as technological context structures. Table 1 illustrates the empirical operationalization of the modes of technology interaction following Sandén and Hillman (2011). To fully capture these technology relations in the long run, we follow Gupta and Jain (2020) and estimate the VECMs not only with FCV but also with EV and ICEV as dependent variables to estimate the coefficients from both sides (see Table B.1, Appendix B).

For comparability with related TIS studies on technology relations, we methodologically restrict our analysis to technology relations within a particular knowledge and technology transfer channel. Hereby, we exclude potential spillover effects between different channels, such as from EV publications to EV or FCV patents. While we acknowledge the limitations this methodological choice imposes on the coverage of potential technology relations between the TISs, we emphasize several potential issues: First, we face issues with reliable citation data between the channels, especially patent citations, which are often distorted by differences in national patent laws and citations added by patents (Grupp, 1997; Noailly & Shestalova, 2017; Oltra & Saint Jean, 2009). Second, there are potential differences in the industry clockspeed that could bias the empirical results in favor of a particular TIS, e.g., the pace by which scientific knowledge is transposed into patent documents is relatively slow in the hydrogen industry (Asna Ashari et al., 2023; Dedehayir & Mäkinen, 2011; Sick et al., 2018). Therefore, we do not consider such analysis within the scope of our present study and refer to it as a pathway for future research.

Table 1
Empirical operationalization of technology relations based on Sandén and Hillman (2011).

Technology relation	Effect on focal TIS (FCV)	Effect on context (EV, ICEV)	Interpretation
Competition	–	–	TIS inhibited if context exhibits positive development and vice versa
Symbiosis	+	+	TIS benefitted if context exhibits positive development and vice versa
Neutralism	0	0	No statistically significant interaction between TIS and context
Parasitism	+	–	TIS benefitted if context exhibits positive development; context inhibited if TIS exhibits positive development
Commensalism	+	0	TIS benefitted if context exhibits positive development; context not affected if TIS exhibits positive development
Amensalism	–	0	TIS inhibited if context exhibits positive development; context not affected if TIS exhibits positive development

+/-: significantly positive/negative coefficient (at least 10% significance level).
0: coefficient not significant (at least 10% significance level).

4.1. Tests for unit root

Applying the Augmented Dickey-Fuller (ADF) test (Dickey & Fuller, 1979, 1981), the Kwiatkowski–Phillips–Schmidt–Shin (KPSS) test (Kwiatkowski et al., 1992), and the Phillips-Perron (P-P) test for unit root (Phillips & Perron, 1988), we determined each variable's order of integration. The latter represents the number of integrations of a time series necessary to turn a non-stationary time series at levels stationary at *n* differences. Without the same order of integration, our variables cannot be cointegrated, and thus our VECM cannot be estimated (Giles et al., 2002; Lütkepohl, 2005).

Table 2 gives an overview of the unit root tests. Except for FCV standards in the KPSS test and the ICEV standards in the P-P test, all tests for unit root confirm the presence of a unit root or non-stationarity in each time series at levels. Due to the non-stationarity at levels, we generated the first difference for each variable. Although the ADF test does not confirm the stationarity of the first differences for FCV publications and EV standards, the KPSS and P-P tests confirm the stationarity of all variables in the first differences. Therefore, all variables are integrated in the same order, I(1). Notably, we double-checked for stationarity by testing the stability of the estimated VECMs (Lütkepohl, 2005).[3]

For the ADF and KPSS tests, the optimal lag lengths were determined using Akaike's information criterion (AIC), Schwarz's Bayesian information criterion (SBIC), the Hannan and Quinn information criterion (HQIC), and the final prediction error (FPE) (Lütkepohl, 2005). However, while testing for unit roots, we added at least one or two lags more than suggested by the information criteria to avoid a potential loss of information caused by a too small lag length. The optimal lag length for the P-P test was already given by the Newey-West lags as part of the test (StataCorp, 2022).

4.2. Tests for cointegration

Given that all our variables are I(1), we continued to test the presence of a stationary long-run cointegration relation among our variables suitable for estimating the VECM (Lütkepohl, 2005). Table 3 provides an overview of the results of the trace statistic test following Johansen (1995). Since we observe a linear trend when plotting publications and standards over time, we test the cointegration relations with an unrestricted constant and a restricted trend. When we identified a significant rank with the restricted trend option, we proceeded to test the significance of the trend component after the VECM estimation or otherwise using the unrestricted constant (Johansen, 1988). For patents, we additionally deploy the restricted constant since we do not observe a common trend of the variables when plotted over time. For consistency, we also tested the restricted constant option for publications and standards. Using a restricted trend and restricted constant, the results suggest a cointegration rank of one for publications. For patents, we observe a rank of one using a restricted constant. For standards, we find a rank of one using an unrestricted constant. We will use these results in the following sections to specify our VECM estimations. Since our analysis of technology relations is based mainly on the estimated VECM coefficients, we describe the respective cointegration relations in Appendix C for completeness.

4.3. VECM causality results

To investigate the short- and long-run causality between the focal FCV-TIS and EV and ICEV in scientific publications, we estimate our first VECM model with *log_FCVpubl* as the dependent variable. To determine the optimal lag length of our VECM, the AIC recommends four lags, the SBIC one lag, and the HQIC two lags. We chose the two-lag model to model both the short- and long-run causality among the three TISs. Following our diagnostic tests, we added an extra lag to account for the remaining autocorrelation in the two-lag model. The results of our trivariate publication model with three lags and a restricted trend are given in Table 4.

For the first *log_FCVpubl* equation, the ECT is insignificant, showing no evidence of a long-run adjustment of *log_FCVpubl* when its growth rate is above or below the long-term development path of the cointegration relation. We find evidence of a short-run causality between the past and present values of *log_FCVpubl*, given by the significantly negative coefficient for the first lag (*Δlog_FCVpubl(−1)*). We find even stronger evidence of a short-run causality between past *log_EVpubl* growth and present *log_FCVpubl* growth, with *Δlog_EVpubl(−1)* having a significant and positive coefficient. In contrast, the coefficient of *Δlog_ICEVpubl(−1)* is insignificant. In the second *log_EVpubl* equation, we find statistical evidence of a long-run causality as an adjustment of *log_EVpubl* by around 34 % per year when the growth rate of *log_FCVpubl* deviates from its long-run development path. When estimating the same model with *log_EVpubl* as the dependent variable, we find no significant ECT for *log_FCVpubl* (Table B.1).[4] For the short run, only *Δlog_ICEVpubl (−1)* has a statistically significant and positive effect on present *log_EVpubl* growth at the 5 % significance level.

In the third *log_ICEVpubl* equation, the significantly positive ECT indicates a downward (or upward) adjustment of *log_ICEVpubl* growth by around 21 % per year when *log_FCVpubl* growth is above (or below) its long-run development path. However, we find no similar evidence for the ECT when using *log_ICEVpubl* as the dependent variable (Table B.1). The significantly negative coefficient of *Δlog_FCVpubl(−1)* indicates a short-run effect on present *log_ICEVpubl* growth, while *Δlog_EVpubl(−1)* has a significantly positive effect on *log_ICEVpubl* growth in the short run.

In sum, for FCV-EV, we find a unidirectional positive short-run causality of past *log_EVpubl* on present *log_FCVpubl*. In the long run, our results show a positive unidirectional effect of *log_FCVpubl* on *log_EVpubl*. For FCV-ICEV, the results show a unidirectional short-run causality between *log_FCVpubl* and *log_ICEVpubl*, with the past values of *log_FCVpubl* having a significantly negative effect on the present values of *log_ICEVpubl*. In contrast, we find a positive unidirectional long-run effect of *log_FCVpubl* on *log_ICEVpubl*.

For our patent VECM, all deployed information criteria point to an optimal lag length of one. However, we added an extra lag to deal with the remaining autocorrelation in the estimated model. The results of the two-lag model with a restricted constant are given in Table 5.

The first *log_FCVpatents* equation shows a significant negative ECT coefficient, implying a fast downward or upward adjustment of *log_FCVpatents* growth by around 17 % per year when the growth rate is above or below the long-run development path. In the short run, our results provide statistically significant evidence of negative causality between the past and present values of *log_FCVpatents*. In contrast, the coefficients of *Δlog_EVpatents(−1)* and *Δlog_ICEVpatents(−1)* are significant and positive, implying a positive short-run impact of these variables on present *log_FCVpatents* growth. In the second *log_EVpatents* equation, we find no statistical evidence of a long-run causality as an adjustment of *log_EVpatents* when the growth rate of *log_FCVpatents* deviates from its long-run development path. However, we find a significantly positive ECT for *log_FCVpatents* when estimating the VECM with *log_EVpatents* as the dependent variable (see Table B.1). In the short run, the past values of *log_FCVpatents* (*Δlog_FCVpatents(−1)*) have a significantly positive effect on present *log_EVpatents* growth. The third *log_ICEVpatents* equation yields an insignificant ECT. However, the ECT for *log_FCVpatents* is significant and positive when estimating the VECM

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[3] The results of the VECM specification tests are available upon reasonable request.

[4] The results of the VECM estimations with EV and ICEV as dependent variables are available upon reasonable request.

Table 2
Unit root test results.

Variable	ADF stat: H0 = no stationarity				KPSS stat: H0 = stationarity				P-P stat: H0 = no stationarity			
	I(0)	Lags	I(1)	Lags	I(0)	Lags	I(1)	Lags	I(0)	Lags	I(1)	Lags
log_FCVpubl	−2.040	2	−2.835	1	0.254***	2	0.101	1	−0.786	3	−7.716***	3
log_EVpubl	−1.999	2	−3.710**	1	0.227***	2	0.077	1	−0.969	3	−3.885***	3
log_ICEVpubl	−2.135	1	−3.626**	1	0.277***	1	0.067	1	−0.814	3	−5.529***	3
log_FCVpatents	−1.233	2	−5.350***	1	0.265***	2	0.0665	1	−1.585	3	−9.973***	3
log_EVpatents	−2.437	1	−4.164***	1	0.261***	1	0.0480	1	−1.370	3	−5.236***	3
log_ICEVpatents	−0.705	1	−4.177***	1	0.372***	1	0.0656	1	−2.375	3	−5.660***	3
FCV_standards	−2.692	1	−3.157*	1	0.085	1	0.0603	1	−1.517	2	−4.197***	2
EV_standards	−1.474	1	−2.312	1	0.189**	1	0.056	1	−1.015	2	−10.961***	3
ICEV_standards	−1.340	2	−5.061***	1	0.158**	2	0.0625	1	−2.898*	2	−9.181***	2

*** p < 0.01, ** p < 0.05, * p < 0.1.

Table 3
Johansen test for cointegration.

Model	Observations	Parameters	Trend	Rank	Lag	trace statistic
Log(Publications)	39	3	Unrestricted constant	0	1	28.09**
	39	9	Restricted trend	1	1	12.72**
	39	6	Restricted constant	1	1	14.81**
Log(Patents)	39	3	Unrestricted constant	0	1	28.94**
	39	3	Restricted trend	0	1	37.68**
	39	6	Restricted constant	1	1	17.61**
Standards	20	8	Unrestricted constant	1	1	8.24**
	20	9	Restricted trend	0	1	36.42**
	20	0	Restricted constant	0	1	32.78**

** p < 0.05.

Table 4
VECM causality results – publications.

Sample: 1982–2019		Number of obs		38
Log likelihood = 25.451		AIC		−0.392
		HQIC		−0.116
		SBIC		0.384
Equation	Variable	Lags	Coef.	Std. Err.
(1) log_FCVpubl	ECT		−0.0607	0.0647
	Δlog_FCVpubl(−1)	LD	−0.408**	0.165
	Δlog_EVpubl(−1)	LD	0.812***	0.163
	Δlog_ICEVpubl(−1)	LD	−0.268	0.205
	_cons		0.197***	0.0447
(2) log_EVpubl	ECT		0.338***	0.0960
	Δlog_FCVpubl(−1)	LD	−0.145	0.245
	Δlog_EVpubl(−1)	LD	−0.144	0.242
	Δlog_ICEVpubl(−1)	LD	0.609**	0.304
	_cons		−0.0139	0.0662
(3) log_ICEVpubl	ECT		0.206***	0.0746
	Δlog_FCVpubl(−1)	LD	−0.560***	0.191
	Δlog_EVpubl(−1)	LD	0.512***	0.188
	Δlog_ICEVpubl(−1)	LD	0.161	0.237
	_cons		0.0810	0.0515

*** p < 0.01, ** p < 0.05, * p < 0.1.

Table 5
VECM causality results – patents.

Sample: 1982–2019		Number of obs		38
		AIC		−1.912
Log likelihood = 51.333		HQIC		−1.682
		SBIC		−1.266
Equation	Variable	Lags	Coef.	Std. Err.
(1) log_FCVpatents	ECT		−0.169*	0.0961
	Δlog_FCVpatents(−1)	LD	−0.462***	0.122
	Δlog_EVpatents(−1)	LD	0.728**	0.302
	Δlog_ICEVpatents(−1)	LD	1.131***	0.306
(2) log_EVpatents	ECT		0.105	0.0523
	Δlog_FCVpatents(−1)	LD	0.0141**	0.0664
	Δlog_EVpatents(−1)	LD	0.222	0.164
	Δlog_ICEVpatents(−1)	LD	0.107	0.166
(3) log_ICEVpatents	ECT		0.0553	0.0559
	Δlog_FCVpatents(−1)	LD	−0.0243	0.0710
	Δlog_EVpatents(−1)	LD	0.178	0.176
	Δlog_ICEVpatents(−1)	LD	0.0931	0.178

*** p < 0.01, ** p < 0.05, * p < 0.1.

with *log_ICEVpatents* as the dependent variable (see Table B.1). In the short run, we find no evidence of any causality.

Overall, our results provide statistically significant evidence of bidirectional and positive short-run causality between *log_FCVpatents* and *log_EVpatents*. In the long-run FCV-EV relation, we find a unidirectional positive effect of *log_EVpatents* on *log_FCVpatents*. In addition, our results point to a unidirectional positive short-run effect of *log_ICEVpatents* on *log_FCVpatents*. In the long-run FCV-ICEV relation, we find a unidirectional positive effect of *log_ICEVpatents* on *log_FCVpatents*.

Finally, we report the results of our third VECM of standards in Table 6. From our information criteria, the SBIQ recommends the smallest lag order of one. However, we add an extra lag to capture possible short-run causalities between our standard variables. The resulting two-lag model shows no significant signs of autocorrelation or non-stationarity.

In the first *FCV_standards* equation, we observe a significantly negative ECT, indicating a relatively fast adjustment of *FCV_standards* to the long-term development path with about 0.4 standards per year when *FCV_standards* are above or below their growth path. In addition, we find a weakly significant but positive short-run effect of a past increase in *ICEV_standards* (*ΔICEV_standards(−1)*) on the present growth of *FCV_standards*. In the second *EV_standards* equation, we observe no significant ECT, although we find a significant positive ECT for *FCV_standards* when using *EV_standards* as the dependent variable (Table B.1) and a significantly positive effect of *FCV_standards* on *EV_standards* in the short run. In the second equation of Table 6, we observe a weakly significant negative short-run effect of a past increase in *EV_standards* (*ΔEV_standards(−1)*) on present *EV_standards* growth. In the third *ICEV_standards* equation, we find a significantly negative ECT, suggesting a fast downward adjustment by 0.72 *ICEV_standards* per year when *FCV_standards* are above (or below) the long-term development path. Similarly, we find a significantly negative ECT for *FCV_standards* when

Table 6
VECM causality results – standards.

Sample: 2000–2019		Number of obs	20
Log likelihood = -117.4623		AIC	13.446
		HQIC	13.611
		SBIC	14.293
Equation	Variable	Coef.	Std. Err.
(1) FCV_standards	ECT	−0.406 ***	0.148
	ΔFCV_standards(−1)	LD 0.159	0.242
	ΔEV_standards(−1)	LD −0.0807	0.160
	ΔICEV_standards(−1)	LD 0.158*	0.0975
	_cons	−0.0769	0.265
(2) EV_standards	ECT	0.0976	0.378
	ΔFCV_standards(−1)	LD −0.6995	0.619
	ΔEV_standards(−1)	LD −0.666*	0.408
	ΔICEV_standards(−1)	LD −0.0069	0.250
	_cons	1.252**	0.679
(3) ICEV_standards	ECT	−0.729*	0.385
	ΔFCV_standards(−1)	LD 0.128	0.631
	ΔEV_standards(−1)	LD −0.777*	0.417
	ΔICEV_standards(−1)	LD −0.251	0.255
	_cons	0.210	0.693

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

using *ICEV_standards* as the dependent variable (Table B.1) and a significantly negative effect of *FCV_standards* on *ICEV_standards* in the short run. In the third equation of Table 6, we find a weakly significant and negative short-run relation of past *EV_standards* (*ΔEV_standards (−1)*) to present *ICEV_standards*. In sum, our results point to unidirectional long-run positive causality of EVs on FCVs and bidirectional long-run causality between FCVs and ICEVs. In the short run, we find a weakly significant unidirectional short-run causality of ICEVs on FCVs.

For a better overview, we further summarized the results of our VECM causality analysis in Table 7, relating the effects on FCV as our dependent variable to the modes of technology interaction by Sandén and Hillman (2011) in the short and long run.

5. Discussion

5.1. Modes of technology interaction

Regarding *RQ1*, our analysis demonstrates that the modes of technology interaction by Sandén and Hillman (2011) can be integrated empirically into the TIS life-cycle framework (Markard, 2020) based on publications, patents, and standards (PPS) as quantitative indicators. As described above, only qualitative research has been previously applied to explore the interplay between the focal TIS and its context structures in the TIS life-cycle framework (Markard et al., 2020). However, quantitative TIS indicators can complement these previous approaches by offering straightforward replicability and operationalization of the TIS-context relations (Weiss, 2022). Moreover, the framework by Sandén and Hillman (2011) offers a more comprehensive conceptional basis for the TIS-TIS relations in the TIS life-cycle framework by distinguishing six modes of technology interaction and three dimensions constituting the respective interaction relations.

Empirical evidence from interactions between the focal FCV-TIS and the EV-TIS and ICEV-TIS as context structures (*RQ2*) indicates rather heterogenous 'multi-modal' interactions, highlighting differences across PPS as indicators and time horizons. For the FCV-EV relation, our publication model results in short-run commensalism in favor of FCVs and long-run commensalism of FCVs on EVs (Table 7). For the FCV-ICEV relation, the results suggest short-run amensalism to the detriment of ICEVs and long-run commensalism in favor of ICEVs. Considering patents, we observe short-run symbiosis between FCVs and EVs and long-run commensalism of EVs on FCVs. In the case of FCV vs. ICEV patenting, our analysis revealed short- and long-run commensalism in favor of FCVs. Our standards model results in short-run neutralism between FCVs and EVs but long-run commensalism in favor of FCVs. For the FCV-ICEV relation, we find short-run commensalism in favor of FCVs but a competition relation in the long run.

Regarding the FCV-EV relation, the publishing, patenting, and standardization dynamics suggest that the technology relations of these powertrain technologies are characterized by complementarity, with both either positively influencing each other (patents in the short run) or one technology unidirectionally benefiting the other, e.g., the positive long-run effect of EVs on FCVs in standards. Potential reasons for this could be that both technologies share similar or complementary raw materials and intermediate products as input factors (Mäkitie et al., 2022; Markard & Hoffmann, 2016). FCVs are a subtype of EVs in which the battery is powered by electricity generated from the fuel cell, while EVs use direct battery propulsion (Chan, 2007). Furthermore, both technologies share a demand for renewable energy as value-chain input to directly propel the vehicle (EV) or to produce green hydrogen as a fuel (FCV).

Our standards model supports the assumption of spillovers in terms of common institutionalization and legitimacy-building processes between both technologies. These processes foster positive expectations in the sense that FCV benefits from accelerating EV adoption (Markard & Hoffmann, 2016; Sandén & Hillman, 2011). From a market perspective, these spillover effects appear to create differentiation into different market segments, combining the benefits of each technology instead of complementarity in the same road-vehicle segment, e.g., battery-electric passenger vehicles vs. fuel-cell electric heavy-duty vehicles (Aguilar & Groß, 2022; Bohnsack et al., 2015; Borgstedt et al., 2017; IEA, 2022; Oltra & Saint Jean, 2009; Van De Kaa et al., 2017).

However, recent data released by the *International Energy Agency* (IEA) reveal that such differentiation has not yet taken place and that vehicle stocks differ greatly across both technologies. The total stock of FCVs amounted to approximately 80,000 as of 2023 (IEA, 2023a) compared to 26 million EVs as of 2022 (IEA, 2023b). These figures highlight that both power technologies have been commercialized to significantly differing degrees. This observation is further amplified by

Table 7
VECM causality results – overview.

Relation	Data	Short run	Mode of technology interaction	Long run	Mode of technology interaction
FCV-EV	Publications	Unidirectional positive effect of EVs on FCVs	Commensalism	Positive unidirectional effect of FCVs on EVs	Commensalism
	Patents	Bidirectional effect, positive of EVs on FCVs, positive of FCVs on EVs	Symbiosis	Positive unidirectional effect of EVs on FCVs	Commensalism
	Standards	No significant effects	Neutralism	Positive unidirectional effect of EVs on FCVs	Commensalism
FCV-ICEV	Publications	Unidirectional negative effect of FCVs on ICEVs	Amensalism	Positive unidirectional effect of FCVs on ICEVs	Commensalism
	Patents	Unidirectional positive effect of ICEVs on FCVs	Commensalism	Positive unidirectional effect of ICEVs on FCVs	Commensalism
	Standards	Unidirectional positive effect of ICEV on FCV	Commensalism	Bidirectional effect, negative of ICEVs on FCVs, negative of FCVs on ICEVs	Competition

the differing availabilities of refueling and charging infrastructures, with 1,100 hydrogen refueling stations (HRSs) vs. 2.7 million public charging points for EVs (IEA, 2023a, 2023b). The cost aspect is another factor hampering the increased adoption of FCVs compared to EVs (Wang et al., 2021). While the average price for small EVs stands at USD 30,000 in Europe and the USA, and even as low as USD 10,000 in China (IEA, 2023b), the purchase price for the best-selling FCV worldwide, the *Hyundai Nexo*, starts at USD 66,000 in the USA and USD 82,700 in Germany (Hyundai Motor America, 2024; Hyundai Motor Deutschland GmbH, 2024). Nonetheless, both powertrain technologies involve different environmental impacts, with EVs particularly burdening natural resources and causing pollution, e.g., due to their dependence on rare earth elements and the high energy consumption in battery production (Yang et al., 2020). Against this backdrop, the complementarity of both technologies gains even greater importance, as FCVs can reduce dependence on specific input factors and tackle the environmental burden posed by an 'all-electric' approach.

In the FCV-ICEV relation, we observe co-dependence in the form of common value-chain artifacts and schemata, such as expectations about the future development of e-fuels and the associated mutual dependence on hydrogen production (Mirzadeh Phirouzabadi et al., 2020a; Sandén & Hillman, 2011; Song & Aaldering, 2019). As Andersen and Gulbrandsen (2020) and Dolata (2009) explain, the interplay between emerging and established technology can be beneficial in sectors with high adaptability, such as the automobile industry. The respective interrelations may merge based on recombination or diversification of established technologies, e.g., hydrogen-based e-fuels for ICEVs, or overlaps in the fueling infrastructure. Notably, such co-dependence between the established technology regime and emerging niche technologies has also been recognized in the case of hybrid vehicles. The latter did not only provide more efficient ICEV-based vehicles but also fostered the acceptance of EVs and recharging among customers (e.g., Dijk et al., 2013; Oltra & Saint Jean, 2009; Weiss & Scherer, 2023).

On the other hand, there are also conflicting interests between FCVs and ICEVs, such as stranded assets in oil refineries and necessary modifications of fueling and manufacturing infrastructure to accommodate the increasing hydrogen demand (Farla et al., 2010). This conflict is also reflected in the long-run FCV-ICEV relationship in standardization. Such competitive dynamics between technological niches and trajectories have been repeatedly explored in the automobile sector (Bakker et al., 2012; Haley, 2015; Lin & Sovacool, 2020; Mirzadeh Phirouzabadi et al., 2020a; Weiss & Scherer, 2023), highlighting the high complexity and heterogeneity within the mobility paradigm (Banister, 2008).

5.2. *Life cycle of the FCV technological innovation system (TIS)*

Regarding *RQ3*, our descriptive results have shown that FCV publications are below those of EVs but ahead of ICEV publications (Fig. 1), while FCV patenting (Fig. 2) and standardization (Fig. 3) lag behind EVs and ICEVs. The empirical results of the VECM estimations illustrate that EVs primarily dominate FCVs regarding the direction of influence. However, FCVs also influence EVs positively in the short-run patenting and the long-run standards relation. In contrast, FCVs unidirectionally impact ICEVs in publications, while ICEVs dominate in the commercially more relevant patents and standards despite the declining nature of the ICEV-TIS (Weiss & Scherer, 2021, 2023).

Following Markard (2020), the context and TIS-context relationships are primarily characterized by a dependence of the focal FCV-TIS on its context structures. Therefore, compared with the competing EV-TIS and ICEV-TIS, the FCV-TIS shows properties of the formative TIS life-cycle phase. Especially for commercially relevant patents and standards, the context structures primarily dominate the focal FCV-TIS and not vice versa. This finding is in line with the bibliometric analysis of Asna Ashari et al. (2023), showing that hydrogen-related publishing is in its growth phase, while patenting and standardization show properties of the formative phase. Therefore, our results further support the findings of Asna Ashari et al. (2023) by comparing FCVs with EVs and ICEVs as powertrain technologies in the TIS context. At the same time, e.g., the descriptive publication results or the short-run FCV-ICEV relationship point to the existing and growing importance of the FCV-TIS within the mobility paradigm. Therefore, the primarily formative FCV-TIS also shows elements of the growth phase (Fig. 4). Much of the future life cycle of the FCV-TIS will depend substantially on the development of the EV-TIS. As the decline of the ICEV-TIS has already been recognized in previous research (e.g., Weiss & Scherer, 2021, 2023), the relationship between FCVs and EVs is likely to reinforce and shape the mobility paradigm toward decarbonizing the ICEV-dominated and currently fossil-fuel-based mobility sector in the future (Ahmadi, 2019).

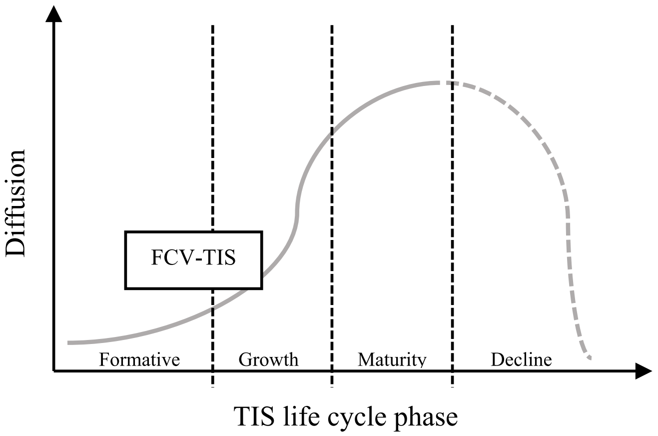

Fig. 4. Life-cycle phase of the FC-TIS based on Hekkert et al. (2011) and Markard (2020).

Thus far, EVs and EV charging infrastructure have received substantial policy support and funding (Baumgarte et al., 2021; Wu et al., 2021). However, hydrogen technologies, including FCVs, have also been subject to increased policy support. As such, 42 countries worldwide have either adopted or committed to adopting a hydrogen strategy since 2020 (Albrecht et al., 2020; Asna Ashari et al., 2023; IEA, 2022). Of these hydrogen strategies, some countries, e.g., South Korea in 2019 and Japan in 2017, have codified the development of hydrogen technologies for mobility, including FCVs (Albrecht et al., 2020; IEA, 2021). Consequently, South Korea's *Hyundai Nexo* and Japan's *Toyota Mirai* accounted for 95 % of worldwide FCV sales in 2019 (Wang et al., 2020). With the vast policy support for FCVs received in both countries, other countries with FCVs as target applications of their national hydrogen strategies, e.g., Germany and France (Albrecht et al., 2020; IEA, 2021), may further contribute to the development of the FCV-TIS in the future. However, our dataset does not cover the increasing policy support for hydrogen technologies since 2020, including FCVs. Therefore, supportive framework conditions could positively influence the development of the FCV-TIS in the future. Accordingly, commercially relevant patents and standards, in particular, could experience further growth. We thus regard the life-cycle phase of the FCV-TIS as dynamic with the potential to gain maturity and dominance in relation to EVs and ICEVs.

6. Conclusion

In this study, we analyzed the relationship between the FCV- and EV- and FCV- and ICEV-TIS in the short and long run to derive implications for the modes of technology interaction within the mobility paradigm. Furthermore, we determined the life-cycle phase of the FCV-TIS based on the comparative descriptive analysis of publications, patents, and standards (PPS) over time, as well as the underlying technology interactions measured by our VECM.

This study makes several contributions to previous research: First, we have contributed to the further conceptualization of the TIS life-cycle framework proposed by Markard (2020), using PPS as indicators. In addition, integrating the modes of technology interaction following Sandén and Hillman (2011), including their empirical validation, contributes to a broader perspective of TIS-context relations. Second, we have proposed a data-driven VECM approach to capture the TIS-TIS relations that can be applied to various research cases. Unlike previous quantitative TIS studies, such as Mirzadeh Phirouzabadi et al., (2020a) and Li et al. (2022), the VECM does not require the formulation of ex-ante structural equations. Moreover, the VECM differentiates short- and long-run technology relations, allowing for more time-sensitive policy approaches to governing competing or complementary TISs in transition processes (Dreher et al., 2016; Noailly & Shestalova, 2017). Compared with Mirzadeh Phirouzabadi et al., (2020a), Li et al. (2022), and Noailly and Shestalova (2017), our results also illustrate that technology relations and associated spillovers have to be analyzed in a more differentiated way by using a variety of indicators and time horizons. Third, we have shown empirically that the transition of the mobility paradigm is governed by multi-modal interactions, which we capture by considering multiple indicators. Thus, our research aligns with the recent study by Mirzadeh Phirouzabadi et al. (2022), emphasizing that, in contrast to the initial quantitative studies on this topic (e.g., Noailly and Shestalova, 2017; Mirzadeh Phirouzabadi et al., 2020a; Li et al., 2022), technology interactions should be considered using a diverse set of indicators to capture their multidimensional nature and to derive effective policy recommendations.

Notably, our PPS-based approach further allows for a comprehensive TIS life-cycle assessment using quantitative methods and complements the previous functional perspective on TIS-TIS interactions (Mirzadeh Phirouzabadi et al., 2020a, 2020b, 2020c; 2020d, 2022). Arguably, echoing the insights from a recent in-depth conceptual review of TIS by Andersson et al. (2023), this represents the initial step toward an integrated structural–functional approach to TIS-TIS interactions, which encompasses the structures of TISs, their life-cycle stages, and their functional dynamics all within a comprehensive analytical framework.

Furthermore, our quantitative approach distinguishes our study from previous TIS life-cycle studies, which rely only on descriptive analyses of qualitative and quantitative indicators (Asna Ashari et al., 2023, 2024; Markard, 2020; Markard et al., 2020), and opens up opportunities for extensive policy analyses involving multiple TISs across countries or sectors (Weiss, 2022).

This study has important implications for policymakers toward the sustainability transition of the road-vehicle sector. With FCVs and EVs as two emerging technologies, the need to significantly reduce greenhouse gas emissions has put the ICEV-TIS (Weiss & Scherer, 2021, 2023) under increasing pressure and facing a potential decline. Currently, discussions about the potential decline of the ICEV-TIS have resurfaced with the European Commission’s decision to ban the sales of new ICEVs after 2035 and the subsequent debate about e-fuels and biofuels as potential future pathways for the survival of ICEVs as a mass-transport solution. This development could reshape the relationship between FCVs and EVs in the sustainable mobility paradigm (e.g., Ravi et al., 2023; Sacchi et al., 2022; Skov & Schneider, 2022). Following the results of our analysis, policymakers aiming to scale up electromobility adaptation should further exploit the complementarities of both technologies (Mäkitie et al., 2022; Markard & Hoffmann, 2016). Therefore, successful policy responses to climate change in mobility necessitate technology-neutral approaches that do not exclude potentially more appropriate technology options.

Analogous to the notion of ’place-sensitive policy solutions’ (Rohe & Chlebna, 2021), we recommend that policymakers implement ’application-sensitive’ technology policies in the mobility sector. Against the backdrop of the e-fuel debate, policy mixes should consider sustainable pathways for the ICEV in hardly-electrifiable applications, such as aviation, heavy-duty vehicles, or shipping. At the same time, policies should scale up electromobility in the form of FCVs and EVs to establish consistent and technology-open policy support for a transition toward sustainable mobility (Kivimaa & Kern, 2016; Schot & Geels, 2008).

Despite the contributions and implications, this study is not without limitations: First, our data cover only a limited number of annual observations per knowledge and technology indicator. Second, despite careful cross-checking, using solely Boolean search terms for collecting publication data yields the risk of including irrelevant documents in our dataset. Third, following our global TIS analysis, we focus only on international ISO and IEC standards, although standards at the regional or national level may also be relevant to the TIS life-cycle progression. Fourth, following Sandén and Hillman (2011), our analysis does not cover all dimensions of technology interaction. Instead, we abstracted the technology interactions only quantitatively from selected indicators. Thus, we ignore factors such as value-chain overlaps, common actor networks, political institutions and regulations, or public discourses and expectations. Furthermore, we do not capture actual cause-and-effect relationships but rather predictive causality, i.e., one variable provides useful information about the development of another (Granger, 1988).

Future research may address some of the limitations of this study. For instance, more sophisticated analyses of TIS-context relations at the national level, combined with in-depth qualitative analyses in a mixed-method design, including the role of regulations and technology policies, could methodologically and theoretically extend this study (Weiss, 2022). In this way, the shortcomings of our purely quantitative approach could be elaborated and extended with complementary insights to capture actual cause-and-effect relations (Weiss, 2022). Furthermore, similar to Li et al. (2022) and Mirzadeh Phirouzabadi et al., (2020a), citation analyses of PPS would allow for analyzing not only the TIS-context relations within each indicator but also the links between different channels across technologies in the form of spillovers. Finally, future research should verify or extend our results using different databases and search strategies.

CRediT authorship contribution statement

Daniel Weiss: Writing – review & editing, Writing – original draft, Validation, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Parsa Asna Ashari:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Knut Blind:** Writing – review & editing, Writing – original draft, Conceptualization.

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.

Data availability

The authors do not have permission to share data.

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Appendix A:. Data collection

This section describes the data collection approach for the variables in our vector error correction model (VECM). Our VECM comprises three time series per FCV, EV, and ICEV technology: publications, patents, and standards (PPS).

Publication data were retrieved from Clarivate Analytics's *Web of Science* (WoS) *Core Collection* (Clarivate Analytics, 2022). We selected this database as it is a comprehensive and high-quality database commonly used for publication analyses (Asna Ashari et al., 2023; Birkle et al., 2020). For each technology, we used Boolean search terms based on previous research (Asna Ashari et al., 2023; Borgstedt et al., 2017; Mirzadeh Phirouzabadi et al., 2020a), which we entered in the 'Topic' field of the WoS, covering title, abstract, and keywords (Table A.1). Furthermore, we limited the queries to English-language research and review articles and proceeding papers published between 1980 and 2019.

Table A.1
Search queries for publication data.

Technology	Boolean search terms	Total records (1980–2019)
Fuel-cell vehicles	TS=(Fuel cell OR Fuel cell electric) AND TS=(vehicle* OR motor vehicle* OR automobile* OR car* OR truck* OR mobilit*)	44,669
Electric vehicles	TS=(Electric OR battery-electric OR battery electric OR electrically propelled) AND TS=(vehicle* OR motor vehicle* OR automobile* OR car* OR truck* OR mobilit*) NOT TS=(fuel cell*)	91,041
Internal combustion engine vehicles	TS=(internal combustion engine OR IC engine OR gasoline OR diesel) AND TS=(vehicle* OR motor vehicle* OR automobile* OR car* OR truck* OR mobilit*)	30,467

For patent data, we used the open-source *Espacenet* (EPO, 2023) patent database of the *European Patent Office* (EPO). For the purpose of this study, we collected patent application data related to FCVs, EVs, and ICEVs between 1980 and 2019 by their earliest priority date. The earliest priority date refers to the earliest date on which the novelty of the invention is established (Borgstedt et al., 2017; The Lens, 2022). Due to the lack of harmonized patent application procedures across various patent offices and difficulties in drawing comparisons (Callaert et al., 2006), we only consider patents filed at the EPO as a globally relevant patent office (Asna Ashari et al., 2023; Ha et al., 2015).

Our data collection approach combines selected IPC (*International Patent Classification*) classes and Boolean search terms (Table A.2) based on previous research to limit the data to relevant mobility-related patent applications (Aghion et al., 2016; Borgstedt et al., 2017; Mirzadeh Phirouzabadi et al., 2020a; Sinigaglia et al., 2019; Weiss & Scherer, 2021). However, since these previous studies use other databases, replicating their keywords does not produce similar document counts. Therefore, we slightly modified our keywords but used the same IPC codes as previous research for data consistency.

Table A.2
Search queries for patent data.

Technology	Search query (IPC codes & Boolean search terms)	Total records (1980–2019)
Fuel-cell vehicles	IPC=(B60* OR H01M*) AND TS=(fuel cell* OR fuel cell electric* OR hydrogen*) AND TS=(vehicle* OR motor vehicle OR automobile* OR car* OR truck* OR mobilit*)	2,366
Electric vehicles	IPC=(B60* OR H01M* OR H02K*) AND TS=(electric* OR battery electric* OR electrically propelled*) AND TS=(vehicle* OR motor vehicle* OR automobile* OR car* OR truck* OR mobilit*) NOT TS=(fuel cell*)	14,694
Internal combustion engine vehicles	IPC=(F01* OR F02B* OR F02D* OR F02F* OR F02M* OR F02N* OR F02P*) AND TS=(vehicle* OR motor vehicle* OR automobile* OR car* OR truck* OR mobilit*)	27,615

We collected data on international standards published under the relevant ICS (*International Classification for Standards*) codes specific to each technology. We used the PERINORM database (PERINORM, 2022) for standards published by the *International Organization for Standardization* (ISO) and the VDE Standards Library (VDE, 2022), and the IEC Webstore (International Electrotechnical Commission, 2022) for standards published by the *International Electrotechnical Commission* (IEC) as databases.

Although the ICS classes are well-defined for all three powertrain technologies, we cross-checked all standards under each ICS code to exclude irrelevant standards. Subsequently, we conducted a simple keyword search to verify that relevant standards published under other ICS codes were also included. Finally, we included withdrawn or revised standards replaced by later standard versions to account for the standardization history more accurately. Table A.3 gives an overview of the data collection approach. Notably, we truncated the period for standards to the years 2000 to 2019 because no standards were published for FCVs and EVs before 2000, and thus, we cannot assume meaningful technology interactions.

Table A.3
Search queries for standard data.

Technology	Main ICS code	Search terms	Total records (2000–2019)
Fuel-cell vehicles	27.070 – Fuel cells	Fuel cell	33
Electric vehicles	43.120 – Electric road vehicles	Electric vehicle	69
Internal combustion engine vehicles	27.020 – Internal combustion engines	Internal combustion engine	110

Appendix B

Table B.1
ECT for FCV with respect to EV and ICEV context developments.

Data	Dependent variable in VECM	ECT for FCV equation Coef.	Std.
Publications	Log_EVpubl	−0.0802	0.0855
	Log_ICEVpubl	0.181	0.193
Patents	Log_EVpatents	0.0607*	0.0346
	Log_ICEVpatents	0.306*	0.174
Standards	EV_standards	0.444***	0.161
	ICEV_standards	−0.356***	0.129

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Appendix C

In this section of the Appendix, we report the cointegration results for our three VECMs. Table C.1 reports the normalized cointegration results for the publication model.

Table C.1
Cointegration relation with Johansen normalization restriction imposed – publications.

Variable	Coef.	Std. Err.
log_FCVpubl	1	.
log_EVpubl	1.323***	0.456
log_ICEVpubl	−2.986***	0.626
_trend	0.0902**	0.0419
_cons	0.734	.

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

The resulting equation for the development of FC publications is:

$$\log\_FCVpubl = -0.73 - 0.09 - 1.32 * \log\_EVpubl + 2.99 * \log\_ICEVpubl \tag{C.1}$$

Given the high significance of the respective coefficients in Eq. (C.1), the cointegration suggests a positive long-run relationship between FCVs and ICEVs and a relatively weaker negative relation to EVs. In particular, a 1 % increase in FCV publications growth is associated with a 1.32 % decrease in EV publications growth and a 2.99 % increase in ICEV publication growth. The cointegration relation suggests the presence of at least one unidirectional Granger causality between these variables (Granger, 1988). Notably, the included trend coefficient is highly significant, too, supporting our unrestricted trend model specification (Table 3).

Looking at our patent data, we observe a positive long-run relationship between *log_FCVpatents* and *log_ICEVpatents*, with a 1 % increase in FCV patent growth being associated with a 1.82 % increase in ICEV patent growth (Eq. (C.2). Notably, we find no evidence of a significant effect of *log_FCVpatents* on *log_EVpatents* (Table C.2).

Table C.2
Cointegration relation with Johansen normalization restriction imposed – patents.

Variable	Coef.	Std. Err.
log_FCVpatents	1	.
log_EVpatents	−0.360	0.455
log_ICEVpatents	−1.816***	0.650
_cons	10.217***	2.380

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

The resulting equation for the development of *log_FCVpatents* is:

$$\log\_FCVpatents = -10.22 - 0.36 * \log\_EVpatents + 1.82 * \log\_ICEVpatents \tag{C.2}$$

Finally, we report the cointegration relation of our standards model in Table C.3. We observe a significantly positive long-run relationship between FCVs and EVs and a negative relationship between FCV and ICEV development. Accordingly, an increase in FCV standards by one is associated with a significant increase in the absolute number of EV standards by 1.09 and a decrease in ICEV standards by 0.88 (Eq. (C.3).

Table C.3
Cointegration relation with Johansen normalization restriction imposed – standards.

Variable	Coef.	Std. Err.
FCV_standards	1	.
EV_standards	−1.093***	0.198
ICEV_standards	0.875***	0.204
_cons	−3.813	.

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

The resulting equation for the development of *FCV_standards* is:

$$FCV\_standards = 3.813 + 1.093{*}EV\_standards - 0.875{*}ICEV\_standards \tag{C.3}$$

References

Acar, C., Beskese, A., Temur, G.T., 2022. Comparative fuel cell sustainability assessment with a novel approach. Int. J. Hydrogen Energy 47 (1), 575–594. https://doi.org/10.1016/j.ijhydene.2021.10.034.

Aghion, P., Dechezleprêtre, A., Hémous, D., Martin, R., Van Reenen, J., 2016. Carbon Taxes, Path Dependency, and Directed Technical Change: Evidence from the Auto Industry. J. Polit. Econ. 124 (1), 1–51. https://doi.org/10.1086/684581.

Aguilar, P., Groß, B., 2022. Battery electric vehicles and fuel cell electric vehicles, an analysis of alternative powertrains as a mean to decarbonise the transport sector. Sustainable Energy Technol. Assess. 53, 102624 https://doi.org/10.1016/j.seta.2022.102624.

Ahmadi, P., 2019. Environmental impacts and behavioral drivers of deep decarbonization for transportation through electric vehicles. J. Clean. Prod. 225, 1209–1219. https://doi.org/10.1016/j.jclepro.2019.03.334.

Albrecht, U., Bünger, U., Michalski, J., Raksha, T., Wurster, R., & Zerhusen, J. (2020). International Hydrogen Strategies. A study commissioned by and in cooperation with the World Energy Council Germany. Retrieved from: https://www.weltenergierat.de/wp-content/uploads/2020/10/WEC_H2_Strategies_finalreport.pdf.

Aminudin, M.A., Kamarudin, S.K., Lim, B.H., Majilan, E.H., Masdar, M.S., Shaari, N., 2023. An overview: Current progress on hydrogen fuel cell vehicles. Int. J. Hydrogen Energy 48 (11), 4371–4388. https://doi.org/10.1016/j.ijhydene.2022.10.156.

Andersen, A.D., Gulbrandsen, M., 2020. The innovation and industry dynamics of technology phase-out in sustainability transitions: Insights from diversifying petroleum technology suppliers in Norway. Energy Res. Soc. Sci. 64, 101447 https://doi.org/10.1016/j.erss.2020.101447.

Andersson, J., Hojcková, K., Sandén, B.A., 2023. On the functional and structural scope of technological innovation systems – A literature review with conceptual suggestions. Environ. Innov. Soc. Trans. 49, 100786 https://doi.org/10.1016/j.eist.2023.100786.

Asna Ashari, P., Blind, K., Koch, C., 2023. Knowledge and technology transfer via publications, patents, standards: Exploring the hydrogen technological innovation system. Technol. Forecast. Soc. Chang. 187, 122201 https://doi.org/10.1016/j.techfore.2022.122201.

Asna Ashari, P., Blind, K., 2024. The effects of hydrogen research and innovation on international hydrogen trade. Energy Policy 186, 113974. https://doi.org/10.1016/j.enpol.2023.113974.

Asna Ashari, P., Oh, H., Koch, C., 2024. Pathways to the hydrogen economy: A multidimensional analysis of the technological innovation systems of Germany and South Korea. Int. J. Hydrogen Energy 49, 405–421. https://doi.org/10.1016/j.ijhydene.2023.08.286.

Bach, H., Bergek, A., Bjørgum, Ø., Hansen, T., Kenzhegaliyeva, A., Steen, M., 2020. Implementing maritime battery-electric and hydrogen solutions: A technological innovation systems analysis. Transp. Res. Part D: Transp. Environ. 87, 102492 https://doi.org/10.1016/j.trd.2020.102492.

Bakker, S., 2010. The car industry and the blow-out of the hydrogen hype. Energy Policy 38 (11), 6540–6544. https://doi.org/10.1016/j.enpol.2010.07.019.

Bakker, S., van Lente, H., Engels, R., 2012. Competition in a technological niche: the cars of the future. Tech. Anal. Strat. Manag. 24 (5), 421–434. https://doi.org/10.1080/09537325.2012.674666.

Banister, D., 2008. The sustainable mobility paradigm. Transp. Policy 15 (2), 73–80. https://doi.org/10.1016/j.tranpol.2007.10.005.

Bauer, F., Coenen, L., Hansen, T., McCormick, K., Palgan, Y.V., 2017. Technological innovation systems for biorefineries: a review of the literature. Biofuels Bioprod. Biorefin. 11 (3), 534–548. https://doi.org/10.1002/bbb.1767.

Baumgarte, F., Kaiser, M., Keller, R., 2021. Policy support measures for widespread expansion of fast charging infrastructure for electric vehicles. Energy Policy 156, 112372. https://doi.org/10.1016/j.enpol.2021.112372.

Behling, N., 2013. Current Global Fuel Cell R&D and Future Research Needs. ECS Trans. 51 (1), 3–26. https://doi.org/10.1149/05101.0003ecst.

Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., Rickne, A., 2008. Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. Res. Policy 37 (3), 407–429. https://doi.org/10.1016/j.respol.2007.12.003.

Bergek, A., Hekkert, M., Jacobsson, S., Markard, J., Sandén, B., Truffer, B., 2015. Technological innovation systems in contexts: Conceptualizing contextual structures and interaction dynamics. Environ. Innov. Soc. Trans. 16, 51–64. https://doi.org/10.1016/j.eist.2015.07.003.

Binz, C., Truffer, B., Coenen, L., 2014. Why space matters in technological innovation systems—Mapping global knowledge dynamics of membrane bioreactor technology. Res. Policy 43 (1), 138–155. https://doi.org/10.1016/j.respol.2013.07.002.

Birkle, C., Pendlebury, D.A., Schnell, J., Adams, J., 2020. Web of Science as a data source for research on scientific and scholarly activity. Quantitative Science Studies 1 (1), 363–376. https://doi.org/10.1162/qss_a_00018.

Blind, K., Fenton, A., 2022. Standard-relevant publications: evidence, processes and influencing factors. Scientometrics. https://doi.org/10.1007/s11192-021-04210-8.

Blind, K., Gauch, S., 2009. Research and standardisation in nanotechnology: evidence from Germany. J. Technol. Transfer 34 (3), 320–342. https://doi.org/10.1007/s10961-008-9089-8.

Blind, K., Petersen, S., Riillo, C., 2017. The impact of standards and regulation on innovation in uncertain markets. Res. Policy 46 (1), 249–264. https://doi.org/10.1016/j.respol.2016.11.003.

Blind, K., Pohlisch, J., Zi, A., 2018. Publishing, patenting, and standardization: Motives and barriers of scientists. Res. Policy 47 (7), 1185–1197. https://doi.org/10.1016/j.respol.2018.03.011.

Bohnsack, R., Kolk, A., Pinkse, J., 2015. Catching recurring waves: Low-emission vehicles, international policy developments and firm innovation strategies. Technol. Forecast. Soc. Chang. 98, 71–87. https://doi.org/10.1016/j.techfore.2015.06.020.

Borgstedt, P., Neyer, B., Schewe, G., 2017. Paving the road to electric vehicles – A patent analysis of the automotive supply industry. J. Clean. Prod. 167, 75–87. https://doi.org/10.1016/j.jclepro.2017.08.161.

Callaert, J., Van Looy, B., Verbeek, A., Debackere, K., Thijs, B., 2006. Traces of Prior Art: An analysis of non-patent references found in patent documents. Scientometrics 69 (1), 3–20. https://doi.org/10.1007/s11192-006-0135-8.

Chan, C.C., 2007. The State of the Art of Electric, Hybrid, and Fuel Cell Vehicles. Proc. IEEE 95 (4), 704–718. https://doi.org/10.1109/jproc.2007.892489.

Clarivate Analytics (2022). *Web of Science*. Retrieved from: https://www.webofscience.com/wos/woscc/basic-search.

De Oliveira, L.G.S., Negro, S.O., 2019. Contextual structures and interaction dynamics in the Brazilian Biogas Innovation System. Renew. Sustain. Energy Rev. 107, 462–481. https://doi.org/10.1016/j.rser.2019.02.030.

Dedehayir, O., Mäkinen, S.J., 2011. Measuring industry clockspeed in the systemic industry context. Technovation 31 (12), 627–637. https://doi.org/10.1016/j.technovation.2011.07.008.

Dickey, D. A., & Fuller, W. A. (1981). Likelihood ratio statistics for autoregressive time series with a unit root. Econometrica: journal of the Econometric Society, 1057-1072. 10.2307/1912517.

Dickey, D.A., Fuller, W.A., 1979. Distribution of the estimators for autoregressive time series with a unit root. J. Am. Stat. Assoc. 74 (366a), 427–431. https://doi.org/10.1080/01621459.1979.10482531.

Dijk, M., Orsato, R.J., Kemp, R., 2013. The emergence of an electric mobility trajectory. Energy Policy 52, 135–145. https://doi.org/10.1016/j.enpol.2012.04.024.

Dolata, U., 2009. Technological innovations and sectoral change. Res. Policy 38 (6), 1066–1076. https://doi.org/10.1016/j.respol.2009.03.006.

Dreher, C., Kovač, M., Schwäbe, C., 2016. Competing technological innovation systems as a challenge for new mission orientation-insights from the German Energiewende. Int. J. Foresight Innov. Policy 11 (1–3), 43–72. https://doi.org/10.1504/IJFIP.2016.078382.

Dziallas, M., Blind, K., 2019. Innovation indicators throughout the innovation process: An extensive literature analysis. Technovation 80–81, 3–29. https://doi.org/10.1016/j.technovation.2018.05.005.

EPO (2023). Espacenet Patent Search. Retrieved from: https://worldwide.espacenet.com/.

Farla, J., Alkemade, F., Suurs, R.A.A., 2010. Analysis of barriers in the transition toward sustainable mobility in the Netherlands. Technol. Forecast. Soc. Chang. 77 (8), 1260–1269. https://doi.org/10.1016/j.techfore.2010.03.014.

Featherston, C.R., Ho, J.-Y., Brévignon-Dodin, L., O'Sullivan, E., 2016. Mediating and catalysing innovation: A framework for anticipating the standardisation needs of emerging technologies. Technovation 48–49, 25–40. https://doi.org/10.1016/j.technovation.2015.11.003.

Ghazinoory, S., Nasri, S., Ameri, F., Montazer, G.A., Shayan, A., 2020. Why do we need 'Problem-oriented Innovation System (PIS)' for solving macro-level societal problems? Technol. Forecast. Soc. Chang. 150, 119749 https://doi.org/10.1016/j.techfore.2019.119749.

Giles, D.E.A., Tedds, L.M., Werkneh, G., 2002. The Canadian underground and measured economies: Granger causality results. Appl. Econ. 34 (18), 2347–2352. https://doi.org/10.1080/00036840210148021.

Granger, C.W.J., 1988. Causality, cointegration, and control. J. Econ. Dyn. Control 12 (2), 551–559. https://doi.org/10.1016/0165-1889(88)90055-3.

Grupp, H., 1997. Messung und Erklärung des Technischen Wandels. In *Grundzüge einer Empirischen Innovationsökonomik*. Springer, Berlin/Heidelberg.

Gupta, H., & Jain, M. (2020). A Vector Error Correction Model (VECM) approach to investigate the linear behaviour of Stocks, Bonds and Hedge Funds. *CASS Studies, 2022*. Retrieved from: https://ssrn.com/abstract=4040547.

Ha, S.H., Liu, W., Cho, H., Kim, S.H., 2015. Technological advances in the fuel cell vehicle: Patent portfolio management. Technol. Forecast. Soc. Chang. 100, 277–289. https://doi.org/10.1016/j.techfore.2015.07.016.

Haley, B., 2015. Low-carbon innovation from a hydroelectric base: The case of electric vehicles in Québec. Environ. Innov. Soc. Trans. 14, 5–25. https://doi.org/10.1016/j.eist.2014.05.003.

Hardman, S., Shiu, E., Steinberger-Wilckens, R., Turrentine, T., 2017. Barriers to the adoption of fuel cell vehicles: A qualitative investigation into early adopters attitudes. Transp. Res. A Policy Pract. 95, 166–182. https://doi.org/10.1016/j.tra.2016.11.012.

Hekkert, M. P., Negro, S. O., Heimeriks, G., Harmsen, R. O., & Jong, S. d. (2011). Technological Innovation System Analysis: A manual for analysts: Utrecht University.

Hekkert, M.P., Suurs, R.A.A., Negro, S.O., Kuhlmann, S., Smits, R.E.H.M., 2007. Functions of innovation systems: A new approach for analysing technological change. Technol. Forecast. Soc. Chang. 74 (4), 413–432. https://doi.org/10.1016/j.techfore.2006.03.002.

Hyundai Motor America (2024). *2023 NEXO Fuel Cell. Our hydrogen-powered SUV*. Retrieved from: https://www.hyundaiusa.com/us/en/vehicles/nexo.

Hyundai Motor Deutschland GmbH (2024). Modellbroschüren und Preislisten. Retrieved from: https://www.hyundai.com/de/de/beratung-kauf/entdecken-und-erwerben/broschueren.html.

IEA (2021). Global Hydrogen Review 2021. Retrieved from: https://www.iea.org/reports/global-hydrogen-review-2021.

IEA (2022). Global Hydrogen Review 2022. Retrieved from: https://www.iea.org/reports/global-hydrogen-review-2022.

IEA (2023a). Global Hydrogen Review 2023. Retrieved from: https://www.iea.org/reports/global-hydrogen-review-2023.

IEA (2023b). Global EV Outlook 2023. Retrieved from: https://www.iea.org/reports/global-ev-outlook-2023.

International Electrotechnical Commission (2022). IEC Webstore. Retrieved from: https://webstore.iec.ch/.

Jaffe, A.B., de Rassenfosse, G., 2019. Chapter 2: Patent citation data in social science research: overview and best practices. In: Jaffe, A.B., De Rassenfosse, G., Depoorter, B., Menell, P.S. (Eds.), Research Handbook on the Economics of Intellectual Property Law, Vol 1: Theory Vol 2. Edward Elgar Publishing, Analytical Methods.

Johansen, S., 1988. Statistical analysis of cointegration vectors. J. Econ. Dyn. Control 12 (2), 231–254. https://doi.org/10.1016/0165-1889(88)90041-3.

Johansen, S., 1995. Likelihood-Based Inferences in Cointegrated Vector Autoregressive Models. Oxford University Press.

Keles, D., Wietschel, M., Most, D., Rentz, O., 2008. Market penetration of fuel cell vehicles – Analysis based on agent behaviour. Int. J. Hydrogen Energy 33 (16), 4444–4455. https://doi.org/10.1016/j.ijhydene.2008.04.061.

Kieft, A., Harmsen, R., Hekkert, M.P., 2021. Heat pumps in the existing Dutch housing stock: An assessment of its Technological Innovation System. Sustainable Energy Technol. Assess. 44, 101064 https://doi.org/10.1016/j.seta.2021.101064.

Kivimaa, P., Kern, F., 2016. Creative destruction or mere niche support? Innovation policy mixes for sustainability transitions. Res. Policy 45 (1), 205–217. https://doi.org/10.1016/j.respol.2015.09.008.

Ko, Y.-C., Zigan, K., Liu, Y.-L., 2021. Carbon capture and storage in South Africa: A technological innovation system with a political economy focus. Technol. Forecast. Soc. Chang. 166, 120633 https://doi.org/10.1016/j.techfore.2021.120633.

Konrad, K., Markard, J., Ruef, A., Truffer, B., 2012. Strategic responses to fuel cell hype and disappointment. Technol. Forecast. Soc. Chang. 79 (6), 1084–1098. https://doi.org/10.1016/j.techfore.2011.09.008.

Kushnir, D., Hansen, T., Vogl, V., Åhman, M., 2020. Adopting hydrogen direct reduction for the Swedish steel industry: A technological innovation system (TIS) study. J. Clean. Prod. 242, 118185 https://doi.org/10.1016/j.jclepro.2019.118185.

Kwiatkowski, D., Phillips, P.C.B., Schmidt, P., Shin, Y., 1992. Testing the null hypothesis of stationarity against the alternative of a unit root: How sure are we that economic time series have a unit root? J. Econ. 54 (1), 159–178. https://doi.org/10.1016/0304-4076(92)90104-Y.

Li, D., Heimeriks, G., Alkemade, F., 2022. Knowledge flows in global renewable energy innovation systems: the role of technological and geographical distance. Tech. Anal. Strat. Manag. 34 (4), 418–432. https://doi.org/10.1080/09537325.2021.1903416.

Li, W., Long, R., Chen, H., Chen, F., Zheng, X., He, Z., Zhang, L., 2020. Willingness to pay for hydrogen fuel cell electric vehicles in China: A choice experiment analysis. Int. J. Hydrogen Energy 45 (59), 34346–34353. https://doi.org/10.1016/j.ijhydene.2020.01.046.

Lin, X., Sovacool, B.K., 2020. Inter-niche competition on ice? Socio-technical drivers, benefits and barriers of the electric vehicle transition in Iceland. Environ. Innov. Soc. Trans. 35, 1–20. https://doi.org/10.1016/j.eist.2020.01.013.

Liu, X., Reddi, K., Elgowainy, A., Lohse-Busch, H., Wang, M., Rustagi, N., 2020. Comparison of well-to-wheels energy use and emissions of a hydrogen fuel cell electric vehicle relative to a conventional gasoline-powered internal combustion engine vehicle. Int. J. Hydrogen Energy 45 (1), 972–983. https://doi.org/10.1016/j.ijhydene.2019.10.192.

Lütkepohl, H., 2005. New introduction to multiple time series analysis. Springer Science & Business Media.

Mäkitie, T., Hanson, J., Steen, M., Hansen, T., Andersen, A.D., 2022. Complementarity formation mechanisms in technology value chains. Res. Policy 51 (7), 104559. https://doi.org/10.1016/j.respol.2022.104559.

Manoharan, Y., Hosseini, S.E., Butler, B., Alzhahrani, H., Senior, B.T.F., Ashuri, T., Krohn, J., 2019. Hydrogen Fuel Cell Vehicles; Current Status and Future Prospect. Appl. Sci. 9 (11), 2296. https://doi.org/10.3390/app9112296.

Markard, J., 2020. The life cycle of technological innovation systems. Technol. Forecast. Soc. Chang. 153, 119407 https://doi.org/10.1016/j.techfore.2018.07.045.

Markard, J., Hekkert, M., Jacobsson, S., 2015. The technological innovation systems framework: Response to six criticisms. Environ. Innov. Soc. Trans. 16, 76–86. https://doi.org/10.1016/j.eist.2015.07.006.

Markard, J., Bento, N., Kittner, N., Nuñez-Jimenez, A., 2020. Destined for decline? Examining nuclear energy from a technological innovation systems perspective. Energy Res. Soc. Sci. 67, 101512 https://doi.org/10.1016/j.erss.2020.101512.

Markard, J., Hoffmann, V.H., 2016. Analysis of complementarities: Framework and examples from the energy transition. Technol. Forecast. Soc. Chang. 111, 63–75. https://doi.org/10.1016/j.techfore.2016.06.008.

Mirzadeh Phirouzabadi, A., Blackmore, K., Savage, D., Juniper, J., 2022. Modelling and simulating a multi-modal and multi-dimensional technology interaction framework: The case of vehicle powertrain technologies in the US market. Technol. Forecast. Soc. Chang. 175, 121412 https://doi.org/10.1016/j.techfore.2021.121412.

Mirzadeh Phirouzabadi, A., Savage, D., Blackmore, K., Juniper, J. (2020d). Tripartite dynamic interactions on the scientific knowledge development of ICEV, BEV and HEV technologies. 33rd Electric Vehicle Symposium (EVS33) Portland, Oregon, June 14 – 17, 1-12. Retrieved from:https://nova.newcastle.edu.au/vital/access/services/Download/uon:38062/ATTACHMENT02.

Mirzadeh Phirouzabadi, A., Juniper, J., Savage, D., Blackmore, K., 2020a. Supportive or inhibitive? — Analysis of dynamic interactions between the inter-organisational collaborations of vehicle powertrains. J. Clean. Prod. 244, 118790 https://doi.org/10.1016/j.jclepro.2019.118790.

Mirzadeh Phirouzabadi, A., Savage, D., Blackmore, K., Juniper, J., 2020b. The evolution of dynamic interactions between the knowledge development of powertrain systems. Transp. Policy 93, 1–16. https://doi.org/10.1016/j.tranpol.2020.04.018.

Mirzadeh Phirouzabadi, A., Savage, D., Juniper, J., Blackmore, K., 2020c. Dataset on the global patent networks within and between vehicle powertrain technologies — Cases of ICEV, HEV, and BEV. Data Brief 28, 105017. https://doi.org/10.1016/j.dib.2019.105017.

Morrison, G., Stevens, J., Joseck, F., 2018. Relative economic competitiveness of light-duty battery electric and fuel cell electric vehicles. Transportation Research Part c: Emerging Technologies 87, 183–196. https://doi.org/10.1016/j.trc.2018.01.005.

Murphy, J.T., 2015. Human geography and socio-technical transition studies: Promising intersections. Environ. Innov. Soc. Trans. 17, 73–91. https://doi.org/10.1016/j.eist.2015.03.002.

Nevzorova, T., Karakaya, E., 2020. Explaining the drivers of technological innovation systems: The case of biogas technologies in mature markets. J. Clean. Prod. 259, 120819 https://doi.org/10.1016/j.jclepro.2020.120819.

Noailly, J., Shestalova, V., 2017. Knowledge spillovers from renewable energy technologies: Lessons from patent citations. Environ. Innov. Soc. Trans. 22, 1–14. https://doi.org/10.1016/j.eist.2016.07.004.

OECD & Eurostat. (2018). Oslo Manual 2018: Guidelines for Collecting, Reporting and Using Data on Innovation, 4th Edition. Retrieved from: https://www.oecd.org/science/oslo-manual-2018-9789264304604-en.htm.

Oltra, V., Saint Jean, M., 2009. Variety of technological trajectories in low emission vehicles (LEVs): A patent data analysis. J. Clean. Prod. 17 (2), 201–213. https://doi.org/10.1016/j.jclepro.2008.04.023.

Ortt, J.R., Kamp, L.M., 2022. A technological innovation system framework to formulate niche introduction strategies for companies prior to large-scale diffusion. Technol. Forecast. Soc. Chang. 180, 121671 https://doi.org/10.1016/j.techfore.2022.121671.

PERINORM database (2022). Retrieved from: https://www.perinorm.com/home/default.aspx?ReturnUrl=%2fsearch.aspx.

Phillips, P.C.B., Perron, P., 1988. Testing for a unit root in time series regression. Biometrika 75 (2), 335–346. https://doi.org/10.1093/biomet/75.2.335.

Pohl, H., Yarime, M., 2012. Integrating innovation system and management concepts: The development of electric and hybrid electric vehicles in Japan. Technol. Forecast. Soc. Chang. 79 (8), 1431–1446. https://doi.org/10.1016/j.techfore.2012.04.012.

Ravi, S.S., Brace, C., Larkin, C., Aziz, M., Leach, F., Turner, J.W.G., 2023. On the pursuit of emissions-free clean mobility – Electric vehicles versus e-fuels. Sci. Total Environ. 875, 162688 https://doi.org/10.1016/j.scitotenv.2023.162688.

Reichardt, K., Rogge, K.S., Negro, S.O., 2017. Unpacking policy processes for addressing systemic problems in technological innovation systems: The case of offshore wind in Germany. Renew. Sustain. Energy Rev. 80, 1217–1226. https://doi.org/10.1016/j.rser.2017.05.280.

Rohe, S., Chlebna, C., 2021. A spatial perspective on the legitimacy of a technological innovation system: Regional differences in onshore wind energy. Energy Policy 151, 112193. https://doi.org/10.1016/j.enpol.2021.112193.

Sacchi, R., Bauer, C., Cox, B., Mutel, C., 2022. When, where and how can the electrification of passenger cars reduce greenhouse gas emissions? Renew. Sustain. Energy Rev. 162, 112475 https://doi.org/10.1016/j.rser.2022.112475.

Sandén, B.A., Hillman, K.M., 2011. A framework for analysis of multi-mode interaction among technologies with examples from the history of alternative transport fuels in Sweden. Res. Policy 40 (3), 403–414. https://doi.org/10.1016/j.respol.2010.12.005.

Schot, J., Geels, F.W., 2008. Strategic niche management and sustainable innovation journeys: theory, findings, research agenda, and policy. Tech. Anal. Strat. Manag. 20 (5), 537–554. https://doi.org/10.1080/09537320802292651.

Sick, N., Bröring, S., Figgemeier, E., 2018. Start-ups as technology life cycle indicator for the early stage of application: An analysis of the battery value chain. J. Clean. Prod. 201, 325–333. https://doi.org/10.1016/j.jclepro.2018.08.036.

Sinigaglia, T., Freitag, T.E., Kreimeier, F., Martins, M.E.S., 2019. Use of patents as a tool to map the technological development involving the hydrogen economy. World Patent Inf. 56, 1–8. https://doi.org/10.1016/j.wpi.2018.09.002.

Sinigaglia, T., Eduardo Santos Martins, M., Cezar Mairesse Siluk, J., 2022a. Technological evolution of internal combustion engine vehicle: A patent data analysis. Appl. Energy 306, 118003. https://doi.org/10.1016/j.apenergy.2021.118003.

Sinigaglia, T., Martins, M.E.S., Siluk, J.C.M., 2022b. Technological forecasting for fuel cell electric vehicle: A comparison with electric vehicles and internal combustion engine vehicles. World Patent Inf. 71, 102152 https://doi.org/10.1016/j.wpi.2022.102152.

Skov, I.R., Schneider, N., 2022. Incentive structures for power-to-X and e-fuel pathways for transport in EU and member states. Energy Policy 168, 113121. https://doi.org/10.1016/j.enpol.2022.113121.

Song, C.H., Aaldering, L.J., 2019. Strategic intentions to the diffusion of electric mobility paradigm: The case of internal combustion engine vehicle. J. Clean. Prod. 230, 898–909. https://doi.org/10.1016/j.jclepro.2019.05.126.

StataCorp. (2022). pperron — Phillips–Perron unit-root test. College Station, TX: Stata Press.

Stephan, A., Schmidt, T.S., Bening, C.R., Hoffmann, V.H., 2017. The sectoral configuration of technological innovation systems: Patterns of knowledge development and diffusion in the lithium-ion battery technology in Japan. Res. Policy 46 (4), 709–723. https://doi.org/10.1016/j.respol.2017.01.009.

Streb, J., Wallusch, J., Yin, S., 2007. Knowledge spillover from new to old industries: The case of German synthetic dyes and textiles (1878–1913). Explor. Econ. Hist. 44 (2), 203–223. https://doi.org/10.1016/j.eeh.2005.11.002.

Suarez, F.F., Utterback, J., Von Gruben, P., Kang, H.Y., 2018. The hybrid trap: Why most efforts to bridge old and new technology miss the mark. Retrieved from: Sloan Manage. Rev. 59 (3), 52–57 https://ink.library.smu.edu.sg/lkcsb_research/5851.

The Lens (2022). Patent Filing Dates vs Priority Dates. Retrieved from: https://support.lens.org/knowledge-base/filing-dates-vs-priority-dates/.

Thomas, C.E., 2009. Fuel cell and battery electric vehicles compared. Int. J. Hydrogen Energy 34 (15), 6005–6020. https://doi.org/10.1016/j.ijhydene.2009.06.003.

Van De Kaa, G., Scholten, D., Rezaei, J., Milchram, C., 2017. The Battle between Battery and Fuel Cell Powered Electric Vehicles: A BWM Approach. Energies 10 (11), 1707. https://doi.org/10.3390/en10111707.

VDE (2022). VDE Normenbibliothek. Retrieved from: https://www.normenbibliothek.de/ vde-xaveropp/normenbibliothek/static/login.

Wang, Y., Seo, B., Wang, B., Zamel, N., Jiao, K., Adroher, X.C., 2020. Fundamentals, materials, and machine learning of polymer electrolyte membrane fuel cell technology. Energy and AI 1, 100014. https://doi.org/10.1016/j.egyai.2020.100014.

Wang, Z., Yang, Z., Zhang, Y., 2012. Relationships between energy technology patents and CO2 emissions in China: An empirical study. J. Renewable Sustainable Energy 4 (3), 031807. https://doi.org/10.1063/1.4730596.

Wang, Y., Yuan, H., Martinez, A., Hong, P., Xu, H., Bockmiller, F.R., 2021. Polymer electrolyte membrane fuel cell and hydrogen station networks for automobiles: Status, technology, and perspectives. Advances in Applied Energy 2, 100011. https://doi.org/10.1016/j.adapen.2021.100011.

Watts, R.J., Porter, A.L., 1997. Innovation forecasting. Technol. Forecast. Soc. Chang. 56 (1), 25–47. https://doi.org/10.1016/s0040-1625(97)00050-4.

Weiss, D., & Scherer, P. (2023). Mapping the territorial adaptation of technological trajectories: The phase-out of the internal combustion engine. In Koretsky, Z., Stegmaier, P., Turnheim, B., van Lente, H. (eds.). Technologies in Decline: Socio-Technical Approaches to Discontinuation and Destabilisation: Routledge.

Weiss, D., Nemeczek, F., 2022. A Media-based Innovation Indicator: Examining declining Technological Innovation Systems. Environ. Innov. Soc. Trans. 43, 289–319. https://doi.org/10.1016/j.eist.2022.04.001.

Weiss, D., Scherer, P., 2021. Mapping the Territorial Adaptation of Technological Innovation Systems—Trajectories of the Internal Combustion Engine. Sustainability 14 (1), 113. https://doi.org/10.3390/su14010113.

Weiss, D. (2022). Technological Innovation Systems: A critical review of quantitative methods. Paper presented at the EU-SPRI 2022 conference.

Wieczorek, A.J., Hekkert, M.P., 2012. Systemic instruments for systemic innovation problems: A framework for policy makers and innovation scholars. Sci. Public Policy 39 (1), 74–87. https://doi.org/10.1093/scipol/scr008.

Wong, E.Y.C., Ho, D.C.K., So, S., Tsang, C.-W., Chan, E.M.H., 2021. Life Cycle Assessment of Electric Vehicles and Hydrogen Fuel Cell Vehicles Using the GREET Model—A Comparative Study. Sustainability 13 (9), 4872. https://doi.org/10.3390/su13094872.

Wu, Y.A., Ng, A.W., Yu, Z., Huang, J., Meng, K., Dong, Z.Y., 2021. A review of evolutionary policy incentives for sustainable development of electric vehicles in China: Strategic implications. Energy Policy 148, 111983. https://doi.org/10.1016/j.enpol.2020.111983.

Xu, J., Zhang, C., Wan, Z., Chen, X., Chan, S.H., Tu, Z., 2022. Progress and perspectives of integrated thermal management systems in PEM fuel cell vehicles: A review. Renew. Sustain. Energy Rev. 155, 111908 https://doi.org/10.1016/j.rser.2021.111908.

Yang, Z., Wang, B., Jiao, K., 2020. Life cycle assessment of fuel cell, electric and internal combustion engine vehicles under different fuel scenarios and driving mileages in China. Energy 198, 117365. https://doi.org/10.1016/j.energy.2020.117365.