Research Policy 54 (2025) 105174

Contents lists available at ScienceDirect

Research Policy

journal homepage: www.elsevier.com/locate/respol

Decline processes in technological innovation systems: Lessons from energy technologies

Nuno Bento [a,*], Alejandro Nuñez-Jimenez [b,c], Noah Kittner [d,e]

[a] Instituto Universitário de Lisboa (ISCTE-IUL), DINÂMIA'CET-IUL, Av. das Forças Armadas, Edifício ISCTE, 1649-026 Lisboa, Portugal
[b] Belfer Center for Science and International Affairs, Harvard Kennedy School of Government, 79 John F. Kennedy Street, Cambridge, MA 02138, USA
[c] Group for Sustainability and Technology, Swiss Federal Institute of Technology Zurich (ETH Zurich), Weinbergstrasse 56/58, 8092 Zürich, Switzerland
[d] Department of Environmental Sciences and Engineering, Gillings School of Global Public Health, University of North Carolina at Chapel Hill, Chapel Hill, NC, USA
[e] Department of City and Regional Planning, University of North Carolina at Chapel Hill, Chapel Hill, NC, USA

ARTICLE INFO

JEL classification:
O33
O38
Q40
Q55

Keywords:
Sustainability transitions
Technological innovation systems
Functions
Decline
Energy technologies

ABSTRACT

Technology decline is gaining attention in sustainability transitions because it can accelerate the adoption of sustainable alternatives and mitigate the lingering impacts of polluting technologies. However, a systematic analysis of the processes driving the decline of established technologies remains absent. This paper addresses this gap by introducing the concept of "decline functions," inspired by the functional analysis of technological innovation systems (TIS). While traditional TIS functions make emerging systems thrive, decline functions contribute to the unravelling of faltering systems. Four decline functions are suggested: delegitimation, guidance toward exit, market decline, and resource demobilization. These functions are applied to four energy-technology cases: incandescent light bulbs, oil-based heating, nuclear power and internal combustion engine cars. Data were collected through a directed literature review. Our analysis reveals that all four decline functions were present and played important roles across the cases. These functions offer a systematic framework for analyzing and comparing cases of declining TIS and can provide actionable insights for policymakers to accelerate sustainability transitions.

1. Introduction

The decline of established technologies has become a focal point in sustainability transition research, as rapidly reducing the use of polluting technologies is critical for addressing societal challenges like climate change (Koretsky et al., 2023; IEA, 2021a; Rinscheid et al., 2021; Markard et al., 2020; Köhler et al., 2019).

In recent years, scholars have explored decline through various lenses, including historical accounts of technology phase-out, regime destabilization, and divestment (Rosenbloom and Rinscheid, 2020; Turnheim and Geels, 2012), as well as the life cycles of technologies, industries, and clusters (Klepper, 1997; Anderson and Tushman, 1990; Peltoniemi, 2011; Østergaard and Park, 2015). Researchers have also examined the socio-economic impacts (Vona, 2019) and pace of decline (Utterback et al., 2019), along with resistance to decline (Adner and Kapoor, 2016). Despite these efforts, the key processes driving technology decline remain understudied.

This paper addresses this gap by applying functional analysis of a technological innovation system (TIS) to technology decline. By decline, we understand the unraveling and eventual disappearance of the innovation system surrounding a specific technology (i.e. a TIS) (Smith and Raven, 2012).[1] A TIS is characterized by networks of actors and institutions engaged in the development, diffusion, and use of a specific technology (Bergek et al., 2008; Carlsson and Stankiewicz, 1991). Although decline often coincides with the emergence of a better-performing technology and efforts to improve the old one (e.g.,

* Corresponding author.
E-mail address: nuno.bento@iscte-iul.pt (N. Bento).

[1] Economic actors and assets linked to the production and consumption elements of the TIS may not necessarily unravel and disappear but instead continue to operate throughout the decline of a TIS by switching to a new technology. For example, the case of the incandescent light bulb shows how the production and consumption system around lighting products continued to operate (and make profits) despite the TIS around incandescent light bulbs entering decline. Similarly, local structures like industrial clusters can continue to thrive throughout the decline of a TIS if the actors and structures in the cluster successfully manage to transition to other technologies. An example could be the local clusters in Switzerland who managed the transition from mechanical watchmaking to nanotechnologies (Raffaelli, 2014).

https://doi.org/10.1016/j.respol.2025.105174
Received 4 February 2022; Received in revised form 20 December 2024; Accepted 7 January 2025

sailing-ship effect) (Rosenberg, 1972; Mendonça, 2013), it is not merely technology displacement. Decline involves deeper transformations, including shifts in actors and institutions, that considering changes in technology production and consumption alone would overlook. Instead, by incorporating broader political, sectoral, and social context structures and focusing on key processes of change, the TIS framework is better suited for studying system decline.

Until now, whether and how functional analysis applies to studying a TIS in decline remains an open question (Markard, 2020). Previous functional analyses have focused on processes in the industrialization of a new technology (Jacobsson and Jacobsson, 2014: 812)[2] that are necessary to the innovation progress (e.g., Bergek et al., 2008) and the construction of the structure underpinning the system's formation and growth (e.g., Hekkert et al., 2007). These studies inspired seminal work on TIS dynamics during the formative phase (Bento and Wilson, 2016; Suurs and Hekkert, 2009; Bergek et al., 2008; Hekkert et al., 2007). However, as a TIS moves on to the growth, maturity, and decline phases, the definition of "functionality" changes (Hekkert et al., 2007; Bergek et al., 2008). When analyzing a TIS in decline, the focus reverses from assessing *how well* the system functions to *how poorly*. To answer such a question, this paper reviews the literature to identify TIS decline functions and tests their usefulness for making sense of empirical observations.

This paper proposes four TIS decline functions: delegitimation, guidance toward exit, market decline, and resource demobilization. They relate to drivers of technology decline observed in prior studies, like external pressures and disruptive events (Markard et al., 2020; Markard, 2020). External pressures can disturb a TIS through sociopolitical pressures and adverse market developments (Smith and Raven, 2012; Bergek et al., 2015; Turnheim and Geels, 2012; Kungl and Geels, 2018; Kivimaa and Kern, 2016; Lamberg et al., 2018), while disruptive events can undermine its increasing economic returns (Arthur, 1989, 2021). The functional approach differs from others, like exnovation, by going beyond policy and company decisions to discontinue technologies (Hartley and Knell, 2022; Davidson, 2019; Kimberly, 1981).

To test their usefulness, the functions are applied to four cases—incandescent light bulbs, heating oil, nuclear power, and internal combustion engine (ICE) cars—that represent energy supply and demand technologies of different scales and complexity and at various stages of decline. The results show that all functions contributed to the decline of the surveyed cases. TISs in decline lose their social license to operate (delegitimation), face weakening demand (market decline), experience worsening expectations about their future (guidance toward exit), and witness resource reallocation (resource demobilization). The functions, whether triggered by external factors or the actions of TIS actors, pushed the TISs into decline, and despite resistance and delays, the cumulative effects of interactions among the functions further accelerated the decline.

This paper provides a foundation for functional analyses of TIS decline. Although future research may refine or expand the functions, these already offer a starting point for more systematic studies of decline, easier comparisons, and better policy guidance. Section 2 develops the paper's conceptual framework, and Section 3 describes the decline functions. Section 4 explains the method for analyzing TIS decline, and the results are shown in Section 5 and discussed in Section 6. Section 7 summarizes key findings and concludes the paper.

[2] Functions cannot be reduced to actions only: "Functions are, therefore, emergent properties of the system and not merely an aggregation of activities pursued by individual actors" (Jacobsson and Jacobsson, 2014: 813). According to this perspective, the functional analysis "involves an examination of the mechanisms, functions, intentions and unanticipated consequences of actions" (idem: 819).

2. Literature review and conceptual framework

2.1. Decline in the innovation and sociotechnical transitions literature

Decline is an essential part of technological change. Established technologies decline as new ones emerge and replace them, as they are phased out or as they become redundant. Although it often has major economic, social, and political consequences, technology decline has received relatively little attention compared to technology emergence (Markard, 2020).

Scholars have investigated technology decline through different lenses, as discussed by Turnheim and Geels (2012). Economists characterize decline as diminishing financial resources due to market (Dintenfass, 1992) and technology changes (Christensen, 1997; Utterback et al., 2019). Economic geographers understand decline as losing the ability to adapt and renew (Østergaard and Park, 2015; Menzel and Fornahl, 2010). Institutional theorists view decline as the process of losing political or cultural legitimacy (Scott, 1995; Oliver, 1992). And management scholars highlight the agency of economic actors by presenting decline as interacting processes within and outside firms (Collins, 2009; Weitzel and Jonsson, 1989; Lamberg et al., 2018).

For sustainability transition scholars, the decline of established technologies is increasingly relevant (Köhler et al., 2019; Markard et al., 2012). Sustainability transitions involve complex, fundamental changes to adopt more sustainable forms of production and consumption (Geels et al., 2023)—while simultaneously abandoning unsustainable technologies. Therefore, transition scholars are increasingly interested in the dynamics that lead to the destabilization of entrenched technologies, investigating how various pressures—economic, technological, and socio-political—accumulate over time to destabilize established sociotechnical regimes (Turnheim and Geels, 2012, 2013). Kungl and Geels (2018) further elaborate on how aligning pressures and sequences influence the destabilization of industry regimes, such as the downfall of the German energy incumbents. Transition research has also studied intentional and policy-driven decline (Rosenbloom and Rinscheid, 2020). Such deliberate decline involves the intentional destabilization of a technology's sociotechnical regime (Turnheim and Geels, 2012), including phase-out and discontinuation policies (Rogge and Johnstone, 2017; Stegmaier et al., 2014) or policy mixes for creative destruction (Kivimaa and Kern, 2016). Deliberate decline can also be led by civil society, for example, through initiatives such as fossil fuel divestment movements (Rosenbloom and Rinscheid, 2020).

Despite the progress made in understanding technology decline within sustainability transitions, significant gaps remain in the literature. Analyses of decline often rely on single-industry, single-country case studies, making comparisons difficult and limiting the findings' generalization (Rosenbloom and Rinscheid, 2020; Lamberg et al., 2018). In addition, frameworks focus on technology emergence and, therefore, lack tools to conceptualize decline (Markard, 2020). For these reasons, a new framework that facilitates systematic analyses of technology decline across various cases and contexts is needed.

2.2. Decline of technology innovation systems

Decline can be understood as the last phase of a TIS life cycle. Existing life cycle models outline the phases technologies (Taylor and Taylor, 2012), products (Utterback and Abernathy, 1975), or industries (Klepper, 1997) typically follow. Although life cycle models often fail to represent how specific cases evolve (Pavitt and Rothwell, 1976; Pavitt, 1984), they are helpful generalizations to study changes over time across different units of analysis (Menzel and Fornahl, 2010; Markard, 2020). Unlike traditional frameworks, which tend to overlook social, political, and sectorial shifts (Pavitt, 1984), TIS provides a systematic approach to analyzing decline that emphasizes sociotechnical interactions and captures changes in the structure of actors, networks, and institutions (Bergek et al., 2015; Markard, 2020) (see Table 1).

Table 1
Contrasting Life Cycle and TIS conceptual approaches to decline.

Approach	Life cycle theories	TIS theories
Scope	Primarily focuses on the economic aspect of production and consumption	Considers broader factors beyond production and consumption, including social, institutional, and sectorial influences
Questions	*How does technology emerge, grow, mature, and decline within a linear life cycle? What factors influence technology's evolution and obsolescence?*	*How do internal and external pressures interact to precipitate decline within a technology innovation system? How do innovation activities and societal contexts contribute to decline processes?*
Method	Relies on analysis of technology/product/industry evolution (e.g., adoption, costs), often employing quantitative methods to track phases of development and obsolescence	Combines structural with functional analysis to study decline as the unravelling of an innovation system, emphasizing innovation and societal influences
Unit	Product, technology, or industry	System, including technology, actors, networks, and institutions
Some references	e.g.; Peltoniemi, 2011; Klepper, 1997	e.g.: Markard et al., 2020; Markard, 2020

A TIS is an innovation system centered around a particular technology, with structural components—actors, networks, institutions—-that contribute to developing, diffusing and using new products and processes (Carlsson and Stankiewicz, 1991; Bergek et al., 2008). Innovation scholars have identified different phases in TIS development (Bergek et al., 2008; Bergek and Jacobsson, 2003; Hekkert et al., 2007). Initially, a *formative phase* occurs when the "constituent elements of the new TIS begin to be put into place, involving entry of some firms and other organizations, the beginning of an institutional alignment and formation of networks." (Bergek et al., 2008: 419). If the TIS continues to expand, a *growth phase* ensues when "the focus shifts to system expansion and large-scale technology diffusion" (Bergek et al., 2008: 420). As the TIS becomes more established, it reaches the *mature phase*, "characterized by high sales and low growth rates[,] low numbers of firm entries and exits[, high] degree of structuration [and high] technology performance" (Markard, 2020: 8). Eventually, a phase of *decline* marks the end of the TIS life cycle (Markard, 2020).

Markard (2020) argues that three dimensions can help analyze the TIS dynamics as it moves through different phases: size and actor base, institutional structure, and technology performance and variation. For example, the *decline phase* typically involves shrinking sales and firm exits, fragmentation of actor networks, worsening expectations, and questioning of the technology's performance. If these processes start within a TIS, it could signal the beginning of its decline.

The decline of a TIS is not merely a consequence of market forces or technological obsolescence that lead to diminished production and consumption. The triggers of technology decline can have multiple sources, external or internal to the system. Decline is often precipitated or accelerated by policy interventions (Rosenbloom and Rinscheid, 2020), shifts in societal norms (Rosa and Dunlap, 1994), and changes within stakeholder networks (Markard et al., 2020). The TIS approach has a distinctive ability to analyze the complexity of technology decline and track destabilization by emphasizing the systemic impacts of interactions among the system's components and with the broader context.

2.3. TIS decline and relationship with the context

A TIS and its context evolve through interconnected but distinct trajectories. Bergek et al. (2015) identify four contextual structures a TIS interacts with: technological, political, sectorial, and geographical. Technological interactions often involve the development of technological complementarities (Markard and Hoffmann, 2016), while political interactions tend to exert regulatory pressures that can destabilize a TIS (Markard et al., 2021). A TIS also operates within sectorial contexts that span multiple technologies, with changes in these sectors potentially impacting the TIS trajectory (Stephan et al., 2019). Geographically, a TIS can share contextual structures, such as actors, institutions, and networks, i.e. structural couplings (Mäkitie et al., 2020), with a specific territory or at multiple scales across different places (Heiberg et al., 2022).

Interactions between a TIS and its contextual structures can be complementary or competitive (Sandén and Hillman, 2011). Complementary interactions, such as firms sharing resources, or institutions aligning to support infrastructure, enhance system development and can be unidirectional or bidirectional (Markard and Hoffmann, 2016). By contrast, competitive interactions, such as rival technologies competing for market share, affect the TIS negatively (Sandén and Hillman, 2011).

Throughout the TIS life cycle, interactions between a TIS and its context evolve. Over time, complementary ties with technologies and sectors may weaken (Markard and Hoffmann, 2016; Mäkitie et al., 2022), reducing access to critical resources like skills or suppliers and hindering functions like market formation and knowledge creation (Bergek et al., 2008). In decline, competitive interactions may overshadow complementarities. A good illustration is the transitions from VHS to DVD and then to streaming, where shifts in sectorial complements facilitated the rise of a new TIS and the decline of the older ones (Markard, 2020).

Contextual shifts, whether due to policy, technological, or sectorial changes, can directly contribute to TIS decline. Events such as new regulatory frameworks, market exits, or changes in global trends disrupt resource flows and weaken sectorial or geographic ties that once supported the TIS (Geels and Schot, 2007). When media companies stopped releasing content on DVDs and moved to streaming, the decline of the TIS around DVDs accelerated (Markard, 2020). Similarly, regional clusters may experience a reduction of their knowledge diversity and adaptability over time, which can also lead to TIS decline (Menzel and Fornahl, 2010; Hassink, 2016). Although the cluster and TIS life cycles differ, many TIS actors are part of both, binding their trajectories within specific regions (Bergek et al., 2015).

While TIS-context relationships provide insights into patterns of the TIS life cycle, including decline, a new tool is needed to analyze what leads the TIS into decline, and TIS functions offer a promising starting point.

3. Decline functions

The study of a TIS in decline poses a challenge to using traditional TIS functions. Scholars have proposed a set of functions required for TIS formation and growth: knowledge creation and diffusion, entrepreneurial activities, guidance of search, market formation, legitimacy creation (legitimation), and resource mobilization (Bergek, 2019; Bergek et al., 2008; Hekkert et al., 2007). The degree to which these functions are fulfilled determines *how well* a TIS performs. A well-performing TIS supports its focal technology's development, diffusion and use, moving along its formative, growth and maturity phases (Markard, 2020).

When investigating a TIS in decline, the question becomes *how poorly* the TIS performs. Answering this question cannot rely on assessing whether the traditional TIS functions are being served but rather whether there are key processes that actively contribute to the decline of the TIS and to what extent they are being fulfilled. The need to extend the notion of TIS functions to include decline has been argued before

(Kivimaa and Kern, 2016; Markard, 2020) and appears in other literature streams, which refer to dysfunctions and extinguishing processes (Poznanski, 1986).

A TIS in decline involves a reduction in the development, diffusion and use of new products and services around its focal technology. Therefore, as an initial step to formulating a set of decline functions, we suggest focusing on the inverse of TIS functions most directly linked with the diffusion and use of the focal technology: delegitimation (*inverse of* legitimation), guidance toward exit (*i.o.* guidance of the search), market decline (*i.o.* market formation), and resource demobilization (*i.o.* resource mobilization).

These four decline functions describe key processes necessary for the decline of a TIS. Although they may not single-handedly precipitate the decline of the technology, they destabilize and weaken the TIS. Other factors can prolong the decline for decades, halt it, or even reverse it.

While many different developments can trigger processes of TIS decline, most studies have focused on external pressures (Turnheim and Geels, 2012; Kungl and Geels, 2018; Kivimaa and Kern, 2016), which often fall into two main groups. One group relates to sociopolitical pressures and deteriorating acceptance, and the other to adverse market dynamics and increasing competition from alternative technologies, and both are aligned with political and market dynamics mentioned in studies of industry decline (Lamberg et al., 2018). Although developments triggering the decline of a TIS can emerge from within the TIS, its context, and the relations between the two, thinking about potential triggers using the two groups of external pressures helps to embed the suggested decline functions in the existing literature.

Sociopolitical pressure and deteriorating acceptance refer to social and political opposition, unfavorable evolution of public discourse, and an increase in the perception of problems associated with the TIS technology, such as environmental and health issues. Two decline functions are related to these developments.

Delegitimation denotes the erosion of social acceptance of the TIS by losing compliance with general rules and regulations, norms, values, and cognitive frames. It is the reverse of the legitimation function during the formative and growth phases, which induces actors to accept the TIS (Bergek, 2019; Suchman, 1995; Suddaby et al., 2017). Developments within the TIS can fulfill the delegitimation function, for instance, disappointing diffusion rates and performance of the focal technology relative to alternatives (Markard, 2020), as well as changes in the TIS context, such as worsening public concerns about the TIS externalities. In fact, public concerns may worsen so much that social movements might establish opposing advocacy coalitions to discredit the TIS's focal technology and to influence the adoption of unfavorable policies (Markard et al., 2020; Hekkert et al., 2007). Governments can deliberately try to accelerate delegitimation by hindering compliance through laws and regulations (Bergek, 2019; Suddaby et al., 2017; Hekkert et al., 2007). As a result, TIS actors find it increasingly difficult to comply with relevant norms, as continuing to do things "the way they were done" is rejected (Oliver, 1992). Eventually, a TIS that is seen as inappropriate or undesirable loses its "social license" to operate and declines.

Guidance toward exit dissuades TIS actors from searching for opportunities to deploy their resources within the TIS. Instead, actors are guided to search away from the TIS (Hekkert et al., 2007). This decline function "work[s] in the opposite direction [of the traditional function guidance of search], inducing exit rather than entry" (Bergek, 2019:10). Guidance toward exit can be started and reinforced by several developments, such as a perceived reduction of market potential and future technological opportunities (Markard et al., 2020; Breschi et al., 2000), disappointment due to overly optimistic visions that never materialize (Andersson et al., 2017), and loss of commitment of the actors (Kungl and Geels, 2018). Governments can deliberately try to serve this function, for example, by withdrawing policy support (Fevolden and Klitkou, 2017). Moreover, the guidance toward exit function is reinforced when prominent actors abandon a TIS (Østergaard and Park, 2015). The exit of a large supplier and intermediator can destabilize value chains and increase the incentives to leave the TIS (Howells, 2006).

The second group, *adverse market dynamics and competition from alternative technologies*, relates to two other decline functions.

Market decline refers to narrowing opportunities for the commercialization of the focal technology of a TIS. It is the inverse of the market formation function and can be triggered by various factors. Demand may decrease due to substitution by competing technologies (e.g., cars replacing horses), redundancy (e.g., online data storage making physical data storage unnecessary), or policy decisions (e.g., phasing out ozone-depleting gases). Customer dissatisfaction with the technology for failing to meet their expectations (Chiesa and Frattini, 2011), particularly among late adopters resistant to technology (Rogers, 2003), can also contribute to market decline. Moreover, saturation may lead to market decline by limiting network economies, scale economies, and technological learning (Arthur, 1989). Governments may intentionally induce market decline through phase-outs policies and bans (Rosenbloom and Rinscheid, 2020; Kivimaa and Kern, 2016).

Resource demobilization denotes human and financial capital and complementary assets, such as physical infrastructures, becoming less and less available to actors in the TIS. It is the opposite function of resource mobilization, which refers to actors allocating more and more resources into the TIS (Hekkert et al., 2007). Firms can pull resources from the TIS and move them elsewhere for various reasons, including protecting themselves from disruptive technologies (Christensen et al., 2004). Resource demobilization makes accessing resources increasingly difficult and costly for TIS actors until it becomes problematic (Hekkert et al., 2007). Not only input but also complementary resources may become scarce, as in the case of the TIS for DVD systems (Markard, 2020). Therefore, the resource demobilization function can be fulfilled by developments that reduce the availability of resources (Hekkert et al., 2007; Christensen et al., 2004), lead to the exit of firms and suppliers (Klepper, 1997), the fragmentation of inter-firm networks (Markard et al., 2020), and the loss of technological complementarities (Markard and Hoffmann, 2016). Governments can hinder access to resources by reducing support for complementary resources (e.g., R&D infrastructures) and shifting investment priorities.

Table 2 lists the functions of TIS decline and suggests characteristic mechanisms and indicators. The list is not exhaustive, and it is reasonable to assume that it will need to be extended and refined by future research. Next, we explain how to use the functions for making sense of four cases of TIS decline.

4. Method for analyzing TIS decline

To illustrate the usefulness of the decline functions, we apply them to study four TISs in decline: incandescent light bulbs (ILBs), oil-based heating, nuclear power, and ICE cars.

We define the unit of analysis as the innovation system around a technology (i.e., the TIS) and focus on the system-level structures and processes that influence the focal technology's development, diffusion, and use. Departing from the concept of operational principle (Murmann and Frenken, 2006), technology is here defined at the level that the final consumer directly purchases and uses to obtain a useful service, such as the car in the case of mobility services. Hence, the TIS encompasses the main product (e.g., ICE cars) and its surrounding infrastructure (e.g., gas stations), as well as service providers (e.g., dealerships, workshops), users, and regulatory and institutional frameworks.

Unlike studies of production and consumption systems (PCS), which primarily examine established dynamics for producing, distributing, and consuming goods, the TIS approach captures the complex, intertwined social and technological dynamics that are consistent with the socio-technical approach to sustainability transitions (Geels, 2024). Some elements of the cases are shared across PCS and TIS, such as actors (e.g., car manufacturers) and infrastructure (e.g., gas stations). Others are unique to the TIS, such as institutions and contextual elements that

Table 2
Functions of TIS decline.

Function	Definition	Mechanisms and indicators
Delegitimation	*TIS loses its "social license" to operate. Compliance with relevant institutions and norms becomes increasingly difficult. TIS is seen as inappropriate or undesirable. Regulations and laws are changed to hinder compliance.*	• Growing concern/disappointment about the technology • Negative advocacy coalitions • Negative opinions in the media • Strong contestation
Guidance toward exit	*TIS becomes unattractive. Expectations and future visions of the TIS worsen. Removal of policy support encourages exit.*	• Exit of firms and suppliers • Perceived reduction of potential • Disappointing performance for users • Investors turn to competing technologies
Market decline	*Demand falls for the TIS focal technology. The substitute's market share grows. TIS becomes the target of deliberate efforts to curb demand.*	• Fewer sales and/or market share reduction • Competition from alternatives • Stagnant or rising costs • Phase-out policies and bans
Resource demobilization	*Flows of human and financial capital into the TIS dry up and become increasingly difficult or costly to access. Key players abandon the TIS actor networks. Active campaigns to divest from the TIS. Governments change public procurement and investment guides.*	• Loss of financial resources • Loss of human resources • Loss of complementarities • Fragmentation of inter-firm networks • Rising pressures to divest

shape technology adoption and use over time as well as processes like the guidance of search, making it possible to study them separately (Malerba, 2002; Bergek, 2019). Thanks to its focus on system-level dynamics that enable or hinder technological change, the TIS approach is well suited to study technology decline.

The cases include TISs where decline is beginning, ongoing, and nearly complete. For example, as momentum around electric vehicles (EV) grows, with a global market share approaching 18 % in 2023, it is increasingly clear that the TIS around ICE cars is taking the first step toward global decline (Meckling and Nahm, 2019; IEA, 2022). Similarly, the TIS around heating oil is entering the decline phase as natural gas furnaces, electric heat pumps, and electric resistive heaters replace oil boilers in many markets (Britton et al., 2021). In contrast, the protracted decline of the nuclear power TIS has been underway for decades since new constructions reached a maximum in the 1970s, and the global share of nuclear electricity peaked in 1996 (Markard et al., 2020). Lastly, the TIS around ILB has undergone a rapid and nearly complete decline and now represents less than 5 % of global lighting sales (IEA, 2020).

Since primary energy flows are only one aspect of energy systems, it is important to understand changes in end-use services such as lighting, heating and transport (Gallagher et al., 2012). Therefore, we examine four TISs around energy technologies that include large-scale, centralized electricity generation, like nuclear power plants, and energy demand applications, such as mobility (ICE cars), thermal comfort (heating oil) and lighting (ILB).

The geographical scope of this study is limited to regions where decline is most noticeable. In some parts of the world, a TIS around a particular technology may show dynamics associated more with growth or maturity than decline. This is the case, for example, of the TIS around nuclear power in China (Markard et al., 2020). Therefore, we focus on geographies where the focal technology of the TIS was (one of) the dominant technologies in the relevant markets (e.g., ICE cars in private vehicles, ILB in lighting) and where policy signals confirm the decline of the focal technology (e.g., phase-out timelines, bans). For the TISs around nuclear power, ILB, and ICE cars, we mainly focus on Europe and, to some extent, the global market, whereas for the TIS around heating oil, the focus is primarily on the United States (US).

We adopt a multi-method approach to deal with the complexity of examining the myriad factors and developments involved in the decline of each TIS. We start by selecting the cases based on expert consultations, including internal meetings, participation in (external) seminars, and informal encounters. Then, we performed a directed literature review to search for prior studies, which revealed a large set of relevant research articles on the decline of the selected cases. Finally, we applied historical event analysis (Poole et al., 2000; Van de Ven et al., 1999) to cluster the information about each decline function and map the sequence of events and interactions between the decline functions in a process akin to assessing the functional pattern of an emergent TIS.

The decline functions are investigated using a directed literature review based on papers that have studied each case. Relevant articles were searched in Scopus based on queries including: "decline" AND ("nuclear" OR "lightbulb" OR "light bulb" OR "light-bulb" OR "incandescent" OR "heating oil" OR "internal combustion engine") AND (technolog* OR innovate* OR industry OR "power" OR "energy"). Duplicates were removed manually.

The initial search provided 1094 results. Many were removed based on subject area and relevance because some search terms overlapped with ecological systems and biology research. A few other publications were found through snowballing, resulting in a final subset of 66 peer-reviewed articles. As described in the next section, the decline functions become apparent when evaluating the four cases.

5. Applying the decline functions to study four energy TISs

5.1. Incandescent light bulbs

In the early 2000s, awareness of the gross inefficiency of ILBs, a century-old technology that had experienced few improvements over the years, was growing. At the same time, more efficient lighting alternatives started to appear, leading to a general perception that the transition to energy-efficient lighting was possible and beneficial. As a result, a diverse group of actors, from industrial groups to environmentalists, began advocating for the transition to new lighting technologies (Stegmaier et al., 2014).

The market decline function played a decisive role in the downfall of the ILB TIS and was primarily triggered by regulatory changes. Many governments, with the support of a broad coalition of stakeholders, implemented phase-out policies for ILB lighting (Stegmaier et al., 2014). As the phase-out date approached, the global market for ILBs collapsed, showing the critical contribution of these policies to the market decline function. Two key milestones in the ILB's decline were the approval of minimum energy efficiency standards for lighting in 2007 in the US and 2008 in the EU, which effectively banned the use of conventional ILBs (Edge and McKeen-Edwards, 2008; Stegmaier et al., 2021).

Meanwhile, progress in the cost and performance of alternatives further contributed to the market decline function of the ILB TIS. For example, light-emitting diode (LED) lamps can produce up to five times more luminescence with the same power consumption as an ILB and last fifty times longer (Kassakian et al., 2017). Such progress softened the initial resistance of consumers, manufacturers, and distributors (Kassakian et al., 2017).

As a response from some incumbents, a new type of incandescent lamp (halogen) was introduced, which was 40 % more efficient and lasted twice as long as conventional ILBs (DOE, 2012). This innovation worked as a "steam ship effect" to slow the transition to alternative lighting technology but did not stop the market decline (Fig. 1). In most markets, compact fluorescent lamps (CFL) and LED lamps gradually replaced ILBs (Zissis and Bertoldi, 2018), though they have not been completely phased out yet (Koretsky, 2021).

The regulatory change that sparked the market decline function

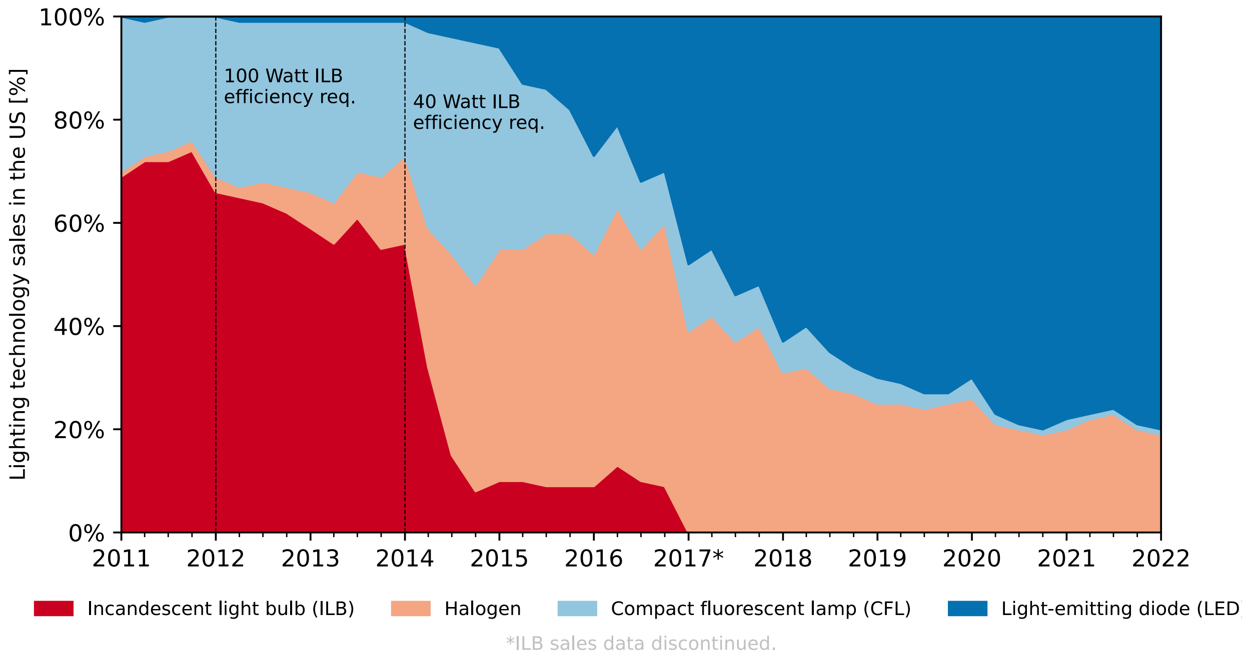

Fig. 1. Market share of lighting technologies in the US Source: NEMA, 2017, 2022. Efficiency requirements for 100-Watt and 40-Watt ILB were introduced in 2007 by the Energy Independence Security Act.

stemmed from the growing disapproval of ILBs. The delegitimation function was activated by environmental concerns over energy inefficiency, which led to the formation of coalitions advocating for the abandonment of conventional ILBs. Various actors—from lighting industry associations and NGOs to national governments and European institutions—collaborated to raise awareness about the environmental impact of lighting (Koretsky, 2021; Stegmaier et al., 2014).

Worsening prospects about the focal technology tarnished its attractiveness, contributing to the guidance toward exit function. Key actors turned away from the ILB TIS and diversified toward more sophisticated products, with less competition and higher mark-ups. This led "the European Lamps Companies Federation (ELC) [to consider] proposing to phase-out ILB before there were any regulations (ELC, 2007)" (Stegmaier et al., 2014: 118). Eventually, the advocacy coalition opposing ILBs succeeded, and phase-out policies and bans spread quickly across many markets, further reinforcing the guidance toward exit. As Stegmaier et al. (2014) note, "[i]mportant driving factors for [ILB bans] diffusion were the low costs of the discontinuation governance and the relative ease of its implementation due to the widespread support from industry and environmentalists." Despite some resistance, notably in the US—where manufacturers and large trade associations challenged the regulations in court and lobbied against the bans—CFL and LED manufacturers ultimately prevailed (Schwartz, 2019).

The fragmentation of the TIS actor networks significantly contributed to the resource demobilization function. Key manufacturers like General Electrics exited the TIS and shifted to new lighting technologies following tightening efficiency standards (Cardwell, 2016). The departure of these companies weakened connections within the actor-network, reducing its resources. Meanwhile, industry associations partnered to develop alternatives and lobbied for stricter lighting regulations. This created the conditions for introducing new standards in European markets that were nearly impossible for TIS actors to meet and were soon adopted by regulators in many other markets (Edge and McKeen-Edwards, 2008). Thus, the switch of key actors to competing technologies and stringent regulations helped fulfill the resource demobilization function. Along with the market decline function, these supply-side shifts further accelerated the decline of the ILB TIS.

5.2. Heating oil

Oil is an energy-dense fuel used for many applications, including heating buildings. Heating oil (as termed in this context) emits carbon dioxide, which contributes to climate change, as well as high levels of particulate matter (PM) and nitrogen oxides (NO_x), which are regulated pollutants known to harm human health (Kheirbek et al., 2014). These environmental and health concerns are major reasons why heating oil has been replaced by natural gas and electricity for heating buildings and water (Carrión et al., 2018). In fact, the pace at which gas and other fuels have phased out heating oil was remarkable in the US (Fig. 2). This transition occurred predominantly at urban scales, mainly through community-driven initiatives rather than top-down approaches, similar to trends observed in other countries (Sovacool and Martiskainen, 2020).

Resource demobilization has been a critical function contributing to the decline of the TIS around heating oil in the US. Loans and capital for upgrading heating oil equipment were no longer available, and with more favorable interest rates and attractive financing options for natural gas, many consumers found it economically unfeasible to pursue upgrades to heating oil boilers. The impacts are evident in Fig. 2, illustrating the significant decline in heating oil consumption since the late 1970s in the US residential sector. After an initial sharp decline, a period of stagnation followed until the late 2000s, when the shale gas revolution spurred a second wave of natural gas adoption, further displacing heating oil usage (especially for new homes).

Heating oil use in the Northeast of the US declined from 29 % to 23 % of homes from 2009 to 2015 due to the rise of fracking technologies and advances in natural gas distribution infrastructure (US EIA, 2015). Simultaneously, the removal of efficiency rebates for heating oil boilers in core markets such as Massachusetts further discouraged property owners from investing in this technology (Nadel, 2020). Incentives such as the Inflation Reduction Act provided key subsidies to switch fuels. In addition, key actors of the TIS, such as utilities and banks, partnered with public groups and NGOs to offer investment calculations, compile a list of contractors providing competitive upgrades, and finance educational campaigns that promoted natural gas as a healthier and cleaner alternative to heating oil fuels.

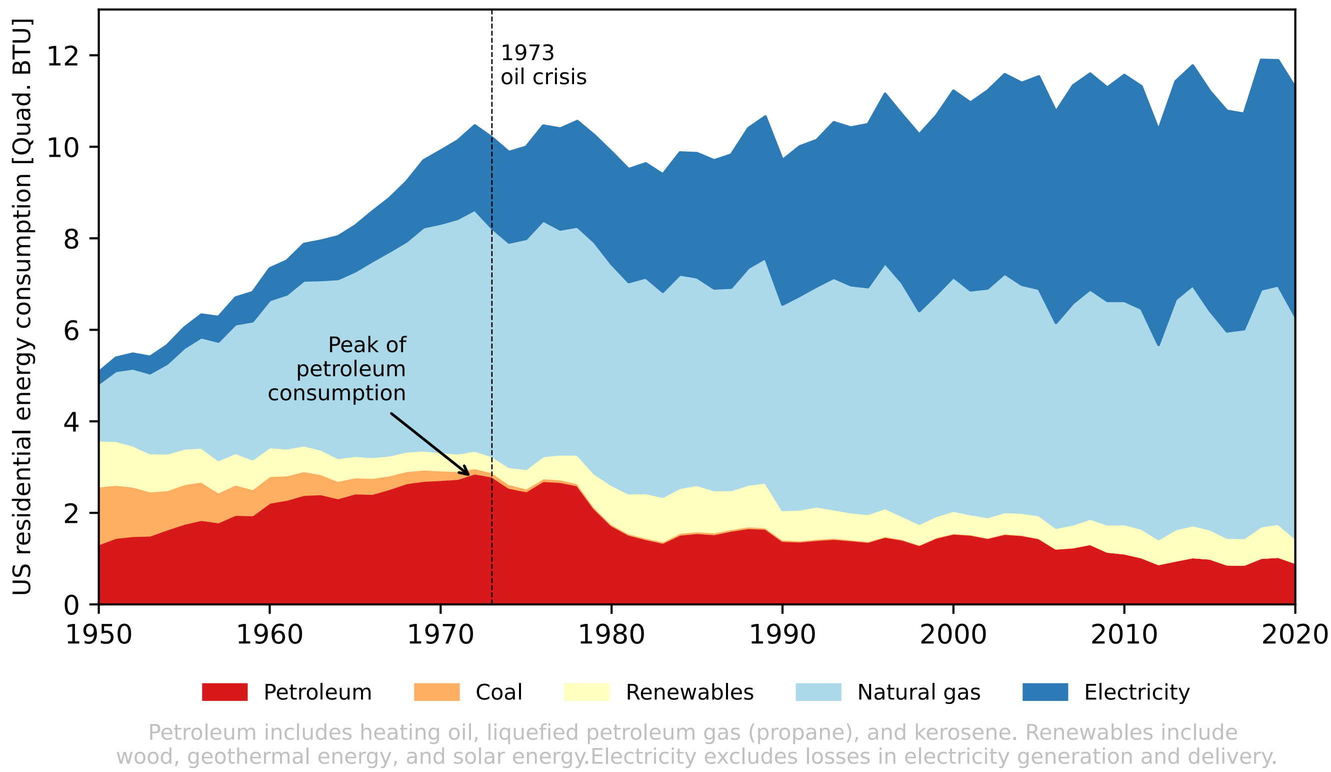

Fig. 2. US residential energy consumption 1950–2020. Data source: US EIA, 2023.

The increasing availability of information on the impacts of burning fossil fuels on air quality, climate, and public health played a critical role in the delegitimation function of the TIS around heating oil. As awareness grew, particularly in local communities dependent on heating oil boilers, concerns about the health impacts of indoor air pollution caused by PM and NOx intensified (Salimfard et al., 2022). This heightened awareness drove consumers toward cleaner and healthier fuel alternatives.

The sudden increase in the availability of cheap natural gas in the US due to the shale gas revolution was a later driver of the market decline function in the TIS for heating oil (Wang et al., 2014). Moreover, regulatory changes enhanced the relative advantages of competing fuels like natural gas, aligning with a broader societal preference for cleaner energy sources. For instance, the removal of subsidies and incentives in several cities in the US (like New York City) significantly boosted the market decline of heating oil (Salimfard et al., 2022). As oil companies lost market share, utilities sought to expand the market for natural gas and alternative fuels, aided by subsidy support. This, in turn, fostered increasingly negative expectations for heating oil's future.

As observed with other declining technologies, the exit of leading companies from the TIS accelerated the guidance toward exit function for heating oil (Salimfard et al., 2022). Rather than relying on top-down national or state-wide policies, the guidance toward exit was primarily driven by community-level efforts. Neighbors and local groups concerned with pollution and public health collaborated with utility companies and banks to expedite the transition away from heating oil (Salimfard et al., 2022). The exodus of companies not only disrupted the heating oil supply chain but also reduced the availability of support services, affecting the convenience for users relying on heating oil systems.

5.3. Nuclear power

Commercial electricity generation with nuclear power[3] began in 1956, but initial expectations for its future never fully materialized. Nuclear power capacity under construction worldwide peaked in 1981, indicating that the TIS around nuclear power has been in decline for several decades (Markard et al., 2020). Meanwhile, the TIS context has undergone significant changes. First, the antinuclear discourse emerged and gained prominence during the 1970s, starting in the TIS's early markets in the US and Europe (Gamson and Modigliani, 1989). Second, electricity demand growth slowed, and interest rates rose, reducing demand for new nuclear power plants in those early markets (IEA, 2019a, 2019b; Rubio-Varas, 2021). Other markets emerged after 2000, as electricity demand grew in countries like China. Third, increasingly liberalized electricity markets challenged the centralized electricity system model based on state-owned utilities, a structure in which nuclear power thrived (Roques et al., 2006). Nevertheless, climate change and increased demand from computer servers have recently renewed attention to nuclear power (Goldstein et al., 2019).

Above all, the TIS around nuclear power has suffered from delegitimation. In the 1960s, the TIS entered its growth phase, with many new nuclear power plants constructed worldwide. As suppliers competed to build larger reactors closer to demand centers, safety concerns gained prominence, culminating in a legitimacy crisis in the 1970s (Campbell, 2019).

[3] Nuclear power can refer to several technologies. This analysis focuses on large, pressurized light-water reactors (nuclear fission), which produce the majority of nuclear power worldwide. Small-scale nuclear reactors, with a capacity of less than 300 MW per unit, have garnered significant attention; however, only three SMRs were operational globally as of 2024 (NEA, 2024).

This legitimation shock led to regulatory changes for nuclear power plants (Cohn, 1997). Although stricter regulations and the external shock of the oil crises helped the nuclear power TIS regain some legitimacy, these gains were short-lived. Public concerns resurfaced following nuclear accidents in 1979 and 1986 (Rosa and Dunlap, 1994; Soni, 2018). A long period of safe operation for most nuclear power plants in subsequent decades gradually rebuilt the TIS legitimacy. However, another accident in 2011 erased it again and halted the growth of new nuclear capacity under construction (see Fig. 3).

Concerns about nuclear proliferation and the inability of TIS actors in many countries to establish permanent solutions for radioactive waste disposal further undermined nuclear power's legitimacy (Lovins, 2019). Recent efforts to counter the delegitimation by emphasizing nuclear power's role in climate action have met with modest success thus far (Feldman and Hart, 2018; Pidgeon et al., 2008).

The market decline function has also been prominent in the nuclear power TIS. Competition from alternative technologies —including coal, natural gas, and, more recently, renewable energies— has been fierce. The liberalization of electricity markets and slower growth in electricity demand further intensified competition (Rubio-Varas, 2021). The inability of the nuclear power TIS to substantially reduce costs in most countries has also strengthened the market decline function (Koomey et al., 2017). Additionally, decisions by governments, most notably Germany, not to extend reactor lifetimes, phase-out operating plants, and halt new construction projects have contributed to market decline (Markard et al., 2020). This process has not been linear, and debates continue about phase-out policies, such as in the UK and Germany, especially after the energy crisis triggered by Russia's invasion of Ukraine. Announcements by some companies, particularly in the technology sector with rapidly increasing energy demands, about their intentions to utilize nuclear power for their operations reinforce the possibility of a non-linear decline (Castelvecchi, 2024).

The guidance toward exit function also played a key role in the nuclear power TIS. Deteriorating market prospects, rising costs, lengthening construction time, and substantial cost overruns in multiple projects led many actors to scale back their commitment to nuclear power and seek opportunities elsewhere (IAEA, 2019; IEA, 2019a; Sovacool et al., 2014; Grubler, 2010). One significant contribution to the guidance toward exit function was the withdrawal of some of the largest nuclear reactor suppliers (Markard et al., 2020).

The fragmentation of the actor-network was the main contributor to the resource demobilization function in the TIS around nuclear power. Major nuclear reactor suppliers exiting the business in the 2000s fragmented the international actor network into isolated and sparsely connected elements (Markard et al., 2020). In addition, increasing financial risk perceptions surrounding nuclear projects, particularly in Western countries, made it harder for TIS actors to access financial resources (Rubio-Varas, 2021). For this reason, nuclear power remains a significant option in countries where state intervention plays a larger role in constructing and operating nuclear power plants, such as Russia and China.

5.4. *Internal combustion engine cars*

The TIS around ICE cars is an example of a mature system entering the decline phase. Introduced commercially in 1888 in Europe, ICE cars prevailed in personal transportation over steam and electric cars due to their greater range and suitability for touring—key advantages when road quality and supporting infrastructure were poor (Hadjilambrinos, 2021). They became widely accessible with Ford's Model T in 1908, rapidly substituting horses and enabling the motorization of personal mobility (Grubler, 2003). However, widespread awareness of the need to reduce greenhouse gas emissions and urban air pollution, which causes millions of premature deaths (McDuffie et al., 2021), along with the emergence of alternatives like EVs challenge the dominance of ICE cars.

The guidance toward exit function plays an important role in the transition to decline of the TIS around ICE cars. Influenced by shifts in the TIS context, including growing consensus on climate action and the rapid improvement of EV technologies, many governments are enacting the guidance toward exit function by setting targets for the sales of competing technologies, mainly battery EVs (Meckling and Nahm, 2019). For example, in 2021, the US government set a target for 50 % of vehicle sales to be EVs by 2030 (White House, 2021).

Many governments have announced policies for phasing out or banning ICE car sales (see Fig. 4). The European Union (EU) intensely debated the issue before deciding in 2023 to phase out ICE car sales after 2035. Although phase-out dates are often set well into the future, they guide actors to seek new opportunities outside the ICE car TIS.

The exit of key actors is another contribution to the guidance toward exit function. Several automakers have committed to ending ICE car production and sales. Aligned with national phase-out targets, 18 of the 20 largest ICE car manufacturers have set ambitious EV sales goals (Financial Times, 2021; IEA, 2021b; Burch and Gilchrist, 2020). However, some carmakers have revised their plans for rapid phase-out. For example, in 2019, Volvo pledged to sell only EVs by 2030 but revised this in 2024, abandoning a full ICE phase-out within that timeframe (Burch and Gilchrist, 2020; Meckling and Nahm, 2019; BBC, 2024).

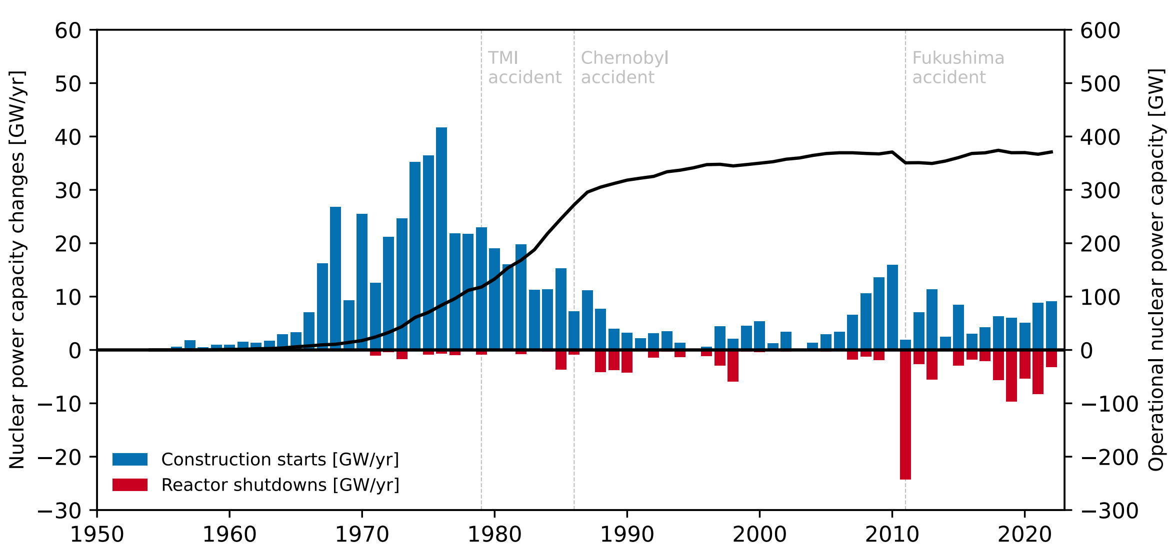

Fig. 3. Annual nuclear power additions, withdrawals, and operational capacity. Source: IAEA, 2023.

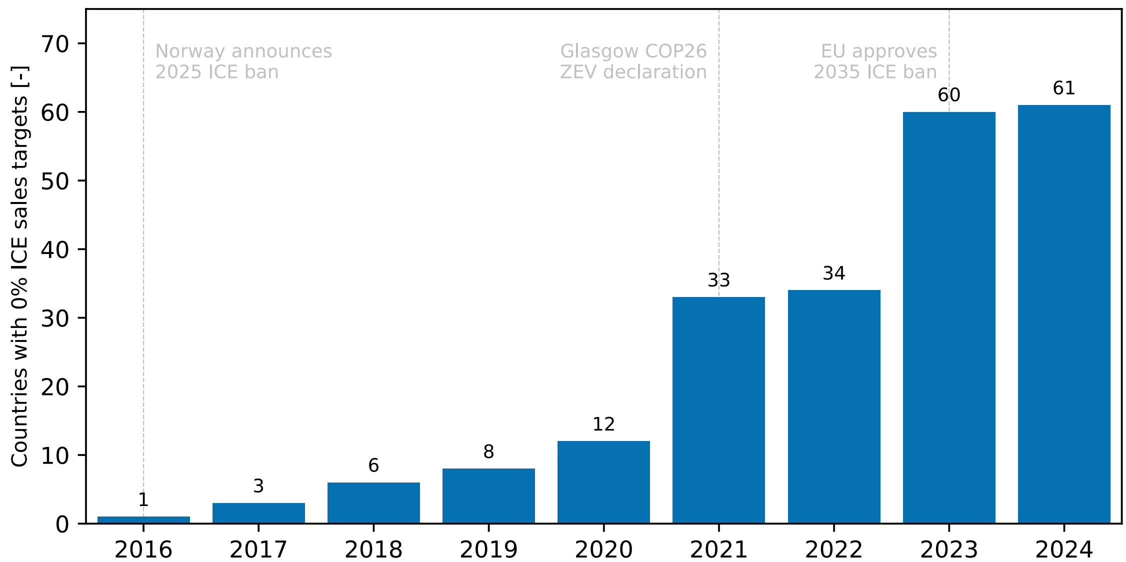

Fig. 4. Countries with 0 % ICE car sales targets. Source: McKerracher, 2021; Burch and Gilchrist, 2020; Meckling and Nahm, 2019; IEA, 2021b. Ambitions, pledges, targets, legislations for phasing out and banning ICE car sales, and 100 % sales targets for zero-emission vehicles (ZEV) were considered.

Mounting evidence of fossil fuel use's environmental, climate, and public health impacts has played a central role in the delegitimation function within the ICE car TIS (Meckling and Nahm, 2019). Public awareness about urban air pollution and its detrimental effects on public health has strengthened delegitimation. While the TIS around ICE cars may still be in the early stages of decline, delegitimation processes are already well advanced. A critical moment was the 2015 "dieselgate" scandal, in which several automakers were found dodging emissions tests with hidden software. This event significantly contributed to the delegitimation of diesel and, thereby, ICE cars (Helmers et al., 2019; Fulton et al., 2019).

The market decline function is currently weak but gaining momentum within the TIS around ICE cars. ICE cars are losing market share to competing technologies, with EVs already accounting for 18 % of global car sales in 2023. Leading markets, such as China and Norway, achieved EV market shares of 38 % and 93 %, respectively (IEA, 2024). Key drivers of market decline include government incentives for EV purchases (Rinscheid et al., 2020) and rapid cost and performance improvements of EV technologies. For instance, EV battery pack prices, a key cost component of EV cars, fell by 90 % between 2010 and 2020, eroding the cost advantage of ICE cars and contributing to ICE cars' gradual market decline (BloombergNEF, 2021).

Actors within the TIS around ICE cars are increasingly reallocating their investments, contributing to the resource demobilization function. Some major automakers have set timelines for ceasing ICE car production and shifting to EVs (Meckling and Nahm, 2019; Financial Times, 2021). For example, in 2021, Daimler announced plans to invest $40 billion in EV development by 2030, cutting investment in ICE and plug-in hybrid technologies by 80 % (Reuters, 2021). As automakers pivot, related industries, such as parts manufacturers, are also redirecting resources toward EV technologies.

Through tightened fuel economy and emissions standards, governments in multiple jurisdictions further reinforce the resource demobilization and guidance toward exit functions. Compliance becomes increasingly costly and technologically challenging, prompting manufacturers to focus on EV development (Fritz et al., 2019).

6. Discussion

This paper contributes to developing tools to study key processes of technology decline in sustainability transitions. Here, we discuss how the findings support this effort and paths for future research.

6.1. Patterns in technology decline

Studying the decline functions in four empirical settings makes it possible to compare cases of technology decline and identify regularities. We find that some functions are fulfilled similarly across cases at specific stages of decline, whereas interactions among functions tend to differ between cases.

As a TIS moves from early to late stages of decline, the most prominent decline function and how it is fulfilled changes in similar ways across the four cases (see Table 3). The delegitimation function appeared early in all four cases, driven by sustainability demands that became more organized as the TIS moved further into decline (e.g., from concerned consumers to negative advocacy coalitions). This resembles dynamics seen in social problems theories, where organized protests precede political and legislative action (Rivoli and Waddock, 2011). Guidance toward exit and resource demobilization tended to follow, driven by adverse policies, and in later stages, market decline gained prominence as competition and adverse policies strengthened.

This regularity suggests a potential pattern in which changes in the TIS context are more relevant early in decline, and changes in the TIS structure gain importance later. The pattern aligns with previous studies showing how contestation catalyzes decline (Koretsky et al., 2023) and legitimation problems emerge early on (Turnheim and Geels, 2012). However, we also found that some ways to fulfill the decline functions were unique to some cases, such as rising technology costs guiding actors toward exiting the nuclear power TIS and actors advocating for phase-out policies leading to delegitimation and market decline in the TIS around ILB. Therefore, more analyses of decline using the functions and studying the TIS context and structure are needed to explore potential patterns.

Another regularity is that, in all cases, decline functions interact with each other and build up cumulative effects that accelerate the decline but through different functional patterns (see Fig. 5). In the ILB case (Fig. 5a), delegitimation and guidance toward exit led to market decline, which in turn reinforced guidance toward exit in a negative loop that also appeared in the case of ICE cars (Fig. 5d). For heating oil (Fig. 5b), delegitimation interacted with resource demobilization in a feedback cycle that eventually led to market decline. In the nuclear power case (Fig. 5c), although delegitimation was the most prominent function, the interactions between market decline, guidance toward exit and resource demobilization created an important reinforcing negative cycle.

These cases illustrate how decline function interactions can lead to

Table 3
Key contributors to the decline functions in the four TISs surveyed. Cases are ordered from early (left, ICE cars) to late (right, ILB) stages of decline and functions by when they are more prominent from early (top, delegitimation) to late (bottom, market decline).

	ICE cars	Nuclear power	Heating oil	ILB
Delegitimation	– Public health and environmental concerns – Perception downturn – Strong contestation and resistance	– Public health and environmental concerns – Strong contestation and resistance	– Public health and environmental concerns – Key actors form a negative advocacy coalition	– Environmental concerns – Key actors form a negative advocacy coalition – Contestation
Guidance toward exit	– Key actors announce exit – Phase-out policies and bans[a] – Policy targets for sales of competing alternatives	– Exit of key actors – Stagnant technology performance – Worsening prospects	– Exit of key actors	– Exit of key actors – Phase-out policies and bans[a] – Support policies for competing alternatives
Resource demobilization	– Key actors switch resources to alternatives – Difficult-to-comply regulation	– Break-up of the actor-network – Difficult-to-comply regulation – Financial costs increase	– Financial costs increase – Key actors switch resources to alternatives	– Break-up of the actor-network – Difficult-to-comply regulation – Key actors switch resources to alternatives
Market decline	– Competition from alternatives – Shrinking market share and uncertainty – Support policies for competing alternatives – Worsening prospects	– Competition from alternatives – Shrinking share in power mix – Phase-out and ban policies[a]	– Competition from alternatives – End of support policies	– Competition from alternatives – Phase-out policies and bans[a]/ mandates

[a] Phase-out and ban policies can contribute to both the guidance toward exit and market decline functions, depending on when (e.g., delayed vs immediate impact) and how (e.g., voluntary vs mandatory) they are introduced.

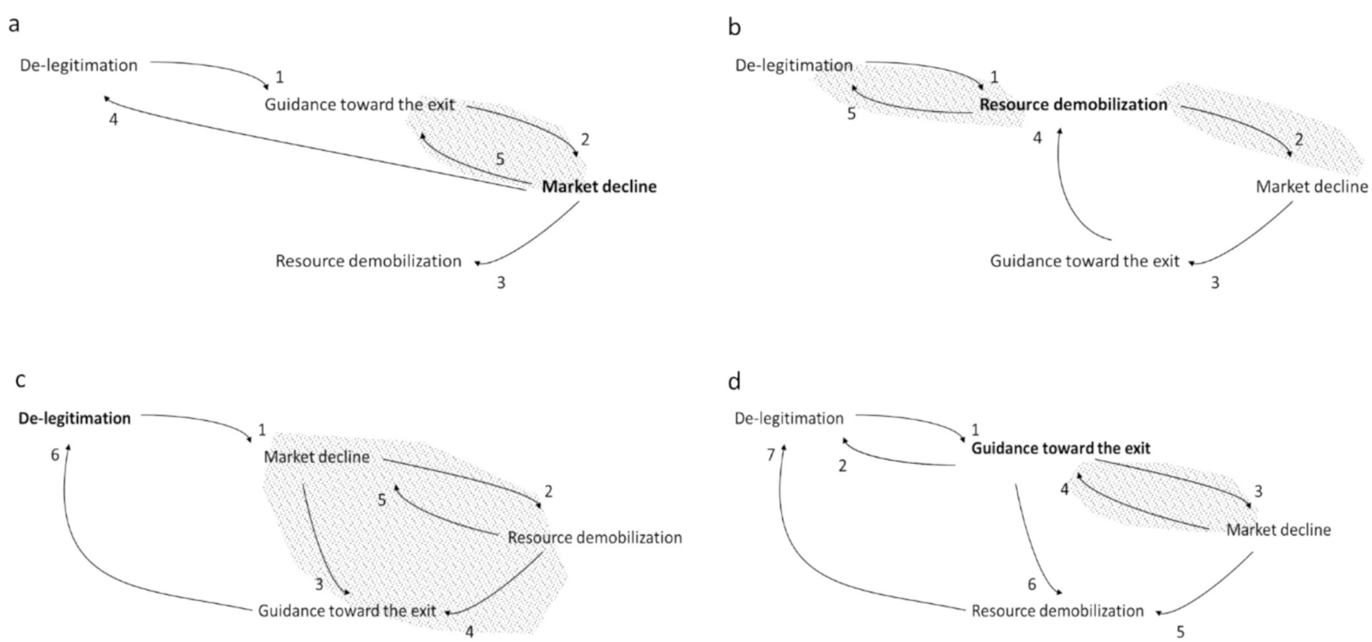

Fig. 5. Key interactions between decline functions in the TIS for (a) ILBs, (b) heating oil, (c) nuclear power and (d) ICE cars. Functions in bold indicate the case's most prominent function, and shaded areas indicate reinforcing loops.

cumulative causation (Suurs and Hekkert, 2009), forming various possible functional patterns of decline. While being different, all functional patterns of decline displayed complexity, self-reinforcement, and co-evolution. Complexity was always present as different functions intervened in the decline of the TIS at the same time, driven by multiple unfolding developments. The effects of the decline functions often strengthened one another, creating self-reinforcing loops, and as the TIS context and structure changed, co-evolution contributed to how the decline functions were fulfilled. These traits resonate with prior studies that showed the importance of co-evolution in decline, emphasizing that multiple, aligned pressures are needed to trigger it (Kungl and Geels, 2018).

6.2. Non-linearity of technology decline

Decline can exhibit non-linear patterns, as different actors may resist change to varying degrees, and the proposed decline functions could help make sense of these patterns.

In all four cases, entrenched actors tried to resist decline by weakening the processes fulfilling the functions and interactions between functions. For example, incumbent efforts to weaken the interaction between guidance toward exit and market decline led the Trump administration to suspend ILB bans in the US—only for them to be reinstated by the following administration (Schwartz, 2019). Similarly, the slower pace of EV sales in countries like Germany and Italy (Fig. 6), despite growing environmental and regulatory pressure, reflects the efforts by domestic industrial lobbies to break the interaction between guidance toward exit and market decline (Wells, 2023). In the case of nuclear power, the EU Commission's decision to include nuclear power in the EU's green investments framework was influenced by efforts led by the nuclear industry and countries like France with significant interests in the technology to weaken the negative feedback loop between

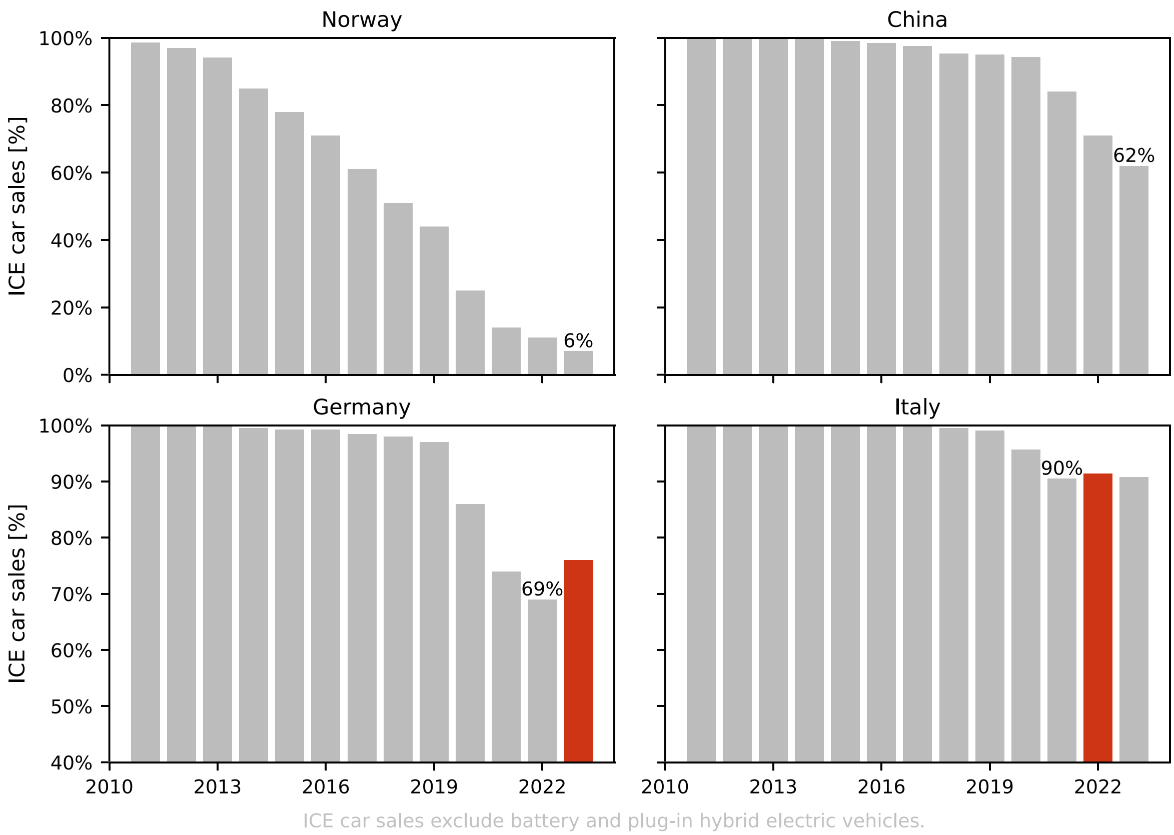

Fig. 6. ICE market share of new car sales in selected countries 2010 to 2023. Source: IEA, 2024. Annotated values indicate the lowest market share of ICE cars. Bars in red indicate an increase in market share from the previous year. Note the differences in the y-scale between the graphs at the top and bottom. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the demobilization of resources, guidance toward exit, and market decline (Politico, 2022). These examples illustrate the non-linear and contested nature of TIS decline, aligning with historical accounts of technology decline such as coal energy or leaded petrol (Koretsky et al., 2023; Turnheim and Geels, 2012).

Finally, technology decline is not necessarily permanent and absolute. Declining technologies can either disappear altogether (e.g., cassette tape), remain like a "zombie" technology (e.g., telex) and in small niches (e.g., horses for recreational transportation) (Fressoz, 2024). Old technologies can also resurge, such as the recent revival of vinyl records, or resurface by incorporating new technology (e.g., digital instant cameras, sail-powered cargo ships). To what extent the proposed decline functions help study cases of technology "revival", for example, in competition with traditional TIS functions, is an opportunity for future research.

6.3. *Agency and the role of policy*

The cases offer good illustrations of the varying roles of agency in technology decline. It can be argued that the Fukushima accident was the 'killer blow' (Kungl and Geels, 2018) of nuclear energy by amplifying social contestation (delegitimation). Similarly, environmental problems and the rise of feasible alternatives created the 'perfect storm' that spurred the decline of ICE cars. However, the declines of ILB and heating oil were more directed by the TIS actors and thus seem different from any of the three patterns presented by Kungl and Geels (2018)—the third one being the "masking effect" of gradual changes in the context. Industry, utilities, and other actors played an important role in influencing changes in regulation at local (heating oil) and national and supra-national levels (ILB).

Policy interventions were important in fulfilling the decline functions. Regulatory changes were a common driver of decline across the four cases examined. Policies such as phase-outs and bans contributed to guidance toward exit and market decline in nuclear power and ILBs, and to a lesser degree, also in the ICE cars case. Governments can shape the decline of technologies, but the effectiveness of their intervention is contingent on the measures employed and the context (Geels et al., 2016). As mentioned before, variations in legislation delayed the decline of conventional lights in the US compared to Europe, while the rapid decline of ICE cars in Norway contrasted with Germany's and Italy's slower transitions.

The results have significant implications for policymakers, particularly governments aiming to accelerate the sustainability transition. Governments can accelerate decline by implementing measures to fulfill decline functions, such as launching information campaigns highlighting the drawbacks of the focal technology (delegitimation), lowering expectations about its future (guidance toward exit), imposing sales bans (market decline), or divesting (resource demobilization). Importantly, our findings suggest that combining policies might amplify their impacts through interactions and negative feedback loops. However, they must be considered carefully to assist communities affected by decline and ensure a just transition (Vona, 2019). Future research might uncover further decline processes and enhance the understanding of resistance, feedback, and co-evolution dynamics in decline.

7. Conclusions

The decline of established technologies is crucial to sustainability transitions. Yet, transition scholars have primarily focused on technology emergence, leaving key gaps in our understanding of technology decline.

This paper extends the traditional TIS framework by proposing four decline functions: delegitimation, guidance toward exit, market decline, and resource demobilization. By applying them to study the TIS around ILBs, heating oil, nuclear power, and ICE cars, the paper illustrates the functions' usefulness in explaining diverse pathways of decline and their potential for deepening our understanding of sustainability transitions.

The results confirm the relevance of the proposed functions, which appear in all cases and reveal the proposed functions' contributions and interactions. Delegitimation and guidance toward exit often appeared early, while market decline and resource demobilization became more prominent in later stages. The functions worked collectively, reinforcing each other through feedback loops.

Although the proposed functions offer a useful new way to study decline, future research could refine and expand upon them, for example, exploring the role of knowledge and technological complementarities in decline (Heiberg and Truffer, 2022). Additional empirical studies across a broader range of technologies and contexts would strengthen the generalizability of our findings, and developing indicators for each function would help in their application. Finally, there remain questions about the sufficiency of the proposed functions, suggesting that additional functions may be needed.

In conclusion, this paper's main contribution, the TIS decline functions, offers a conceptual and analytical foundation for studying the decline of unsustainable technologies. By better understanding these processes, researchers and policymakers can more effectively design strategies to phase out polluting technologies and accelerate sustainability transitions.

CRediT authorship contribution statement

Nuno Bento: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Alejandro Nuñez-Jimenez:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Noah Kittner:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, 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.

Acknowledgements

The authors would like to thank Jochen Markard for his insightful comments in early versions of the paper. Nuno Bento acknowledges financial support from the Energy Demand changes Induced by Technological and Social innovations (EDITS) project, which is part of the initiative coordinated by the Research Institute of Innovative Technology for the Earth and International Institute for Applied Systems Analysis and funded by Ministry of Economy, Trade and Industry, Japan. Alejandro Nuñez-Jimenez acknowledges financial support from the Swiss Competence Center for Energy Research (SCCER CREST) through the Innosuisse grant 1155000154. During the preparation of this work the authors used ChatGPT 4.0 for feedback on language and shortening potentials. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Appendix 1. Function interaction (feedbacks)

Fig. A.1 systematizes the origin of the decline functions' fulfillment, along with the sequence and interaction of the functions as the TIS decline advances. The location dimension refers to where the developments that fulfill the decline functions originate. These developments can be traced back to changes in the context, such as sociopolitical pressures and emerging alternatives, and their subsequent impacts on the TIS-context interactions, such as loosening technology complementarities and structural couplings. They can also be linked to elements of the TIS structure, including changes in technology, actors' base, networks, and institutions. The time dimension refers to the phase of decline, which spans from an initial stage, with minimal signs of decline in the TIS-context relations and the TIS structure, to an advanced stage of decline, marked by moderate to high levels of decline in both the TIS-context relations and the TIS structure (for a discussion on the indicators for these dimensions, see Markard et al., 2020). Finally, the two graphs on the top illustrate two alternative patterns possible for the dynamics of the decline functions: context-driven decline (left-hand); and structural-driven decline (right-hand).

While all decline functions had relevant roles in the surveyed TIS, some were more prominent than others. The delegitimation function (D) was pivotal in pushing all four TISs into decline. In this sense, the importance of delegitimation during the initial stage of decline can be compared to the relevance of the traditional TIS functions of “legitimation” and “development of positive externalities”[4] during the formative phase of a TIS (Bergek et al., 2008; Bento and Wilson, 2016). On the other hand, market decline (M) and guidance toward exit (G) are often featured in interactions between the decline functions. The market decline and guidance toward exit functions create feedback loops in which decline functions reinforce each other, pushing the TIS further into decline.

Contextual developments tended to be more important during the initial stage of decline. Developments related to both socio-political acceptance and competition from alternative technologies appear in the initial stage of decline in all the TISs studied (see the prevalence of a) and b) in the first quadrants). These contextual developments can lead to the loss of sectoral complementarities like fewer and less diverse external suppliers (e.g., a shortage of skilled labor in several positions, from engineers to welders (DOE, 2022), limiting the available suppliers to assist in the maintenance of existing nuclear power plants and the construction of new ones), leading to further resource demobilization (R). However, the reduction of technology complementarities is not as prominent in the analyzed cases, except for heating oil, which saw increasing products and services for alternatives such as natural gas, electric resistive heaters, heat pumps, and solar thermal water heaters. This indicates that losing technological complementarities may not be necessary for a TIS to enter decline.

Structural developments gain more prominence as TIS decline advances. For technologies in a more advanced phase of decline, functions triggered by changes in the structure become more important, like actors losing market share in heating oil (M) or key manufacturers divesting resources in ILBs (R). On the other hand, the most prominent decline function (represented in bold) already appears in the initial stage in the four cases. Moreover, the

[4] Bergek et al. (2019: 5) defines “Development of positive externalities” as “Development of free utilities in the system, e.g. pooled labour markets and specialized component suppliers.”

effects of interactions between functions (marked with an asterisk) tend to accumulate, generating cumulative impacts that expedite decline. The functional patterns in the decline of the four TIS are contextual-driven, although the sequence of what functions were more salient throughout the decline stage (marked by the letters) does not always necessarily follow from the context to the TIS structure (e.g., heating oil, ILB).

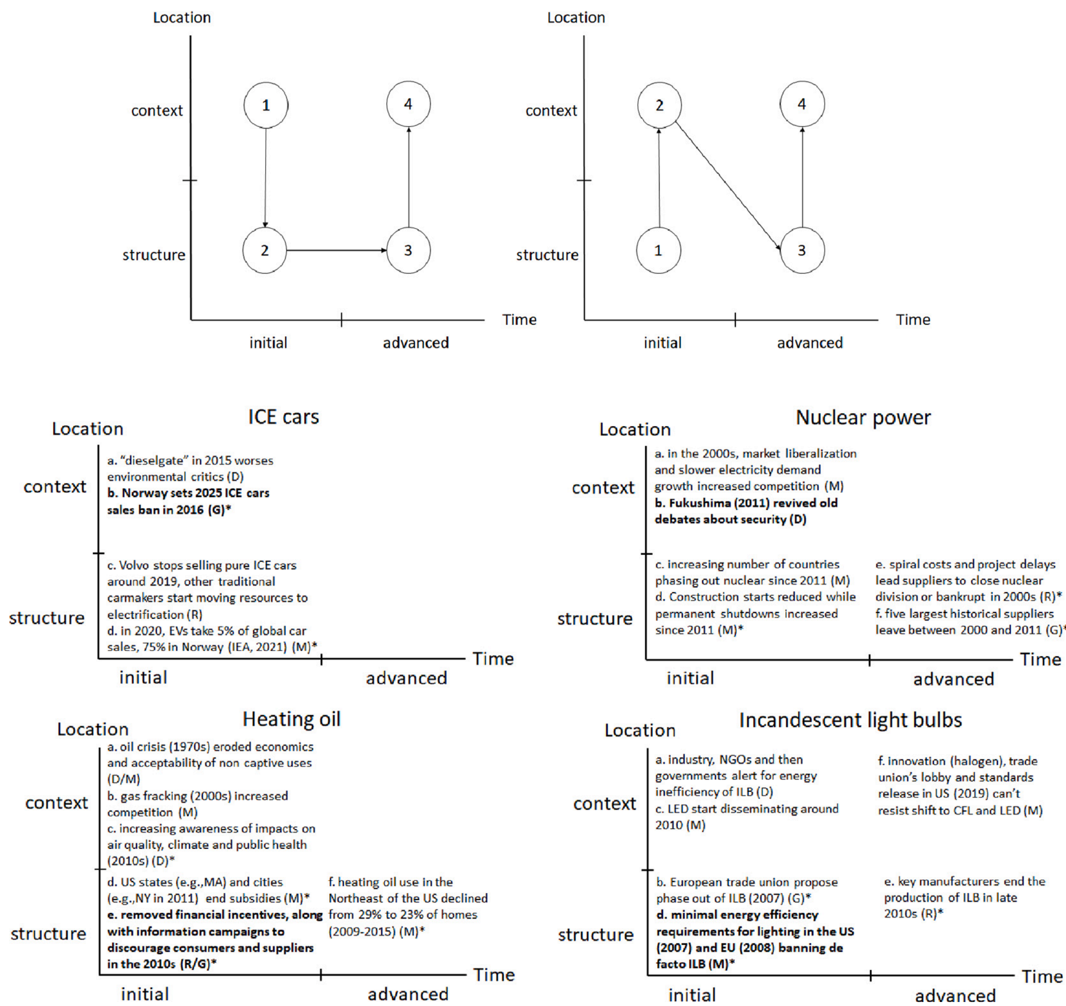

Fig. A.1. Key contributors to TIS decline functions by location and time (or phase of decline). General framing (top) and implementation by case (bottom). Cases are ordered by progress in decline, increasing from left to right, top to bottom. The corresponding functions are noted by their initials in brackets: Delegitimation (D); Guidance toward exit (G); Resource demobilization (R); and Market decline (M). In bold are the functions that were relatively more important in each case. Asterisk (*) denotes the functions that had central interactions in decline. See more details in the text.

We observe that decline functions often interact with each other and build up cumulative effects that accelerate TIS decline. For instance, in the ILB case, sustainability concerns (D) combined with prospects of higher revenues from alternative lighting technologies (G, R) led to lobbying for stricter efficiency regulations (D), ultimately contributing to market decline (M). Similar dynamics unfolded in the heating oil sector, where environmental and health concerns fueled delegitimization (D), interacting with the perceived cleanliness of natural gas (D, G), leading to further shifts to natural gas (R) and market declines (M). Similarly, in the nuclear power case, stringent regulations resulting from safety concerns (D) increased costs, while competition from alternatives and stagnant demand created a negative feedback loop between market decline (M), resource demobilization (R), and guidance toward exit (G). Finally, the decline of the TIS around ICE cars has been pushed by climate awareness (D) and advancements in EV technology, reinforcing the guidance toward exit (G) and market decline (M) functions stimulated by policies favoring alternative vehicles. These examples illustrate how decline functions are complex and interconnected, leading to cumulative causation (Suurs and Hekkert, 2009), and various possible functional patterns of decline, summarized in Fig. 6.

Data availability

Data will be made available on request.

References

Adner, R., Kapoor, R., 2016. Innovation ecosystems and the pace of substitution: re-examining technology S-curves. Strateg. Manag. J. 37 (4), 625–648.
Anderson, P., Tushman, M.L., 1990. Technological discontinuities and dominant designs: a cyclical model of technological change. Adm. Sci. Q. 35, 604–633.
Andersson, J., Perez Vico, E., Hammar, L., Sandén, B.A., 2017. The critical role of informed political direction for advancing technology: the case of Swedish marine energy. Energy Policy 101, 52–64.
Arthur, W.B., 1989. Competing technologies, increasing returns, and lock-in by historical events. Econ. J. 99 (394), 116–131.
Arthur, W.B., 2021. Foundations of complexity economics. Nature Reviews Physics 3 (2), 136–145.
BBC, 2024. Volvo gives up plan to sell only EVs by 2030 (last accessed in 18/12/2024). https://www.bbc.com/news/articles/c3ejye39434o.
Bento, N., Wilson, C., 2016. Measuring the duration of formative phases for energy technologies. Environ. Innov. Soc. Trans. 21, 95–112. https://doi.org/10.1016/j.eist.2016.04.004.

Bergek, A., 2019. Technological innovation systems: a review of recent findings and suggestions for future research. Handbook of Sustainable Innovation 200–218.

Bergek, A., Jacobsson, S., 2003. The emergence of a growth industry: A comparative analysis of the German, Dutch and Swedish wind turbine industries. In: Change, Transformation and Development. Physica-Verlag HD, pp. 197–227.

Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., Rickne, A., 2008. Analyzing the functional dynamics of technological innovation systems: a scheme of analysis. Research Policy 37 (3), 407–429.

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.

BloombergNEF, 2021. Battery Pack Prices Fall to an Average of $132/kWh, But Rising Commodity Prices Start to Bite. November 30, 2021. https://about.bnef.com/blog/battery-pack-prices-fall-to-an-average-of-132-kwh-but-rising-commodity-prices-start-to-bite/ (last access 4/5/2024).

Breschi, S., Malerba, F., Orsenigo, L., 2000. Technological regimes and Schumpeterian patterns of innovation. The Economic Journal 110 (463), 388–410.

Britton, J., Minas, A.M., Marques, A.C., Pourmirza, Z., 2021. Exploring the potential of heat as a service in decarbonization: evidence needs and research gaps. Energy Sources, Part B: Economics, Planning, and Policy 1–17.

Burch, I., Gilchrist, J., 2020. Survey of Global Activity to Phase out Internal Combustion Engine Vehicles: March 2020 Revision. Center of Climate Protection, Santa Rosa, CA, USA.

Campbell, J.L., 2019. Collapse of an Industry: Nuclear Power and the Contradictions of US Policy. Cornell University Press.

Cardwell, D., 2016. GE to Phase Out CFL Bulbs. New York Times. February 1, 2016.

Carlsson, B., Stankiewicz, R., 1991. On the nature, function and composition of technological systems. J. Evol. Econ. 1 (2), 93–118.

Carrión, D., Lee, W., Hernández, D., 2018. Residual inequity: assessing the unintended consequences of new York City's clean heat transition. Int. J. Environ. Res. Public Health 15 (1), 117.

Castelvecchi, D., 2024. Will AI's huge energy demands spur a nuclear renaissance? Nature 635 (8037), 19–20.

Chiesa, V., Frattini, F., 2011. Commercializing technological innovation: learning from failures in high-tech markets. J. Prod. Innov. Manag. 28 (4), 437–454.

Christensen, C.M., 1997. The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail. Harvard Business School Press, Boston, MA.

Christensen, C.M., Anthony, S.D., Roth, E.A., 2004. Seeing What's Next: Using the Theories of Innovation to Predict Industry Change. Harvard Business Press.

Cohn, S.M., 1997. Too Cheap to Meter: An Economic and Philosophical Analysis of the Nuclear Dream. SUNY Press.

Collins, J., 2009. How the Mighty Fall, and Why Some Companies Never Give In. Random House, London.

Davidson, D.J., 2019. Exnovating for a renewable energy transition. Nat. Energy 4 (4), 254–256.

Dintenfass, M., 1992. Managing Industrial Decline: The British Coal Industry Between the Wars. Ohio State University Press.

DOE, 2012. Solid-state lighting research and development: multi-year program plan. In: Lighting Research and Development Building Technologies Program. US Department of Energy.

DOE, 2022. Nuclear Energy: Supply Chain Deep Dive Assessment. US DOE Office of Policy (PO), Washington DC (United States).

Edge, J., McKeen-Edwards, H., 2008, June. Light bulbs and bright ideas? The global diffusion of a ban on incandescent light bulbs. In: 80th Annual Conference of the Canadian Political Science Association. University of British Colombia.

Feldman, L., Hart, P.S., 2018. Climate change as a polarizing cue: framing effects on public support for low-carbon energy policies. Glob. Environ. Chang. 51, 54–66.

Fevolden, A.M., Klitkou, A., 2017. A fuel too far? Technology, innovation, and transition in failed biofuel development in Norway. Energy Res. Soc. Sci. 23, 125–135.

Financial Times, 2021. Biden sets electric vehicle target in drive to cut emissions, 5/8/2021.

Fressoz, J.-B., 2024. In: Lane, Allen (Ed.), More and More and More: An All-Consuming History of Energy.

Fritz, M., Plötz, P., Funke, S.A., 2019. The impact of ambitious fuel economy standards on the market uptake of electric vehicles and specific CO2 emissions. Energy Policy 135, 111006.

Fulton, L.M., Jaffe, A., McDonald, Z., 2019. Internal Combustion Engine Bans and Global Oil Use. Institute of Transportation Studies (ITS), UC Davis. Research reports 1-11-2019.

Gallagher, K.S., Grubler, A., Kuhl, L., Nemet, G., Wilson, C., 2012. The energy technology innovation system. Annu. Rev. Env. Resour. 37 (1), 137–162.

Gamson, W.A., Modigliani, A., 1989. Media discourse and public opinion on nuclear power: a constructionist approach. Am. J. Sociol. 95 (1), 1–37.

Geels, F.W., 2024. Advanced Introduction to Sustainability Transitions. Edward Elgar Publishing.

Geels, F.W., Schot, J., 2007. Typology of sociotechnical transition pathways. Research Policy 36, 399–417.

Geels, F.W., Kern, F., Fuchs, G., Hinderer, N., Kungl, G., Mylan, J., Neukirch, M., Wassermann, S., 2016. The enactment of sociotechnical transition pathways: a reformulated typology and a comparative multi-level analysis of the German and UK low-carbon electricity transitions (1990–2014). Research Policy 45 (4), 896–913.

Geels, F.W., Kern, F., Clark, W.C., 2023. Sustainability transitions in consumption-production systems. Proc. Natl. Acad. Sci. 120 (47), e2310070120.

Goldstein, J.S., Staffan, A.Q., Pinker, S., 2019. Nuclear Power Can Save the World, 6. The New York Times, 2019. https://www.nytimes.com/2019/04/06/opinion/Sunday/climate-change-nuclear-power.html (last access 17/10/2022).

Grubler, A., 2003. Technology and Global Change. Cambridge University Press.

Grubler, A., 2010. The costs of the French nuclear scale-up: a case of negative learning by doing. Energy Policy 38 (9), 5174–5188.

Hadjilambrinos, C., 2021. Reexamining the Automobile's past: what were the critical factors that determined the emergence of the internal combustion engine as the dominant automotive technology? Bull. Sci. Technol. Soc. 41 (2–3), 58–71.

Hartley, J., Knell, L., 2022. Innovation, exnovation and intelligent failure. Public Money Manag. 42 (1), 40–48.

Hassink, R., 2016. Cluster decline and political lock-ins. In: Unfolding Cluster Evolution. Routledge, pp. 218–230.

Heiberg, J., Truffer, B., 2022. The emergence of a global innovation system–a case study from the urban water sector. Environ. Innov. Soc. Trans. 43, 270–288.

Heiberg, J., Truffer, B., Binz, C., 2022. Assessing transitions through socio-technical configuration analysis–a methodological framework and a case study in the water sector. Res. Policy 51 (1), 104363.

Hekkert, M.P., Suurs, R.A., Negro, S.O., Kuhlmann, S., Smits, R.E., 2007. Functions of innovation systems: a new approach for analysing technological change. Technol. Forecast. Soc. Chang. 74 (4), 413–432.

Helmers, E., Leitão, J., Tietge, U., Butler, T., 2019. CO2-equivalent emissions from European passenger vehicles in the years 1995–2015 based on real-world use: assessing the climate benefit of the European "diesel boom". Atmos. Environ. 198, 122–132.

Howells, J., 2006. Intermediation and the role of intermediaries in innovation. Research Policy 35 (5), 715–728.

IAEA, 2019. PRIS Data Set. Personal communication, 2019.

IAEA, 2023. Nuclear Power Reactors in the World. https://www.iaea.org/publications/15485/nuclear-power-reactors-in-the-world.

IEA, 2019a. Nuclear Power in a Clean Energy System. International Energy Agency/OECD, Paris.

IEA, 2019b. IEA Headline Global Energy Data, 2019 edition. IEA/OECD, Paris. https://www.iea.org/media/statistics/IEA_HeadlineEnergyData.xlsx. (accessed in 28/2/2020).

IEA, 2020. Global EV Outlook 2020. IEA, Paris. https://www.iea.org/reports/global-ev-outlook-2020.

IEA, 2021a. World Energy Outlook 2021. IEA, Paris.

IEA, 2021b. Global EV Data Explorer 2021. IEA, Paris. https://www.iea.org/articles/global-ev-data-explorer.

IEA, 2022. Global EV Data Explorer 2022. IEA, Paris. https://www.iea.org/articles/global-ev-data-explorer.

IEA, 2024. Global EV Outlook 2024. IEA, Paris. https://www.iea.org/reports/global-ev-outlook-2024 (last access 6/5/2024).

Jacobsson, T., Jacobsson, S., 2014. Conceptual confusion–an analysis of the meaning of concepts in technological innovation systems and sociological functionalism. Tech. Anal. Strat. Manag. 26 (7), 811–823.

Kassakian, J., Hu, E., Black, I., Clanton, N., Davis, W., Ettenberg, M., Spencer, M., 2017. Assessment of Solid-State Lighting, Phase Two. The National Academies Press.

Kheirbek, I., Haney, J., Douglas, S., Ito, K., Caputo Jr., S., Matte, T., 2014. The public health benefits of reducing fine particulate matter through conversion to cleaner heating fuels in new York City. Environ. Sci. Technol. 48 (23), 13573–13582.

Kimberly, J., 1981. Managerial innovation. In: Nystrom, P., Starbuck, W. (Eds.), Handbook of Organizational Design. Oxford University, pp. 84–104.

Kivimaa, P., Kern, F., 2016. Creative destruction or mere niche support? Innovation policy mixes for sustainability transitions. Res. Policy 45 (1), 205–217.

Klepper, S., 1997. Industry life cycles. Ind. Corp. Chang. 6 (1), 145–182.

Köhler, J., Geels, F.W., Kern, F., Markard, J., Onsongo, E., Wieczorek, A., Wells, P., 2019. An agenda for sustainability transitions research: state of the art and future directions. Environ. Innov. Soc. Trans. 31, 1–32.

Koomey, J., Hultman, N.E., Grubler, A., 2017. A reply to "historical construction costs of global nuclear power reactors". Energy Policy 102, 640–643.

Koretsky, Z., 2021. Phasing out an embedded technology: insights from banning the incandescent light bulb in Europe. Energy Res. Soc. Sci. 82, 102310.

Koretsky, Z., Stegmaier, P., Turnheim, B., Van Lente, H., 2023. Technologies in Decline: Sociotechnical Approaches to Discontinuation and Destabilization. Taylor & Francis, 294 p.

Kungl, G., Geels, F.W., 2018. Sequence and alignment of external pressures in industry destabilization: understanding the downfall of incumbent utilities in the German energy transition (1998–2015). Environ. Innov. Soc. Trans. 26, 78–100.

Lamberg, J.A., Ojala, J., Peltoniemi, M., 2018. Thinking about industry decline: a qualitative meta-analysis and future research directions. Bus. Hist. 60 (2), 127–156.

Lovins, A., 2019. Does Nuclear Power Slow or Speed Climate Change? Forbes. November 18, 2019.

Mäkitie, T., Hanson, J., Steen, M., Hansen, T., Andersen, A.D., 2020. The Sectoral Interdependencies of Low-carbon Innovations in Sustainability Transitions. NTRANS Report. https://hdl.handle.net/11250/2731103.

Mäkitie, T., Hanson, J., Steen, M., Hansen, T., Andersen, A.D., 2022. Complementarity formation mechanisms in technology value chains. Research Policy 51 (7), 104559.

Malerba, F., 2002. Sectoral systems of innovation and production. Research Policy 31 (2), 247–264.

Markard, J., 2020. The life cycle of technological innovation systems. Technological Forecasting and Social Change 153, 119407.

Markard, J., Hoffmann, V.H., 2016. Analysis of complementarities: framework and examples from the energy transition. Technological Forecasting and Social Change 111, 63–75.

Markard, J., Raven, R., Truffer, B., 2012. Sustainability transitions: an emerging field of research and its prospects. Research Policy 41 (6), 955–967.

Markard, J., Bento, N., Kittner, N., Nuñez-Jimenez, A., 2020. Destined for decline? Examining nuclear energy from a technological innovation systems perspective. Energy Research & Social Science 67, 101512. https://doi.org/10.1016/j.erss.2020.101512.
Markard, J., Rinscheid, A., Widdel, L., 2021. Analyzing transitions through the lens of discourse networks: coal phase-out in Germany. Environ. Innov. Soc. Trans. 40, 315–331.
McDuffie, E.E., Martin, R.V., Spadaro, J.V., Burnett, R., Smith, S.J., O'Rourke, P., Brauer, M., 2021. Source sector and fuel contributions to ambient PM2. 5 and attributable mortality across multiple spatial scales. Nature Communications 12 (1), 1–12.
McKerracher, C., 2021. Hyperdrive Daily: Phasing Out Europe's Combustion Engine Cars. Bloomberg, 20/7/2021. https://www.bloomberg.com/news/newsletters/2021-07-20/hyperdrive-daily-phasing-out-europe-s-combustion-engine-cars?sref=jjXJRDFv (Accessed 27/7/).
Meckling, J., Nahm, J., 2019. The politics of technology bans: industrial policy competition and green goals for the auto industry. Energy Policy 126, 470–479.
Mendonça, S., 2013. The "sailing ship effect": reassessing history as a source of insight on technical change. Research Policy 42 (10), 1724–1738.
Menzel, M.P., Fornahl, D., 2010. Cluster life cycles—dimensions and rationales of cluster evolution. Industrial and Corporate Change 19 (1), 205–238.
Murmann, J.P., Frenken, K., 2006. Toward a systematic framework for research on dominant designs, technological innovations, and industrial change. Research Policy 35 (7), 925–952.
Nadel, S., 2020. Programs to Electrify Space Heating in Homes and Buildings. In: ACEEE Topic Brief. June 2020.
NEA, 2024. The NEA Small Modular Reactor Dashboard, Second edition. OECD Publishing, Paris.
NEMA, 2017. First Quarter 2017 Year-Over-Year LED A-Line Lamp Shipments Up, Halogen, Incandescent and CFL Shipments Decline press release published online June 23, 2017.
NEMA, 2022. Lamp Indices. https://www.nema.org/analytics/lamp-indices (last access 10/5/2024).
Oliver, C., 1992. The antecedents of deinstitutionalization. Organ. Stud. 13 (4), 563–588.
Østergaard, C.R., Park, E., 2015. What makes clusters decline? A study on disruption and evolution of a high-tech cluster in Denmark. Reg. Stud. 49 (5), 834–849.
Pavitt, K., 1984. Sectoral patterns of technical change: towards a taxonomy and a theory. Res. Policy 13 (6), 343–373.
Pavitt, K., Rothwell, R., 1976. A comment on "a dynamic model of process and product innovation". Omega 4 (4), 375–377.
Peltoniemi, M., 2011. Reviewing industry life-cycle theory: avenues for future research. Int. J. Manag. Rev. 13 (4), 349–375.
Pidgeon, N.F., Lorenzoni, I., Poortinga, W., 2008. Climate change or nuclear power—no thanks! A quantitative study of public perceptions and risk framing in Britain. Glob. Environ. Chang. 18 (1), 69–85.
Politico, 2022. Parliament votes to give green labels to nuclear and gas. https://www.politico.eu/article/parliament-votes-to-give-green-labels-to-nuclear-and-gas/ (last access 6/5/2024).
Poole, M.S., Van de Ven, A.H., Dooley, K., Holmes, M.E., 2000. Organizational Change and Innovation Processes: Theory and Methods for Research. Oxford University Press.
Poznanski, K.Z., 1986. The extinguishing process: a case study of steel technologies in the world industry. Technovation 4 (4), 297–316.
Raffaelli, R.L., 2014. Mechanisms of Technology Re-emergence and Identity Change in a Mature Field: Swiss Watchmaking, 1970–2008. Harvard Business School working paper series# 14-048.
Reuters, 2021. Daimler to invest more than 40 bln euros by 2030 in electric vehicles. July 22. https://www.reuters.com/article/daimler-electric-idUSL1N2OY0MV (last view 5/9/2023).
Rinscheid, A., Pianta, S., Weber, E.U., 2020. Fast track or Slo-Mo? Public support and temporal preferences for phasing out fossil fuel cars in the United States. Climate Policy 20 (1), 30–45.
Rinscheid, A., Rosenbloom, D., Markard, J., Turnheim, B., 2021. From terminating to transforming: the role of phase-out in sustainability transitions. Environ. Innov. Soc. Trans. 41, 27–31.
Rivoli, P., Waddock, S., 2011. "First they ignore you…": the time-context dynamic and corporate responsibility. Calif. Manage. Rev. 53 (2), 87–104.
Rogers, E.M., 2003. Diffusion of Innovations, 5th edition. Simon & Schuster, New York.
Rogge, K.S., Johnstone, P., 2017. Exploring the role of phase-out policies for low-carbon energy transitions: the case of the German Energiewende. Energy Res. Soc. Sci. 33, 128–137.
Roques, F.A., Nuttall, W.J., Newbery, D.M., de Neufville, R., Connors, S., 2006. Nuclear power: a hedge against uncertain gas and carbon prices? Energy J. 27 (4).
Rosa, E.A., Dunlap, R.E., 1994. The polls—poll trends: nuclear power: three decades of public opinion. Public Opin. Q. 58 (2), 295–324.
Rosenberg, N., 1972. Factors affecting the diffusion of technology. Explor. Econ. Hist. 10 (1), 3.
Rosenbloom, D., Rinscheid, A., 2020. Deliberate decline: an emerging frontier for the study and practice of decarbonization. Wiley Interdiscip. Rev. Clim. Chang. 11 (6), e669.
Rubio-Varas, M., 2021. The changing economic context influencing nuclear decisions. In: Kaijser, A. (Ed.), Engaging the Atom: The History of Nuclear Energy and Society in Europe From the 1950s to the Present, pp. 70–110. West Virginia.
Salimfard, P., Buonocore, J.J., Konschnik, K., Azimi, P., VanRy, M., Cedeno Laurent, J.G., Hernandez, D., Allen, J.G., 2022. Climate policy impacts on building energy use, emissions, and health: New York City local law 97. Energy 238, 121879.
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. Research Policy 40 (3), 403–414.
Schwartz, J., 2019. White House to Relaz Energy Efficiency Rules for Light Bulbs. The New York Times. September 4. https://www.nytimes.com/2019/09/04/climate/trump-light-bulb-rollback.html [15/10/2020].
Scott, W.R., 1995. Institutions and Organizations, second ed. Sage publications, Thousand Oaks, CA.
Smith, A., Raven, R., 2012. What is protective space? Reconsidering niches in transitions to sustainability. Research Policy 41 (6), 1025–1036.
Soni, A., 2018. Out of sight, out of mind? Investigating the longitudinal impact of the Fukushima nuclear accident on public opinion in the United States. Energy Policy 122, 169–175.
Sovacool, B.K., Martiskainen, M., 2020. Hot transformations: governing rapid and deep household heating transitions in China, Denmark, Finland and the United Kingdom. Energy Policy 139, 111330.
Sovacool, B.K., Nugent, D., Gilbert, A., 2014. Construction cost overruns and electricity infrastructure: an unavoidable risk? Electr. J. 27 (4), 112–120.
Stegmaier, P., Kuhlmann, S., Visser, V.R., 2014. The discontinuation of sociotechnical systems as a governance problem. In: Borrás, S., Edler, J. (Eds.), The Governance of Sociotechnical Systems. Edward Elgar, Cheltenham, pp. 111–131.
Stegmaier, P., Visser, V.R., Kuhlmann, S., 2021. The incandescent light bulb phase-out: exploring patterns of framing the governance of discontinuing a socio-technical regime. Energy Sustain. Soc. 11 (1), 1–22.
Stephan, A., Bening, C.R., Schmidt, T.S., Schwarz, M., Hoffmann, V.H., 2019. The role of inter-sectoral knowledge spillovers in technological innovations: the case of lithium-ion batteries. Technol. Forecast. Soc. Chang. 148, 119718.
Suchman, M.C., 1995. Managing legitimacy: strategic and institutional approaches. Acad. Manage. Rev. 20 (3), 571–610.
Suddaby, R., Bitektine, A., Haack, P., 2017. Legitimacy. Acad. Manag. Ann. 11 (1), 451–478.
Suurs, R.A., Hekkert, M.P., 2009. Cumulative causation in the formation of a technological innovation system: the case of biofuels in the Netherlands. Technological Forecasting and Social Change 76 (8), 1003–1020.
Taylor, M., Taylor, A., 2012. The technology life cycle: conceptualization and managerial implications. Int. J. Prod. Econ. 140 (1), 541–553.
Turnheim, B., Geels, F.W., 2012. Regime destabilization as the flipside of energy transitions: lessons from the history of the British coal industry (1913–1997). Energy Policy 50, 35–49.
Turnheim, B., Geels, F.W., 2013. The destabilization of existing regimes: confronting a multi-dimensional framework with a case study of the British coal industry (1913–1967). Research Policy 42 (10), 1749–1767.
US EIA - Energy Information Administration, 2015. Residential Energy Consumption Survey. https://www.eia.gov/consumption/residential/reports/2015/overview/. Last Accessed 15 December 2021.
Utterback, J.M., Abernathy, W.J., 1975. A dynamic model of process and product innovation. Omega 3 (6), 639–656.
Utterback, J.M., Pistorius, C., Yilmaz, E., 2019. The Dynamics of Competition and of the Diffusion of Innovations. MIT Sloan School of Management, Pistorius. Working Paper 5519-18.
Van de Ven, A.H., Polley, D.E., Garud, R., Venkataraman, S., 1999. The Innovation Journey. Oxford University Press, New York.
Vona, F., 2019. Job losses and political acceptability of climate policies: why the 'job-killing' argument is so persistent and how to overturn it. Clim. Pol. 19 (4), 524–532.
Wang, Q., Chen, X., Jha, A.N., Rogers, H., 2014. Natural gas from shale formation–the evolution, evidences and challenges of shale gas revolution in United States. Renew. Sustain. Energy Rev. 30, 1–28.
Weitzel, W., Jonsson, E., 1989. Decline in organizations: a literature integration and extension. Adm. Sci. Q. 34 (1), 91–109.
Wells, P.E., 2023. Sustainability transitions in consumption-production systems: system confluence and the reinvention of automobility. Proc. Natl. Acad. Sci. U. S. A. 120 (47).
White House, 2021. FACT SHEET: President Biden Announces Steps to Drive American Leadership Forward on Clean Cars and Trucks. August 5. https://www.whitehouse.gov/briefing-room/statements-releases/2021/08/05/fact-sheet-president-biden-announces-steps-to-drive-american-leadership-forward-on-clean-cars-and-trucks/ (last access 8/12/2021).
Zissis, G., Bertoldi, P., 2018. Status of LED-Lighting World Market in 2017. European Commission, Ispra. JRC 85636606.