



Towards a theory of industrial modernity

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ABSTRACT

The deepening socio-environmental polycrisis has stimulated calls to rethink industrial modernity: the currently dominant societal assumptions about the natural environment, science and technology. However, the genesis and long-term co-evolution of these deep macro-level assumptions has rarely gained systematic attention in innovation studies. This is an important oversight given that the historical legacy of industrial modernity continues to shape the policy framing of current sustainability challenges as well as the design of appropriate interventions. In this paper we seek to develop a conceptual vocabulary for theorizing the historical evolution of industrial modernity. Combining the Deep Transitions framework from sustainability transitions studies with insights on long-term industrialization-related trends from various fields, we 1) present a systematically validated inventory of 38 constituent ideas, institutions and practices of industrial modernity; 2) map their emergence over the past 250 years; 3) identify 10 recurrent controversial outcomes generated by the interactions of these traits; 4) distinguish between three phases in the long-term evolution of industrial modernity. We conclude with a research agenda for studying the historical evolution, current impacts and policy implications of industrial modernity.

1. Introduction

The balance sheet of industrial modernization remains ambivalent and contested. Starting from the late 18th century science and technology have enabled vast increases in productivity, translating further into unprecedented economic growth, reduction of absolute poverty and rise in life expectancy (van Zanden et al., 2014; OECD, 2021). Evidence is mixed on inequality, where attempts to address its particular forms through new technologies have created other types of inequalities elsewhere. For example, increased access to electricity and mobility has also generated uneven health impacts resulting from differing proximity to power plants and urban highways, with marginalized communities often suffering the worst (Cushing et al., 2023; Donaghy et al., 2023). Finally, industrialization has made possible new devastating forms of war and genocide (Friedel, 2007; Agar, 2012) and considerably amplified environmental degradation, including pollution, loss of biodiversity and climate change (McNeill and Engelke, 2014; IPBES, 2019; IPCC, 2023).

In academic and policy circles one dominant response to this unfolding socio-environmental polycrisis is captured by the term

‘ecological modernization’ (Spaargaren and Mol, 1992; Wiedmann et al., 2020). This framework recognizes the severity of current environmental problems while suggesting that these can be solved through science, technology and markets. Yet lately there seem to be growing doubts about the capability of conventional modes of knowledge production and technological innovation to rise to the sustainability challenge. This is evidenced by an increasing amount of scholarly literature at the intersection of science, technology and innovation studies expressing grave dissatisfaction with many taken-for-granted societal assumptions about technoscience. Examples of these assumptions include beliefs in the value-neutrality of scientists and engineers, technocratic policymaking, narrow problem framing of research, development and innovation activities, or extensive reliance on techno-fixes to address the problems created by prior technologies. Proposed alternatives to dominant ways of framing, regulating and practising technoscience include mid-tech development (Kostakis et al., 2023), frugal innovation (Weyrauch and Herstatt, 2017; Albert, 2019), inclusive innovation (Chataway et al., 2014; Mortazavi et al., 2021), grassroots innovation (Smith et al., 2014; Hossain, 2016), value-sensitive design and engineering (Friedman and Hendry, 2019; Spiekermann and

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Winkler, 2022), slow science (Stengers, 2018), responsible research and innovation (Owen et al., 2012, 2021), mission-oriented innovation policy (Mazzucato, 2018; Kirchherr et al., 2023), and transformative innovation policy (Schot and Steinmueller, 2018; Diercks et al., 2019), to name a few.

This ongoing problematization, however, only raises the question of how exactly these dominant societal assumptions about science and technology emerged and how they became deeply embedded into the fabric of contemporary industrial societies in the first place. In this regard, existing literature is characterized by two limitations. First, although long-term macro-level continuities and ruptures related to technoscience have been extensively discussed in several research streams such as science, technology and innovation studies (Bresnahan and Trajtenberg, 1995), sociology of modernity (Giddens, 1991), critical approaches (Feenberg, 1991), history (McNeill, 2001; Landes, 2003), and sustainability studies (Cohen, 2021), different findings are often discussed within specific research communities. This results in a high degree of disciplinary fragmentation (Clark and Harley, 2020) making the overall situation remains difficult to grasp: it is unclear which taken-for-granted assumptions about science and technology are still characterized by deep historical continuities, which ones are already experiencing ruptures, and what is the magnitude and timing of all these changes in relation to each other. Second, long-term socio-technical change tends to be theorized in particular ways. In science, technology and innovation studies frameworks like the Multi-level Perspective on socio-technical transitions (Geels, 2005), long waves (Freeman and Louçã, 2001), and Large Technical Systems (Hughes, 1983) focus on the meso-level aiming to theorize patterns in system/sector evolution, usually in a multi-decade time-frame. In macro-sociological theories (e.g. Beck, 1992; Moore, 2015), on the other hand, industrialization is often viewed in combination with other long-term trends such as the spread of capitalism, democratization or individualization, and the explanatory focus is on shifts in the entire social order. Save for a few exceptions (e.g. Mumford 1967–1970; Beniger, 1986; Arthur, 2009) broadly shared societal assumptions about science and technology are rarely a focal point of analysis in their own right.

Taken together, this results in a paradoxical situation in which much is known about different facets of industrialization, yet the specific technoscientific assumptions underpinning industrial societies, as well as their co-evolution over time, remain under-conceptualized. This oversight has an important implication for innovation policy: without addressing dominant technoscientific assumptions explicitly, comprehensively and systematically even the most well-meaning contemporary sustainability-related policies and interventions – including many calling themselves ‘radical’, ‘disruptive’ or ‘transformative’ (Morrison et al., 2022; Perdana et al., 2023) – risk reproducing the historical failures of industrial societies, thereby undermining efforts towards addressing shared global challenges.

In this paper we address the above-mentioned two gaps in existing literature – disciplinary fracture and under-conceptualization of deep societal assumptions about science and technology – by developing a conceptual vocabulary for theorizing how long-term macro-level technoscience-related continuities of industrial societies are created, maintained and transformed. For this purpose, we draw on the notion of industrial modernity as used in the Deep Transitions (DT) framework (Schot and Kanger, 2018). Here, industrial modernity refers to a set of interconnected traits, i.e. pervasive and durable ideas, institutions and practices related to the natural environment, science and technology that are present in any contemporary industrial society. Building on two tentative attempts to list these traits (Kanger and Schot, 2019; Kanger et al., 2022), we aim to develop a more processual understanding of industrial modernity, including its emergence, acceleration and crisis over a 250-year time-frame. We therefore focus on the following questions:

1. What are the core ideas, institutions and practices of industrial modernity?
2. When did these particular traits emerge?
3. Which recurrent controversial outcomes have these traits produced?
4. What does the changing magnitude of these outcomes over time imply for the periodization of industrial modernity?
5. How does the historical legacy of industrial modernity shape the current sustainability interventions?

The paper is structured as follows. Section 2 reviews five literature streams that have studied macro-level structural assumptions about technoscience, assessing their strengths and limitations for answering our research questions. We then summarize existing research on Deep Transitions and industrial modernity, highlighting its current shortcomings. Addressing the latter, Section 3 describes the research design for producing and validating a new version of traits of industrial modernity. The following sections will present the core conceptual contribution of the paper. Synthesizing a range of insights on long-term industrialization-related trends from different fields, Section 4 provides a significantly revised and thematically expanded inventory of 38 traits of industrial modernity. These are used to create a timeline of the emergence of each trait, covering the period from the pre-industrial era to the present. Section 5 argues that interacting traits of industrial modernity have historically produced 10 recurrent controversial outcomes, regularly undermining optimistic societal expectations about science and technology. To illustrate the lingering presence of these outcomes we discuss three sustainability interventions: solar geo-engineering, climate modelling and housing insulation. Looking at the entire industrial revolution, Section 6 develops a three-stage periodization of the evolution of industrial modernity based on its historical, ongoing and anticipated transformations. Section 7 concludes with a research agenda for studying the historical genesis, current impacts and policy implications of industrial modernity.

2. Literature review

In this section we first summarize several strands of literature offering building blocks for conceptualizing the evolution of industrial modernity as well as prior work on Deep Transitions explicitly using this notion.

2.1. Long-term continuities in industrialization

Existing literature on industrialization and modernization is far too voluminous to be covered comprehensively in a single paper. Therefore, we will only perform a highly stylized review of five different branches of literature – science, technology and innovation studies, sociology of modernity, critical approaches, history, environmental and sustainability studies – that have seriously engaged with the study of long-term socio-technical change. We recognize that such an approach has serious limitations: the grouping of literature is somewhat subjective, many possibly important works are likely to be excluded, many seminal works can be plausibly associated with more than one group, and our generalizations will undoubtedly overlook many nuances and exceptions in each stream. Nevertheless, this exercise is useful insofar as each strand of literature places a different emphasis on describing, explaining, conceptualizing or criticizing different facets of industrialization, resulting in particular strengths and weaknesses.

In relation to the latter an important qualification should be made. That is, in the following the ‘strengths and weaknesses’ of each field are specified only in relation to our overall aim: development of a middle-range theory (Merton, 1968), characterized by a limited number of interrelated concepts and propositions about a particular empirical phenomenon (industrial modernity). This means that in every branch of reviewed literature we are looking for 1) trends, empirical generalizations, or concepts; 2) about human-nature relations, science, and

technology that are; 3) long-term, and; 4) macro-level. The point is therefore not to criticize different literatures for their failure to deliver a particular type of middle-range theory – after all, these fields have developed particular disciplinary foci over time for particular reasons quite independently from our own goals – but to see how their differing insights could be mobilized and synthesized in the spirit of appreciative theorizing and analytic eclecticism (Nelson and Winter, 1982: 46; Sil and Katzenstein, 2010) (see Sections 4–6 on how this potential has been realized).

Explicit focus on technoscientific factors and attempts to conceptualize them constitute the core strengths of science, technology and innovation studies. Works in this strand tend to have somewhat different emphases though. On one hand, innovation scholars often uncover (and debate) particular long-term trends such as the rise of green patents (Probst et al., 2021; Corrocher et al., 2024), disruptiveness of scientific research and technological innovation (Park et al., 2023; Macher et al., 2024), or diffusion of general purpose technologies (Bresnahan and Trajtenberg, 1995; Rosenberg and Trajtenberg, 2004). However, precision of focus is frequently achieved at the expense of scope. Even the most encompassing theoretical frameworks in innovation studies, such as the Multi-level Perspective on socio-technical transitions (Geels, 2002, 2005; Geels and Schot, 2007), long waves (Freeman and Louçã, 2001; Tylecote, 2019; Doehne and Rost, 2021), or development blocks (Dahmén, 1988; Nuvolari, 2019; Taalbi, 2021), mainly restrict their attention to meso-level systemic or sectoral shifts, often in a multi-decade time-span. While broadly shared societal assumptions about technoscience can play a significant explanatory role, e.g. as exogenous ‘landscape’ events influencing socio-technical transitions (Geels, 2005) or semi-autonomous subsystems of science and technology shaping successive long waves (Freeman and Louçã, 2001: 124–130), the identification and co-evolution of these assumptions is not a core concern of these frameworks. Combined with the field’s explanatory orientation to novelty and disruption (e.g. emergence of new general purpose technologies, transitions in socio-technical systems, long waves characterized by new techno-economic paradigms), this means that frameworks in innovation studies tend to place less conceptual emphasis on various macro-level historical continuities accumulating and amplifying during the 250-year industrialization process.

On the other hand, several works in science and technology studies (STS) have explicitly analysed some macro-level features of industrial societies, e.g. the role of socio-technical imaginaries in shaping modernity (Jasanoff and Kim, 2015), or the conceptual separation between Nature and Society (Latour, 1993). However, STS has also been criticized for a gap between very detailed case descriptions and fairly simple abstract conceptual schemes used to frame them (Geels, 2007). As a result, its insights mostly have a sensitizing quality. That is, while STS studies can usefully highlight certain aspects of industrialization, they often do not engage in middle-range theorizing.

A stream of sociological works focuses on theorizing the emergence and (heavily debated) transformation of modernity (Giddens, 1991; Eisenstadt, 2002; Rosa, 2013). Such theories often emphasize interacting macro-level economic, political, social and cultural shifts operating over long time-frames such as the spread of capitalism, changes in class structure, democratization, or post-material values (Wallerstein, 1974–2011; Sztompka, 1993; Inglehart, 2018). This sometimes leads to useful generalizations, e.g. the role of industrialization in creating a new type of ‘risk society’ (Beck, 1992). However, existing literature on modernity is also often characterized by three closely interrelated limitations (see Brey, 2003, for a detailed analysis): 1) prioritization of ‘social’ explanatory factors to the relative downplaying of material ones, e.g. Polanyi (2001) analysing Great Transformation as an interaction between the market and the state; 2) tendency to reduce technological factors to some ‘social’ system perceived as the main driver, e.g. Moore (2015) treating the industrial revolution as yet another stage in the history of capitalism; 3) subsuming technological factors to a more general and often highly abstract phenomenon, e.g. Giddens (1991)

counting industrialism as one of the four main institutions of modernity, alongside capitalism, surveillance capacities and control of the means of violence. As a result, sociology of modernity often has fairly little to say about the exact constituents and internal dynamics of industrialism.

The common thread of the third stream is its critical stance towards technoscience. Studies in this vein often demonstrate connections between technoscientific rationality, dominant power structures and various forms of inequality with accompanying calls for broader social transformation to rectify the current situation. At the largest scale, philosophical critiques of technological efficiency and instrumentalism (Mumford, 1934; Ellul, 1964; Feenberg, 1991), marxist analyses of technologically-mediated forms of capitalist domination (Braverman, 1974; Fuchs, 2009), and studies leveraging non-Western approaches to technoscience can offer useful starting points for imagining alternatives to deep societal assumptions about technoscience, e.g. pluriversal design (Escobar, 2018), or technologies for degrowth (Samerski, 2018). At the scale of individual case studies, feminist and decolonial STS scholars, alongside historians and anthropologists, have investigated interconnections between specific technoscientific institutions and masculine, Western and imperial forms of power (Anderson, 2002; TallBear, 2013; Hecht, 2014). Scholars working along these lines have fruitfully emphasized the contingency of many configurations of modernity often portrayed as “inevitable”, by showing them as products of political choices made in historically specific settings, e.g. the concept of “technopolitics” (Hecht, 1998; Mitchell, 2002). Limitations of these approaches are two-fold: 1) theoretical works often make sweeping claims about the imperialist foundations of highly abstract notions like the “Western technoscientific episteme” (Lehman and Johnson, 2022: 23). While useful in highlighting alternative and indigenous cosmologies, such critiques risk overlooking adaptations and contestations within the Western framework (Cooper, 2005: 113–150); 2) case-study based approaches fruitfully demonstrate the co-construction of social and technological factors, but rarely develop middle-range theories that connect the contingencies of specific cases to longer evolutionary perspectives.

The fourth stream includes various historical studies of industrialization, conducted from particular disciplinary perspectives like environmental history (McNeill, 2001; Warde et al., 2018), economic history (Mokyr, 1990; Landes, 2003), or history of science and technology (Hughes, 1989; Misa et al., 2003; Agar, 2012). Works in this stream offer comprehensive, rich and nuanced narratives – often unfolding over multiple geographical locations and long time-frames – that emphasize contingency and human agency (Pomeranz, 2000), highlight numerous alternative pathways of industrialization (Sabel and Zeitlin, 1997), and try to find a mid-way between determinist and contextualist accounts of change (Sicilia, 1993). They thereby provide a strong factual basis for identifying the key developments and impacts of industrialization. Many works in this stream have provided theory-guided accounts of the industrial revolution, highlighting the role of the Industrial Enlightenment (Mokyr, 2002) or war capitalism (Beckert, 2014). Yet other influential historians have criticized these accounts for ignoring manifold divergences from the purported models (Osterhammel, 2014), and for sometimes inadvertently reproducing the self-confident or borderline teleological assessment of modernity, even in works that seek to critique it (Cooper, 2005; Ogle, 2015). Furthermore, historians’ disciplinary emphasis on contingent narrative explanations means that works in this stream are often less interested in formal, generalizable theory-building.

The final stream includes various studies on nature-society interactions, including fields like socio-metabolism (Haberl et al., 2017), environmental sociology (Pellow and Nyseth Brehm, 2013) and ecological economics (Farley and Kish, 2021). Works in this stream have identified various socio-environmental macro-level long-term trends, e.g. continuing increases in material use over the 20th century with a corresponding decrease in circularity (Krausmann et al., 2018; Haas et al., 2020), or a rise in environmental values, institutions and movements (Frank et al., 2000; Dietz et al., 2005; Giugni and Grasso, 2015).

Other studies highlight the root causes, drivers and impacts of current environmental problems, e.g. identification of the core features of the “Human Exceptionalism Paradigm” in environmental sociology (Catton Jr and Dunlap, 1978: 42–43). However, the very diversity of this stream is also its weakness. As Clark and Harley write about sustainability science, “the field remains somewhat fractured into distinct schools of thought, research programs, and other island empires, each characterized by its own idiosyncratic origins, terminologies, publication venues, case studies, and conceptual frameworks” (2020: 335). The stream's preoccupation with environment and sustainability has also meant placing less emphasis on technoscientific factors and theory of innovation (ibid.: 356). This, in turn, has frequently resulted in a highly simplified understanding of innovation, e.g. the ecological modernization paradigm (Spaargaren and Mol, 1992; Huber, 2000; Jänicke, 2008) which has been much criticized for its techno- and market-centric approach to solving the sustainability challenges (Wiedmann et al., 2020; Cohen, 2021: 47–67). Table 1 provides a summary of our key observations.

In sum, the differing emphases of each branch of literature mean that the current situation is characterized by disciplinary fracture: while each stream offers valuable insights about long-term industrialization processes, these often remain scattered across different literatures. As a result, the co-evolutionary patterns, broader outcomes and driving mechanisms of these trends remain under-theorized. In the following section we will therefore review the notion of industrial modernity from the Deep Transitions framework which has taken the first steps towards systematizing them.

2.2. Deep Transitions and industrial modernity

The Deep Transitions framework (Schot and Kanger, 2018; Kanger and Schot, 2019; Kanger, 2022) conceptualizes industrialization through the long-term co-evolution of multiple socio-technical systems such as energy, mobility, food, waste management or housing (see Davies and Schot, 2026, for an overview). It does so by synthesizing insights from the Multi-level Perspective on socio-technical transitions (Geels, 2005), neoschumpeterian version of long wave theory (Perez, 2002), and industrialization literature (Stearns, 2021).

The DT framework starts from the premise that novel technological and social innovations posing alternatives to currently dominant socio-technical systems emerge and mature in specific shielded spaces called niches. For example, the precursors of Henry Ford's mass production included the interchangeability of parts pioneered in French weapons production at the late 18th century, or the idea of moving work to worker as practised in Cincinnati slaughterhouses from the 1860s (Kanger and Sillak, 2020). Notably, both niche formation and the destabilization of existing systems require active struggle by individual and collective actors who produce new innovations and build coalitions for accelerating niche development or limiting their proliferation. Thus, any story of the emergence of interchangeable parts, for instance, needs

to account for the power of French armorers and merchants, who prevented this niche from breaking through in revolutionary France, while tighter control over skilled craftsmen in New England allowed managers to overcome political contestation and succeed where the French had failed (Smith, 1977; Alder, 1997; Sabel and Zeitlin, 1997).

Combining this idea with Perez's (2002) periodization, Schot and Kanger (2018) developed a model to explain the cyclical rise and fall of rule-sets coordinating multiple socio-technical systems called ‘meta-regimes’ (e.g. electrification from the 1870s, mass production from the 1910s) that have underpinned five successive 40–60 year and increasingly global ‘great surges of development’. The model shows how different niche principles emerge, grow, become gradually linked and break through in single systems (e.g. mass production in American mobility system at the early 20th century), accelerate through competition between alternatives (e.g. Fordist vs. Sloanist mass production in the interwar era), consolidate through external shocks (e.g. the role of World War II in stimulating mass production for military and civil purposes), become dominant in a broad array of socio-technical systems (e.g. the international take-up of mass production in mobility, agriculture, housing and other systems after World War II), and finally enter a crisis prompting a shift to another surge driven by new emerging niches (e.g. digitalization from the 1970s) (Johnstone et al., 2026). Subsequent studies have highlighted the role of actors called ‘system entanglers’ in creating connections between different systems (van der Vleuten, 2019; Groß et al., 2022).

Whereas the model described above seeks to explain how five discontinuities in industrial revolution have come about, Kanger and Schot (2019) further argued for the existence of major continuities that, once having emerged, keep being reproduced from one surge to another. To capture the latter, the framework uses the notion of industrial modernity. It is defined as a “socio-material structure

1. encompassing the domains of the natural environment (as a source of inputs), science, technology and innovation;
2. including mutually supporting foundational beliefs and assumptions (ideas), formal and informal rules (institutions), and characteristic behaviour (practices);
3. that characterize two or more successive great surges of development, and;
4. [...] have become so widespread that they can be found in almost any socio-technical system in almost any industrial society” (Kanger et al., 2022: 3).

In earlier studies, the traits of industrial modernity were defined on the basis of a broad but also highly selective interpretive synthesis of insights from science and technology studies, history of technology, sociology, and socio-ecological approaches (Kanger and Schot, 2019; Kanger et al., 2022) without following any clearly identifiable systematic methodological procedures. This resulted in the definition of 42 traits, reduced to two core themes characterizing the entire

Table 1
Comparison of literature on long-term socio-technical change.

Strand of literature	Representative works	Strengths	Weaknesses
Science, technology and innovation studies	Latour, 1993; Freeman and Louçã, 2001; Geels, 2005	Explicit focus on technoscientific factors and conceptualization	Limited scope of theorization; emphasis often on novelty and disruption (innovation studies); lack of attention to middle-range theorizing (science and technology studies)
Sociology of modernity	Giddens, 1991; Beck, 1992; Moore, 2015	Explicit focus on holistic conceptualization and macro-level processes	Tendency to prioritize ‘social’ factors in explanations; analytical reductionism; conceptual subsumption
Critical approaches	Feenberg, 1991; Escobar, 2018; Samerski, 2018	Strong focus on criticizing the problematic outcomes of industrialization and the underlying assumptions producing them	Occasional overgeneralization; relative lack of attention to middle-range theorizing
History (environmental, economic, science, technology)	Mokyr, 1990; McNeill, 2001; Agar, 2012	Detailed and nuanced narrative explanations over long time-frames	Formal theory-building is often not a primary objective
Environmental and sustainability studies	Catton Jr and Dunlap, 1978; Haberl et al., 2017; Clark and Harley, 2020	Explicit focus on macro-level socio-environmental trends and conceptualization	Internal disciplinary fracture; less attention to technoscientific factors and theory of innovation

industrialization process: 1) environment as a blind spot, resulting in its relative neglect in rhetoric, institution-building and resource use; 2) overconfidence in science and technology, resulting in a regular overestimation of their promises, underestimation of their perils and mis-specification of their impacts (Kanger et al., 2022).

Conceptually, industrial modernity is an ideal type, “a collection of attributes that is maximal in that it includes all nonidiosyncratic characteristics that together define the concept in its purest, most ideal form” (Gerring, 2012: 426). While ideal types are informed by empirical observations, they do not necessarily have a specific real-life empirical referent. In other words, there is no single representative region in which all traits of industrial modernity would be equally present throughout the entire industrial revolution; instead one would expect to find considerable temporal and geographical variation. This has been confirmed by empirical results from five G20 countries (Kanger et al., 2022, 2023) and seven countries in the Nordic/Baltic region (Ertelt et al., 2025) that have mapped the long-term dynamics of a selected number of traits over the last 120 years. Whereas the conceptualization offered in this paper primarily focuses on defining the ideal type, confronting it with empirical evidence remains crucial for assessing its relevance, providing a building block for constructing a more nuanced middle-range process theory of industrial modernization that recognizes the formation of alternative visions of modernization and the role of unequal power relations in prioritizing certain future pathways over other ones (see also the research agenda in Section 7).

Existing empirical findings, however, reveal four general trends: 1) existence of many ideational, institutional and practice-related deep continuities between 1900 and 2020, e.g. continuously high and positive public discourse on science and technology, dominance of reactive and conservation-oriented environmental regulations, or continued

increases in material use with a fairly low share of recycling; 2) significant ruptures in some traits, e.g. increasing prevalence of environmental public discourse from the 1960s, and sharp growth in the adoption of international environmental treaties from the 1980s; 3) in general, ideational shifts have occurred earlier than institutional ones which, in turn, precede practice-related shifts; 4) ideational and institutional changes related to the environmental domain have occurred earlier and have been more far-reaching than technoscience-related changes (Kanger et al., 2022, 2023; Ertelt et al., 2025). Points 3) and 4) were also confirmed by Pakker et al. (2024) who compared the current legacy of industrial modernity in 63 countries. Fig. 1 summarizes the main findings.

The Deep Transitions framework has been criticized for its limited engagement with major recent socio-economic trends like marketization, financialization, income stagnation, increasing indebtedness, individualization and lifestyle fragmentation (Kemp et al., 2022; Geels, 2024: 119). While true, this oversight largely stems from the way in which the notion of industrial modernity was initially delimited in the framework. Arguing that “industrial modernity constitutes a selection environment with particular characteristics and internal dynamics that is relatively independent from other societal realms” (Kanger and Schot, 2019: 10), the scope of the concept was explicitly restricted to macro-level traits related to the natural environment, science and technology only (Kanger et al., 2022). For this reason, the critique of neglect is arguably somewhat misplaced as it essentially accuses the Deep Transitions framework for overlooking the factors it was not designed to endogenize in the first place. The difference in emphasis is also pertinent for this paper. That is, rather than seeking to develop a new holistic theory of modernity covering the interaction of an entire range of technoscientific, economic, political, social and cultural macro-trends,

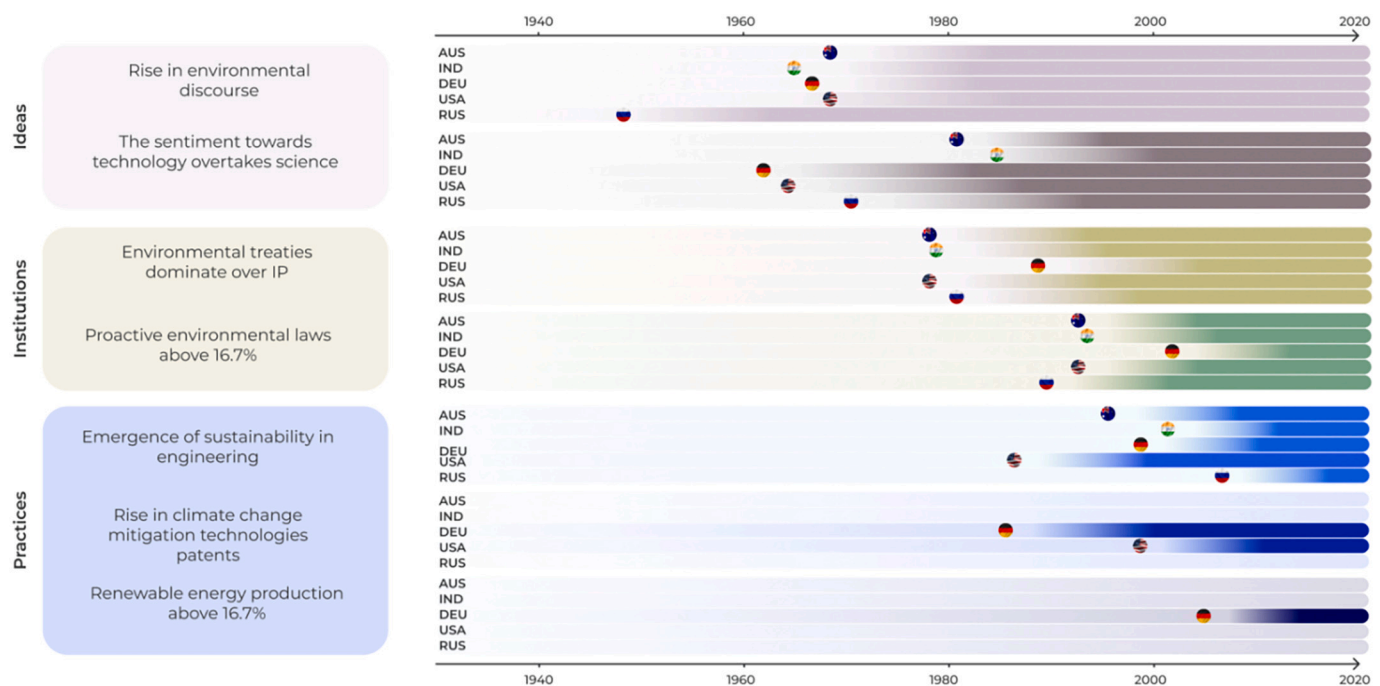


Fig. 1. The timing of shifts in industrial modernity in five G20 countries, 1950–2020 (adapted from Kanger et al., 2023: 12).

Note. The countries are Australia, Germany, India, USA and USSR/Russia. The ruptures are defined as follows (main sources in parentheses): 1) the start of rapid growth in the frequency of keywords related to the natural environment (countries' newspapers); 2) the sentiment towards technology overtaking science (countries' newspapers); 3) the adoption of major international environmental treaties overtaking the adoption of intellectual property related treaties (ECOLEX, WIPO Lex); 4) country's proactive environmental regulations crossing the 16.7% threshold (ECOLEX); 5) the emergence of the sustainability theme in engineering science (MS Academic); 6) the start of rapid growth in climate change mitigation technologies related patents per 100,000 people (PATSTAT, EPO, USPTO); 7) country's renewable energy production crossing the 16.7% threshold (The Shift Project, US EIA) (see Appendix E in Kanger et al., 2023, for more details on structural break identification). The country flag marks the moment when each country crosses the threshold. For each parameter, the moment when 3 countries have crossed the threshold is marked by the coloured background indicating different dimensions: grey for ideas, green for institutions and blue for practices. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

we focus only on the constituents, co-evolution and outcomes of industrial modernity as a relatively under-conceptualized phenomenon in existing streams of literature.

Even so the current conceptualization of industrial modernity suffers from three significant limitations:

1. The notion remains insufficiently comprehensive. Even the latest list of traits (Kanger et al., 2022) still neglects many key trends well established in the history of industrialization: belief in the autonomy of science for ensuring the production of useful knowledge, privileging of quantitative indicators in governance, increasing societal authority of science and the marginalization of indigenous knowledge systems, standardization of innovation and manufacturing activities, or the expanding role of the state in catalysing technoscientific innovation for the purposes of imperial expansion and warmaking, to name a few (Nisbet, 1994; Conklin, 1997; Mokyr, 2009; Agar, 2012; Beckert, 2014; McClellan III and Dorn, 2015; Porter, 2020);
2. The choice of traits in quantitative studies on the historical evolution of industrial modernity (Kanger et al., 2022, 2023; Ertelt et al., 2025) has been significantly conditioned by the availability of digitized newspaper corpora and existing databases – a constraint that is likely to remain salient for future empirical work. As a result, existing studies have yet to explore the historical emergence of the majority of the traits;
3. The current definition of industrial modernity also assumes that once established, the traits of industrial modernity continue to persist during successive surges, expanding into new territories and taking new forms. However, save for some empirical studies described above, this assumption has not been confirmed for most of the traits.

In the following section we will describe our methodological approach for addressing these challenges.

3. Research design for trait identification and validation

Whereas prior conceptual work on industrial modernity (Kanger and Schot, 2019; Kanger et al., 2022) was mostly focused on trait definition through the loose exploration of different streams of literature, the theory-building process used in this paper adopted a more systematic approach. Four research strategies were combined to address both exploratory and confirmatory aspects of concept formation. Note that although they have been described sequentially, the actual research process entailed constant iteration between different stages, a feature stressed as essential for any theory-building exercise (see Shepherd and Sutcliffe, 2011; Rivard, 2021; Furnari et al., 2021).

The first stage included a conceptual analysis and revision of the list of traits developed in previous work on industrial modernity (Kanger and Schot, 2019; Kanger et al., 2022). The aim of this step was to assess the substantive coverage and clarity of formulation of the traits, in particular to ensure that they were: 1) mutually exclusive, i.e. not containing any overlapping elements; 2) collectively exhaustive, i.e. not excluding any important, pervasive and durable environment-, science- and technology-related idea, institution or practice recognized as central in existing literature on industrialization; and 3) parsimonious, i.e. preventing the creation of an excessive amount of extra traits making the overall conceptualization unwieldy (Gerring, 2012; Kanger, 2024).

Following Kanger et al. (2022) we retained the distinction between ideas, institutions and practices. This approach enables us to distinguish between three qualitatively different modes of engaging with the world and treat them on an equal footing: what actors believe to be true (descriptive component with no normative disposition), rules specifying how actors ought to act (prescriptive component with a normative disposition), and what actors actually do (also capturing the constraints and opportunities posed by material factors). This distinction is meaningful and analytically useful for several reasons: 1) studies on value-

behaviour (Leiserowitz et al., 2006) or institution-implementation gaps (Hofmann, 2019) have shown that ideas, institutions, and practices may not be in alignment and can frequently contradict each other; 2) the alignment can often take decades if not centuries to achieve and may be the result of retrospective legitimation, e.g. techno-fixes were employed from the early industrial revolution as improvised responses to various emerging problems, but came to be expressed as an explicit doctrine much later in post-WWII USA (Johnston, 2020); 3) contradictions between ideas, institutions and practices can play an instrumental role in offsetting the promises accompanying successive waves of innovations and, as such, are crucial for understanding the evolution of industrial modernity; 4) close attention to the tension between ideas, institutions and practices allows us to avoid the danger of reifying the assumptions of industrial modernity and narrating its evolution as more coherent and hegemonic than the historical evidence allows (Cooper, 2005). These points will be illustrated in more detail in Sections 4.2 and 5.

The conceptual analysis led to a number of improvements to the typology. These included 1) changing the wording of an existing trait; 2) extending the trait to cover multiple domains (e.g. from science only to science and technology); 3) moving the trait to another category (e.g. from ideas to institutions); 4) merging some substantively similar traits; 5) deleting redundant traits, 6) adding new traits, based on the domain expertise of the author team (three transitions scholars, two historians) and recommendations from experts (see below). Cross-disciplinary consensus in the author team was required to confirm each change. This resulted in the reduction of the overall number of traits, while the thematic coverage of the concept was increased by 40% (see Section 4.1).

One of the key insights of the conceptual analysis was the recognition that practices characteristic of industrial modernity should be better distinguished from their immediate and historically recurrent outcomes, e.g. use of fossil fuels and the resulting socio-metabolic profile of industrial societies (Haberl et al., 2019; Haas et al., 2020). Furthermore, we realized that these outcomes can be plausibly linked to multiple traits of industrial modernity including ideational and institutional ones. For example, Bonneuil and Fressoz have argued for the role of geology in the first half of the 19th century uncovering an “*endless reservoir of resources ... thus transform[ing] Malthus's ‘dismal science’ into a reassuring argument for limitless growth*” (2016: 171). This suggests that the socio-metabolic profile of industrial societies has also been supported by societal beliefs in limitless supply of resources. These considerations prompted us to revisit and expand the ‘pervasive and persistent problems’ category in the original conceptualization of industrial modernity (Kanger and Schot, 2019). Combining the reclassification of some traits (from practices to outcomes), additional secondary literature from different literature streams discussing different impacts of industrialization (e.g. Ellul, 1964; McNeill, 2001; Moore, 2015; Haberl et al., 2017) and unintended consequences of innovation (e.g. Tenner, 1997; Huesemann and Huesemann, 2011; Sveiby et al., 2012) as well as expert feedback, we introduced “recurrent controversial outcomes” (RCO) as a new conceptual category and identified 10 different RCO-s (see Section 5).

In the second stage, each trait was placed on a timeline indicating a period in which it became part of industrial modernity *on a systematic basis*. Here, the goal was to specify a period in which an idea, an institution or a practice ceased to be an exceptional and highly localized novelty and instead came to be a persistent feature shared by a group of actors in an organizational field (e.g. scientific community, industry, universities) in one or more countries, reproduced and amplified over subsequent surges. This approach sought to find a mid-way between early but sporadic historical precursors (often mentioned in various historical works) and global mass diffusion of the traits (often occurring decades or even a century after their emergence). It should be explicitly noted that we do not equate the systemicity of a trait with its dominance from the outset – especially in early stages many traits co-existed with multiple alternatives and it was often unclear for the contemporaries

which of these would eventually become dominant. Furthermore, as all these traits have diverse historical roots, they cannot be associated with a single trigger event. Therefore, each trait was associated with a particular 'great surge of development' as defined by Perez (2002, 2010), leading to the following periodization: 1) pre-industrial era (1543); 2) the Industrial Revolution (1771); 3) Age of Steam and Railways (1829); 3) Age of Steel, Electricity and Heavy Engineering (1875); 4) Age of Oil, the Automobile and Mass Production (1908).¹

We recognize that the notion of "systematic" is open to quite different interpretations and entails a significant amount of interpretive flexibility when it comes to making decisions about the placement of different traits. Therefore, we sought to justify our choices by finding relevant quotes from existing literature on the history of industrialization. Characteristics of an ideal quote included: 1) originating from an authoritative study – in practice, often a monograph by a distinguished historian; 2) making a clear reference to a specific point in time (e.g. specific years or decades); 3) including both a specific event (e.g. a particular invention) as well as an overall trend highlighting the broader importance of the event; 4) in case the trait preceded the first great surge, an indication of it obtaining heightened significance during the Industrial Revolution. In case of disagreements, additional quotes were sought to provide better justifications for placement. In more severe cases, lingering differences in interpretation led to reformulating the underlying trait itself to increase its clarity.

The third step entailed additional work with the literature to document the persistence of each trait through successive great surges of development. That is, if the trait emerged during surge 3 (electrification), we also sought to find illustrative quotes for its existence during surges 4 (mass production) and 5 (digitalization). Furthermore, in order to account for the internal transformation of industrial modernity from the 1960s (see Section 6), we aimed to find quotes illustrating major changes in certain environmental ideas and institutions. The quote quality criteria were the same as described above with an additional one emphasizing geographical diversity to better demonstrate the widespread presence of the traits. Difficulties with finding suitable quotes were treated as indications of problematic conceptualization. Hence some traits were also reformulated, merged or dropped in this stage. The initial set was screened to select the most illustrative ones, resulting in a total of 159 quotes (see Appendix A for the final selection).

In the fourth stage we arranged 2 workshops with 9 historians (environment, science, technology). Additional written and/or oral feedback was obtained from 4 other scholars with expertise in environmental history, history of technology, and socio-metabolism. The experts were asked to identify possible gaps, errors and inaccuracies in the list of traits and recurrent controversial outcomes, assess the positioning of the traits on the timeline, and suggest additional sources to consult. We then collated feedback and identified recurring suggestions, as well as proposals that fell outside the scope of the present paper (for instance, detailed discussions of causality and amplification mechanisms, which some workshop participants requested, remains on the agenda for future research, see Section 7 for more detail). Major revisions included developing new traits that addressed the role of the state, imperialism and the military-industrial complex across the 19th and 20th centuries (traits 11, 23, 34, 36), expanding the geographical range of examples, clarifying wording and occasionally reclassifying traits.

¹ Perez's scheme also includes the fifth surge called the Age of Information and Telecommunications (1971). This was not included in our timeline because, by definition, the notion of industrial modernity includes traits covering two or more successive surges only. Therefore, in order to qualify as a trait of industrial modernity, it should have emerged during the fourth surge at the latest.

4. Industrial modernity: Traits and emergence

In the following we will present an outline of the key building blocks of our conceptualization. To make the entire line of argument easier to follow, Fig. 2 highlights the main concepts as well as their interrelations to be discussed in detail in Sections 4–6.

Our key goal is to expand from well-established findings in existing literature describing various direct macro-level impacts of technoscience such as increases in productivity, economic growth, societal welfare, and environmental degradation (e.g. McNeill, 2001; Ponting, 2007; Gordon, 2016; van Zanden et al., 2014; OECD, 2021). In order to do so, Section 4 first opens up the black box of technoscience by explicitly identifying various ideas, institutions and practices that have stimulated scientific research and technological innovation throughout the entire industrial revolution. By gathering, ordering and synthesizing a range of insights from different streams of literature the notion of industrial modernity is expanded substantively in terms of its defining traits, and temporally by showing the accumulation of different traits throughout successive great surges of development. Section 5 explores different ways in which the traits of industrial modernity have indirectly contributed to offsetting the positive impacts of industrialization by introducing the notion of recurrent controversial outcomes as an intermediate concept. Finally, focusing on the entire loop, Section 6 shows how these interactions have provoked gradual changes in industrial modernity, leading gradually from a continued optimization of its traits to more fundamental transformations in its two core themes. The dominance of these particular emphases can be used to divide the industrialization process into distinct phases.

4.1. Traits of industrial modernity

In order to conceptualize the historical evolution of industrial modernity we first need to define its constituent traits. Table 2 provides an overview of 38 extensively revised traits, highlighting the changes compared to the last published version (Kanger et al., 2022). The traits were classified as 1) ideational, when they were primarily concerned with beliefs about the natural environment and technoscience; 2) institutional, when they were mainly about regulating, standardizing, rationalizing or otherwise attempting to simplify the complexity of the real world in order to guide and incentivize actors to behave in a certain manner; 3) practice-related, when they were first and foremost occupied with specific activities related to altering the natural environment, the conduct of scientific research, or the development and use of technological innovations. Although the classifications are not clear-cut, we nevertheless believe that the distinction between ideas, institutions, and practices is a useful heuristic for conceptualizing and analysing the patterns and outcomes of industrial modernization (see Sections 3, 4.2 and 5 for more detail).

Overall, the revised version contains 11 ideas, 15 institutions and 12 practices. Domain-wise, there are 9 environmental, 7 science-, 8 technology-related traits, and 14 covering both science and technology. Notably, the wording of only 3 traits has remained unchanged. For 8 traits the wording has been improved with no changes in cell positioning. In 3 instances the trait has been extended from a single dimension to two dimensions, whereas in 8 cases the trait has been either moved to a different dimension, merged with another trait or a combination of the two. 16 new traits were added to the list, while 3 were deleted. Finally, 10 traits from the previous conceptualization were moved to the category of "recurrent controversial outcomes", including additional changes in wording and/or merging with another trait (see Section 3 for the rationale and Section 5 for the results).

4.2. Timeline of industrial modernization

Fig. 3 presents the timeline of the emergence of each trait, whereas Table 3 provides an overview of the results by dimension and domain.

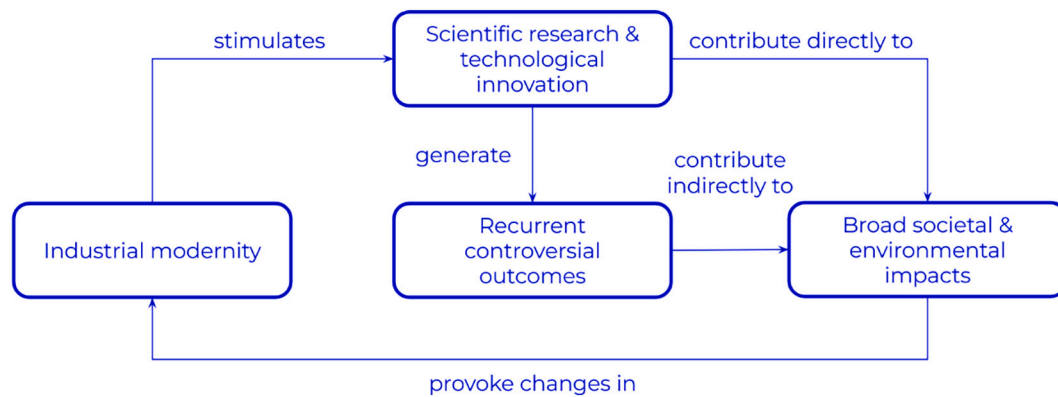


Fig. 2. Building blocks for conceptualizing the evolution of industrial modernity.

We will now present a stylized narrative about the historical accumulation of industrial modernity and then tentatively suggest some general patterns.

Thematically, successive surges have contributed to industrial modernity in quite different ways. Significantly building on pre-industrial developments in science (traits no. 1, 2, 13 in Table 2), surge 1 was characterized by a flurry of new ideas, institutions and practices that collectively amounted to a highly uncertain societal experimentation with new technological capabilities. This was further enabled by tapping huge fossil fuel energy reserves across increasingly disparate geographies, a process made possible by the expansion of European empires (23, 27, 31). The experimental nature of this surge also meant reliance on many heuristics – e.g. adoption of technology without much attention to social and environmental considerations (35), improvised techno-fixes to emerging problems (38), or institutional focus on dealing mainly with the consequences of innovation (21) – that proved to be increasingly problematic later on (see Sections 5 and 6). Industrialization at this stage was limited – confined largely to mainland Britain – uneven and contested, as workers resisted, often successfully, many features of industrial modernity such as rationalization of labour (25) or mechanization (31) (Beckert, 2014; Malm, 2016). Meanwhile, proponents of industrial modernity in Britain leveraged the power of the state, remaking the institutional and political landscape more friendly to industrialization via the introduction of measures such as work requirements, prison and poorhouse labour etc. (Thompson, 1968; Beckert, 2014).

The initial success of industrialization seems to have stimulated a theme of perpetual societal progress (11) in surge 2, further supported by beliefs in limitless availability of environmental resources (7), aspiration of control over the environment (12), emerging ideas about value-free objective science devoted to the ever-expanding discovery of laws of nature (8), and the professionalization of science as a separate societal domain of activity (30). Indeed, the period between 1750 and 1900 has been called a peak of progressivist beliefs in the West (Nisbet, 1994: 171; Scott, 1998: 89–90). Societies that embraced industrialization began to see dramatic changes in social organization and state power. New innovations, from the steam-powered gunboat to quinine antimalarials demonstrated the usefulness of technoscience for warfare (34). Practices of “rational management” began to emerge in manufacturing and plantation slavery in the US, setting the stage for the rapid scaling up of industrialization (25). As much as champions of progress touted the successes of industrialization, however, in practice these empires also relied critically on low-tech, non-industrial, and often coerced forms of expertise and labor: plantation slavery in the Americas, peasant agriculture and artisanal production, for instance through trade with India and China (Beckert, 2014; Osterhammel, 2014). And while European and American empires largely adopted ideologies of progress, institutions and practices were more heterogeneous, with old elites and new experts often blocking reforms that threatened their power. For

example, French merchant and artisan classes successfully limited the expansion of mass production up to the Franco-Prussian war, while new institutions like the Public Works Service and the Forest Service started identifying and regulating the environmental consequences of natural resource use (Woronoff, 1997; Ford, 2016).

Following the maturation of science, surge 3 was dominated by the professionalization of engineering and the emergence of many key ideas and norms still with us today. These include techno-solutionism (6), techno-neutrality (9), or efficiency as a widespread ideal (14). In this period science finally became directly linked to technological innovation (Mokyr, 2002; Friedel, 2007: 482–483; McClellan III and Dorn, 2015: 348). As argued by Arthur (2009: 171), the construction of precise instruments (e.g. thermometer, calorimeter) for close observation of natural phenomena led to new areas of application (e.g. industrial chemistry, electricity, electronics) which led to the discovery and capture of ever new phenomena (e.g. X-radiation, radio-wave transmission). The increasingly systematic feedback between scientific discovery and technological innovation rapidly started contributing to the potential for combinatorial technological innovation in industrial societies. Meanwhile, the technology-propelled expansion of European empires led to increasing standardization and formalization of weights, measures, time-keeping, and other logistical tools, thus reducing barriers to the expansion of industrial modernity around the globe. These reforms often remained limited in their reach, hardly extending outside Euro-American metropolises, and even there appearing far more complete on bureaucratic paper than in everyday practice. Standardized time zones were proposed at the Prime Meridian Conference in 1884, and yet even in the 1930s many places in Europe and America had not yet adopted mean times. Outside of Europe and the US, colonial subjects defended time rhythms based on natural or religious patterns, and Muslim cities, from Istanbul to Alexandria, continued to operate under multiple time regimes without any single one dominating (Huber, 2013; Ogle, 2015). Moreover, the increasing propagation of industrial modernity through imperial expansion stimulated the challenging of both through alternative visions of development such as the negritude movement or Catholic personalism (Goebel, 2015; Ford, 2016).

In many ways surge 4 was about the expansion of the technoscientific mindset to new societal domains, as reflected in beliefs about natural science as the role model (5) and the main driver of innovation (10), preference of quantitative indicators for assessing societal progress (19), or technocratic policymaking (26). In this period technoscience delivered significant benefits and expanded in scale, as states realized the military gains that could be achieved through systematic deployment of science (34) for warmaking (Agar, 2012: 263–300). This, in turn, led to the emergence of new science-based industries, civilian spill-overs of technologies created by the military-industrial complex, and unprecedented global economic growth after World War II (Toniolo, 1998; Channell, 2017; Schot and Steinmueller, 2018). Yet simultaneously, the costs of industrialization became ever more apparent, including two

Table 2

Revised and expanded traits of industrial modernity.

	Natural environment	Science	Technology and innovation
Ideas	1. Belief in human exceptionalism, treating nature and society as separate realms while privileging the latter*	2. Belief in the autonomy of science as the best long-term guarantee for producing socially useful knowledge****	3. Belief in technology as an autonomous force, having an inevitable and irreversible impact on society****
	4. Instrumental view of nature as a resource to be harnessed and manipulated by humans for humans	5. Belief in natural science as the role model and quantifiability as an ideal for advancing knowledge in every domain and solving any societal challenge*	6. Belief in the virtue of substituting any human task and addressing any societal problem through technological innovation***
	7. Belief in limitless supply or substitutability of resources, disregarding resource constraints and waste as fundamental problems***	8. Belief in the possibility of context-free and self-correcting science, focused on producing objective truths about the world*	9. Assumption that technologies are inherently neutral means to any goal
	12. Superiority, control over and independence from the natural environment as key aspirations shaping the governance of nature***	11. Belief that science and technology, while largely unpredictable in the short term, will enable limitless long-term societal progress, expressed in cultural, racial or civilizational hierarchies***	13. Communalism, universalism, disinterestedness and organized scepticism as key norms in science****
Institutions	15. Simplified, selective and standardized representation and valuation of nature*	16. Mathematization of science, codification of scientific knowledge and formalization of research procedures****	14. Efficiency, calculability, predictability and control as key ideals in engineering****
	18. Prioritization of societal concerns over environmental ones in institutional design and indicators of progress***	19. Institutional preference for quantitative indicators of progress discounting values, policy measures and outcomes that are difficult to quantify****	17. Standardization of technological infrastructures, artefacts and components as well as invention, development, design and manufacturing processes****
		20. Science as an increasing source of authority replacing tradition and religion or forcing them to adapt****	21. Institutions mainly focus on stimulating the volume and speed of innovation*
		22. Institutions mainly focus on regulating the consequences of technoscience with scientists and engineers not held accountable for the societal impacts of their activities**	
Practices	27. Growing speed, breadth and depth of natural resource extraction, coupled with the increasing global mobility of extractive industries****	23. Emphasis on increasing state capacity as a precondition for delivering technoscientific and social progress****	
	29. Growing generation of waste and dominance of a throwaway consumer culture***	24. Commodification of ideas and knowledge through intellectual property rights regimes****	
	31. Use of fossil fuels and mineral resources as key inputs*	25. Rationalization of operations in socio-technical systems through formal coordination of labour, materials, and machines as equivalent functional parts****	
		26. Technocratic – elitist, anti-pluralist, progressivist, scientist and efficiency-oriented – reasoning and decision-making in policy circles**	
Core themes		28. Growing scale, organization and specialization of industrial manufacturing, technological innovation and scientific research activities****	
		30. Professionalization and organization of science and engineering as specific domains of activity***	
		32. Systematic use of science as an input to engineering and technological innovations to prompt new scientific research**	
		33. Systematic use of technology and science to feed economic growth and growth-oriented investment for guiding research, development and innovation activities****	
		34. Systematic deployment of technology and science to increase the war-making capacity of states and state-sponsored development of military, often dual-use innovations****	
		35. Neglect, redefinition or normalization of various socio-environmental risks and harmful impacts of scientific research, innovation and technology adoption***	
		36. Marginalization of vernacular forms of knowledge and other non-scientific competences****	37. Mechanization: gradually growing and self-propelling use of technological artefacts in all areas of life*
			38. Techno-fixes: attempts to solve various socio-environmental problems created by existing technologies through the introduction of new and more complex ones*
	Environment as a blind spot, resulting in its relative neglect in rhetoric, institution-building and resource use	Overconfidence in science and technology, resulting in a regular overestimation of their promises, underestimation of their perils and misspecification of their impacts	

Note. Merged cells refer to 1) traits shared by different domains (environment, science, technology), or; 2) developments in two domains connected to each other. The asterisks indicate the following:

* changed wording, no change in cell.

** horizontal shift (trait extended to a new dimension).

*** vertical shift (trait moved to a different category and/or combined with another one).

**** added trait.

highly technologized and destructive World Wars, industrialized genocide (Holocaust), the development of potentially world-ending nuclear weapons, and increasing levels of industrial pollution. As such, this period also started to see increasingly vocal contestation of industrial modernity (Warde et al., 2018) (see Section 6).

The stylized narrative presented above enables the identification of

two general patterns of development. First, key traits of industrial modernity emerged early on, with more than half of the traits appearing in surges 1 and 2. Surge 2, in particular, seems to have unlocked beliefs, institutions, and practices that enabled the amplification and expansion of industrial modernity around the world, such as the standardization of infrastructures (17), the linking of technoscientific progress and

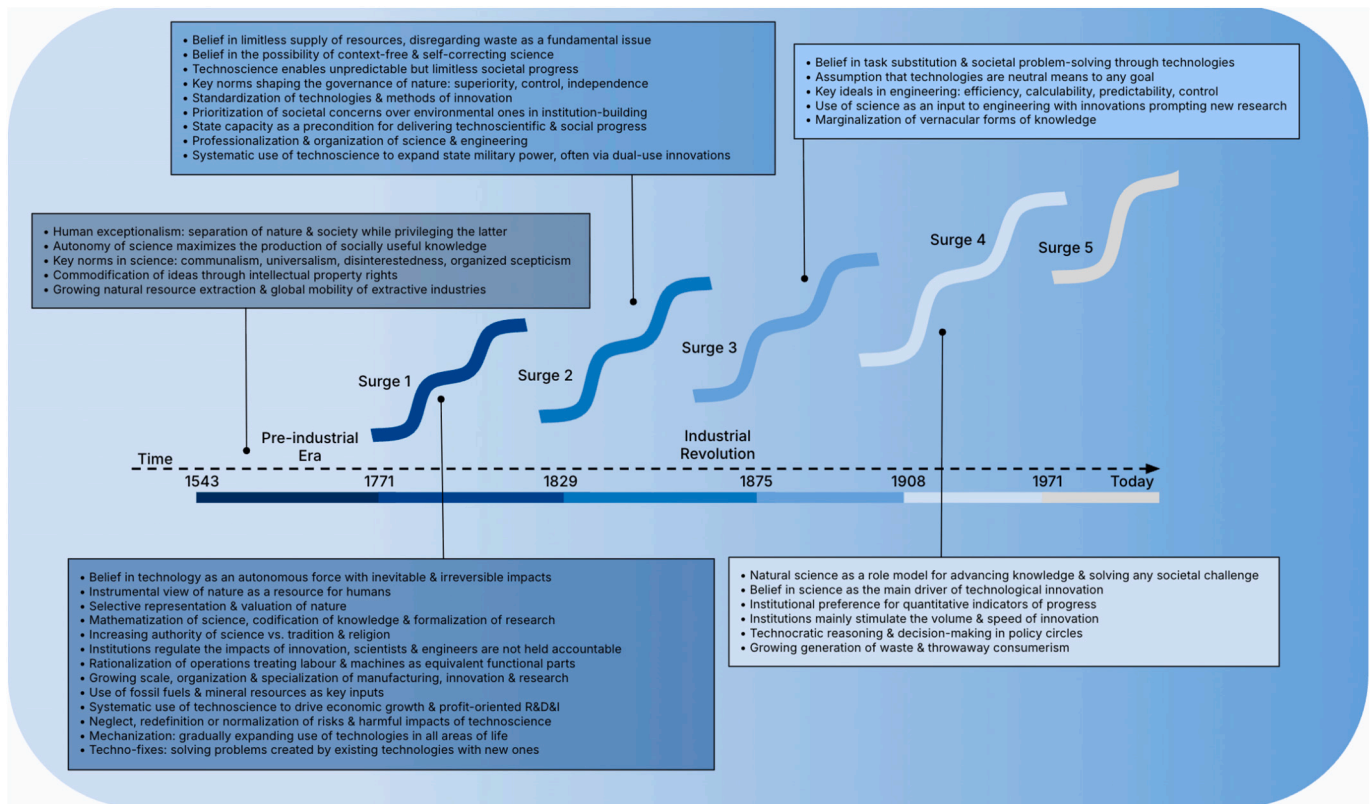


Fig. 3. Emergence of industrial modernity.

Table 3

The traits of industrial modernity by emergence, dimension and domain.

Traits	Preindustrial (1543)	Surge 1 (1771)	Surge 2 (1829)	Surge 3 (1875)	Surge 4 (1908)	Total
Ideas	2	2	3	2	2	11
Institutions	2	6	3	1	3	15
Practices	1	6	2	2	1	12
Environment	2	3	3	0	1	9
Science	3	8	4	2	4	21
Technology	1	9	4	4	4	22

Note. Traits covering two dimensions have been double-counted.

increased state capacity (23), or the deployment of technoscience for the purposes of war (34) – even as many groups successfully resisted these changes at the time. Subsequent surges primarily realized these gains, while embedding industrial modernity in the political, bureaucratic and expert institutions of the core industrializing countries (32, 36, 19, 26). Hence we can distinguish between the emergence (surges 1–2) and consolidation of industrial modernity (surges 3–4).

Second, ideologies of industrial modernity were regularly contradicted by its practices. One example includes ideas about the separation of nature and society (Latour, 1993) in the 19th-century Britain and USA, while industrial enterprises, from cotton mills to steelworks became more, not less reliant on their surrounding ecosystems (Cronon, 1992; Malm, 2016). Another example concerns proclamations about the neutrality of technology and the virtues of expert rule by policymakers, which was paralleled by the use of technological innovations, from DDT to nuclear power, for explicitly political ends (Hecht, 1998; Mitchell, 2002). We observe that many traits that emerged in the later surges functioned effectively to hide, legitimate or resolve these tensions. For instance, marginalization of vernacular knowledge (36) and privileging of technocratic reasoning (26) helps maintain the authority of

formalized and objective science (2, 16, 20) even if the outcomes generated by the latter turn out to be highly controversial. This is exemplified by the well-known case of the British government using the authority of science to dismiss the farmers' local expertise about radioactive contamination in areas around the Sellafield Nuclear Plant (Wynne, 1996). It is to these controversial outcomes that we will now turn.

5. Recurrent controversial outcomes

In this section we move from the traits of industrial modernity to particular types of consequences that have indirectly contributed to the macro-level impacts of industrialization. Building on combined insights from existing literature (see Sections 2 and 4) we propose that over the last 250 years interacting traits of industrial modernity have produced several “recurrent controversial outcomes” (RCO-s), regularly undermining optimistic hopes attached to successive waves of innovations. Table 4 provides an overview of 10 RCO-s including a selection of 3 traits of industrial modernity potentially involved in generating them. Each RCO has been illustrated with two empirical examples, one from the history of industrialization and one related to current sustainability interventions. To further show how reliance on conventional assumptions can reproduce well-known RCO-s for sustainability solutions, we discuss three cases from Table 4 – solar geoengineering, climate modelling, housing insulation – in more detail.

Solar geoengineering refers to techniques aiming to decrease the trapping of outgoing thermal radiation or increase the reflection of incoming solar radiation (NASEM, 2021). This can be achieved through various means, such as stratospheric aerosol injection, marine cloud brightening, cirrus cloud thinning, space mirrors, or surface-based albedo modification (Ricke et al., 2023). However, geoengineering proposals largely seem to rely on several historically dominant assumptions about technoscience, e.g. belief in the virtue of addressing societal problems through technological innovation, belief that although

Table 4
Recurrent controversial outcomes of industrialization.

Recurrent controversial outcome	Contributing traits (no in Table 2)	Historical example	Sustainability-related example
Distinct socio-metabolic profile of industrial societies, characterized by changing land use patterns, increasing resource use, non-circularity and waste, the impacts of which on humans and non-humans are largely ignored	Instrumental view of nature (4), belief in limitless supply or substitutability of resources (7), use of fossil fuels and mineral resources as key inputs (31)	Globally expanding need for fertilizer, combined with the decline of waste recycling in Europe leads to the extraction of seabird guano from South American islands in the mid-19th century, only to have this resource become exhausted in a few decades (Cushman, 2013)	Future renewable energy systems will likely lead to increases in materials use under various scenarios (Kalt et al., 2022)
Exacerbation of existing social divisions between the technocratic elite and citizens through the underestimation of place-specific or non-formalized knowledge of the latter and their superficial inclusion in political decision-making	Belief in natural science as the role model (5), technocratic policymaking (26), marginalization of non-scientific competences (36)	Activists in nuclear weapons testing regions (e.g. Bikini Atoll) or plutonium production sites (e.g. Hanford) reported negative health effects for years, while being dismissed by experts on account of national security considerations or industry pressure to demonstrate the safety of nuclear technologies (Brown, 2013; Mitchell, 2017, 2021)	Technocratic top-down approach to clean energy transition can create various types of injustices related to insufficient recognition and inclusion of local stakeholders in planning as well as uneven distribution of impacts (Carley and Konisky, 2020)
Critical societal dependence on globally distributed socio-technical systems characterized by high energy and resource use, built-in assumptions about the availability of expensive infrastructures, and high accessibility thresholds assuming a certain level of purchasing power	Belief in addressing any societal problem through technological innovation (6), standardization of technological infrastructures, artefacts and components (17), use of fossil fuels and mineral resources as key inputs (31)	US Federal Aviation Administration spending \$41 billion at the end of the 1990s to upgrade 2 to 3 generation old guidance systems installed in the 1950s–1960s with limited success (Unruh, 2000)	Widespread adoption of ACES mobility (Autonomous, Connected, Electric, Shared), implemented through tightly interconnected energy, mobility and communication systems, potentially deepening reliance on a highly capital-intensive mode of transport
The benefits of new technologies are increasingly spatially and temporally separated from their socio-environmental costs; the latter are displaced onto politically expendable “sacrifice zones” within or beyond state boundaries	Reactive institutional approach to the impacts of technoscience (22), intensification of natural resource extraction (27), growing generation of waste (29)	Deforestation in southeastern Brazil from the 18th century for gold mining as well as sugar and coffee cultivation, mainly for foreign export markets (Stearns, 2021)	Lithium-ion battery products using cobalt from Congo, which relies on exploitative mining practices, human rights abuses and child labour (Williams et al., 2021)
Communities that technocratic elites consider “backward”, “anti-progress” or not sufficiently developed, are forced to industrialize or considered expendable in the development of industrial progress	Technoscientific progress expressing cultural, racial or civilizational hierarchies (11), systematic deployment of science and technology for war-making (34), marginalization of non-scientific competences (36)	European “scramble for Africa” under the ideology of a progress-oriented “civilizing mission” in the late 19th century led to the colonization and exploitation of nearly the entire continent, particularly in the service of extractive industries and infrastructure (i.e. railroads) (Conklin, 1997)	Continuing indigenous displacement in Brazil and Indonesia to enable biofuel production (Lima, 2022)
Normal accidents: individual devices become safer, yet complex, tightly coupled systems increase risk of catastrophic failure	Belief in unpredictable but beneficial technoscientific progress (11), mechanization (37), techno-fixes (38)	Derailments of American trains led to the development of air-brakes and other innovations, which allowed for faster, heavier trains, which in turn led to more train traffic and systemic risk of train collisions in the 1870s (Aldrich, 2006)	Possibility of a termination shock resulting from reliance on solar geoengineering the use of which may be rapidly disrupted because of societal conflicts (Stephens et al., 2021)
Emergence of highly technologized spaces, uniform in their functions, designs, social meanings and seemingly isolated from the natural environment, while remaining critically dependent on it	Superiority, control over and independence as key values for human-nature relations (12), efficiency, calculability, predictability and control as key engineering ideals (14), standardization of technological infrastructures (17)	Urban planning and architecture after World War II frequently neglecting the economic and social functions of urban areas as well as the individual needs of the inhabitants (Scott, 1998)	Sustainable insulation materials prioritizing technological performance and economic cost while ignoring the residents’ concerns about aesthetic impacts (Sunikka-Blank and Galvin, 2016) can impoverish spatial quality in mass housing districts
Improvements in technological productivity and efficiency are offset by rises in demand stimulated by these improvements, resulting in pervasive rebound effects	Belief in addressing any societal problem through technological innovation (6), amplification of technoscience and economic growth (33), neglect, redefinition or normalization of socio-environmental risks (35)	Efficiencies in British coal use in the mid-19th century led to the expansion of coal-powered machinery, reigniting concerns over resource exhaustion (Jevons, 1865)	Economy-wide rebound effects may erode more than 50% of expected savings from improved energy efficiency; this undermines the assumption of decoupling between GDP and energy use characterizing many global scenarios (Brockway et al., 2021)
Quickening pace of innovation contributing to the normalization of temporary and technological unemployment, constant pressure towards the upgrading of education and skills, increasing sense of time-space compression and acceleration of everyday life	Belief in autonomous and inevitable technological development (3), assumption of neutral technologies (9), systematic rationalization (25)	Luddite movement in the early 19th century: English workers destroying particular types of textile machines that were perceived to make workers unfairly redundant, produce unemployment and lower product quality (Schot, 2003)	Populist backlash to current environmental challenges in the form of climate science denialism, climate policy nationalism and climate policy conservatism (Vihma et al., 2021)
Controversial policy decisions in the present are postponed on the pretext of collecting more scientific evidence about current challenges and/or optimistic estimations about the availability of future technologies	Belief in addressing any societal problem through technological innovation (6), belief in the possibility of objective and context-free science (8), discounting of difficult-to-quantify factors (19)	In the 1950s and 1960s, the US tobacco industry purposefully used scientific institutions to sow doubt about the carcinogenic effects of smoking, by suggesting through corporate-sponsored research that the science was as yet unsettled (Proctor, 2012)	Beginning from the 1990s various climate models have constantly overestimated the future availability of various mitigation technologies (McLaren and Markusson, 2020)

proposed solutions are complex and uncertain, their net gains outweigh the possible harms, or the nature of geoengineering as a ‘techno-fix’ practice which, if successful, would enable societies to continue on their current trajectory of development without undertaking any major socio-economic reforms. As such, geoengineering proposals have been criticized from several angles, e.g. whether the full range of its impacts can be fully understood before deployment, inability of the current international political system to guarantee a just and inclusive use of these technologies, or the risk of termination shock if the current global economic system would come to rely on geoengineering which, for some reason or another, could suddenly not be sustained any more (McKinnon, 2019; Stephens et al., 2021). These criticisms can be interpreted as concerns about the lack of safeguards preventing the large-scale re-occurrence of historically familiar and highly controversial outcomes. The latter include a continued deepening of the fossil fuel-based, ‘mineral’ and linear resource use of industrial societies, uneven spatial distribution of the benefits and harms of geoengineering (especially if used unilaterally), or critical dependence on complex technological systems which remain vulnerable to external shocks and ‘normal accidents’ (Perrow, 1984). This has led to academic and political calls for an international non-use agreement (Biermann et al., 2022), expressed recently by African countries at the 6th United Nations Environment Assembly (Biermann and Gupta, 2024).

Several traits of industrial modernity, such as beliefs in objective and context-free scientific expertise, discounting of factors that are difficult to quantify and belief in techno-solutionism, have shaped climate modelling. A recent study has identified a five-phase co-evolution of climate politics, policy targets and framing, modelling methods and scenarios, and technological promises from the 1990s to the present (McLaren and Markusson, 2020). It has been shown that each phase was driven by significant overestimations about the future availability of particular technologies like nuclear power, carbon capture and storage (CCS), or bioenergy with CCS. Furthermore, the selection of technologies was strongly influenced by how well they could be modelled and how well they matched the extant climate policy frames. Arguably, this has led to the reproduction of yet another outcome known from the history of industrialization: constantly delaying decisive policy action in the present on the pretext of being able to tackle this problem better in the future (Carton, 2019; Carton et al., 2020; McLaren and Markusson, 2020).

Yet another example concerns attempts to increase the energy performance of the housing stock in Europe, often by retrofitting. It has been estimated that the member states of the European Union could save 44% of final energy used for heating through the insulation of residential buildings (BPIE, 2023). At the same time, it has also been found that residents often value the aesthetics of retrofitting as highly as cost and energy saving potential (Sunikka-Blank and Galvin, 2016; Seifhashemi and Elkadi, 2022). However, if renovation focused on traditional engineering concerns about efficiency, narrowing down the problem to finding the best trade-off between technological performance and economic cost, while seeking the standardization of insulation practices to minimize the latter, it can well lead to the reproduction of highly technologized and alienating urban spaces, often exemplified by the failures of modernist city planning (Scott, 1998: 103–146). A powerful visual critique of this threat has recently been made by the Estonian exhibition at the 2025 Venice Architecture Biennale (Fig. 4). Wrapping a historical Italian *palazzo* into modern insulation materials, the architects clearly expose the potentially impoverishing impact of standardized insulation on the spatial quality of housing.

6. The evolution of industrial modernity

So far we have identified the traits of industrial modernity (Section 4.1), mapped their emergence (Section 4.2), summarized tentative empirical evidence of ruptures in their evolution over the last 40–70 years (Section 2.2), and argued that interacting traits have generated

various recurrent controversial outcomes throughout the history of industrialization up to the present (Section 5). In this section we will add the final element: long-term impacts resulting from the interplay between the traits of industrial modernity and recurrent controversial outcomes. A synthesis of these empirical and conceptual building blocks leads us to propose that the historical rise, current crisis and possible future transformation of industrial modernity can be divided into 3 phases: industrial modernization, ecological modernization and responsible modernization (see Fig. 5 for a visual summary).

The first, industrial modernization phase (from the 1770s) was characterized by the gradual emergence, increasing accumulation and linking of dominant assumptions about the natural environment and technoscience. Taken together, these traits decisively accelerated innovative activities, enabling vast increases in societal welfare, but with core industrializing regions reaping the largest share of benefits (van Zanden et al., 2014; OECD, 2021). The capacity of humans to reshape their environment also increased correspondingly. In some core countries, competing elites, experts, workers’ movements, and colonized populations successfully blocked the proliferation of certain institutions and practices of industrial modernity (see, for instance, the above example of France’s initial rejection of mass production). However, proponents of industrialization were equally adept at building coalitions, particularly when it came to seizing the power of the state and its war machine to expand modernization. In addition, most controversial outcomes were displaced 1) in space, to expendable ‘sacrifice zones’ such as the alkali industry in Europe during the 19th century (Friedel, 2007: 271–273; Fressoz, 2024: 144–150); 2) in time, through the delayed costs of fossil fuel use; 3) onto marginalized populations with few resources for contesting industrialization. As long as perceived benefits of societal welfare outweighed the burdens of environmental degradation by dominant actors, the answer to emerging problems created by industrial modernity was simply more industrial modernity. This resulted in the successive accumulation of traits (see Section 4.2 for more details) and the crystallization of the two core themes of industrial modernity – environment as a blind spot and overconfidence in science and technology (Fig. 5a).

The Great Acceleration of a broad range of Earth System and socio-economic trends (McNeill and Engelke, 2014; Steffen et al., 2015) resulted in worsening environmental conditions in different parts of the world in the post-WWII era and triggered the second, ecological modernization phase (from the 1960s). This was marked with changes in one of the core themes of industrial modernity as the natural environment ceased to be a blind spot of industrial societies (Fig. 5b). The change was reflected in increasing global environmental awareness from the 1960s, followed by shifts in environmental institutions (Kanger et al., 2022, 2023; Ertelt et al., 2025) and the emergence of sustainability as a new and increasingly widespread societal objective from the 1980s. Another trend was the rise of alternative niches rethinking human-nature relations such as deep ecology in Norway, precautionary principle in German environmental law, or the Chipko movement in India (Næss, 1973; McNeill, 2001; Lees, 2007). While some radical critiques of technoscience were also formulated (e.g. Ellul, 1964; Illich, 1973; Schumacher, 1973), shifts in innovative activities generally remained rather limited (e.g. modest rise in green and climate change mitigation related patents and related scientific research). As such, the second core theme of industrial modernity – overconfidence in science and technology – remained largely unchallenged. Taken together, this reflected the dominance of the ecological modernization frame perceiving environment as a problem and technoscience as *the* solution (Spaargaren and Mol, 1992; Wiedmann et al., 2020). Meanwhile, the increasing technological capabilities of humanity continued to intensify the scale and scope of various RCO-s, manifested, for example, in the discussion of ‘normal accidents’ of complex technological systems (Perrow, 1984) or treating ‘risk’ as the defining feature of contemporary societies (Beck, 1992).

Arguably, our current situation is marked by the crisis of industrial



Fig. 4. Estonian exhibition “Let Me Warm You” (ERR, 2025). Author of the photo: Joosep Kivimäe.

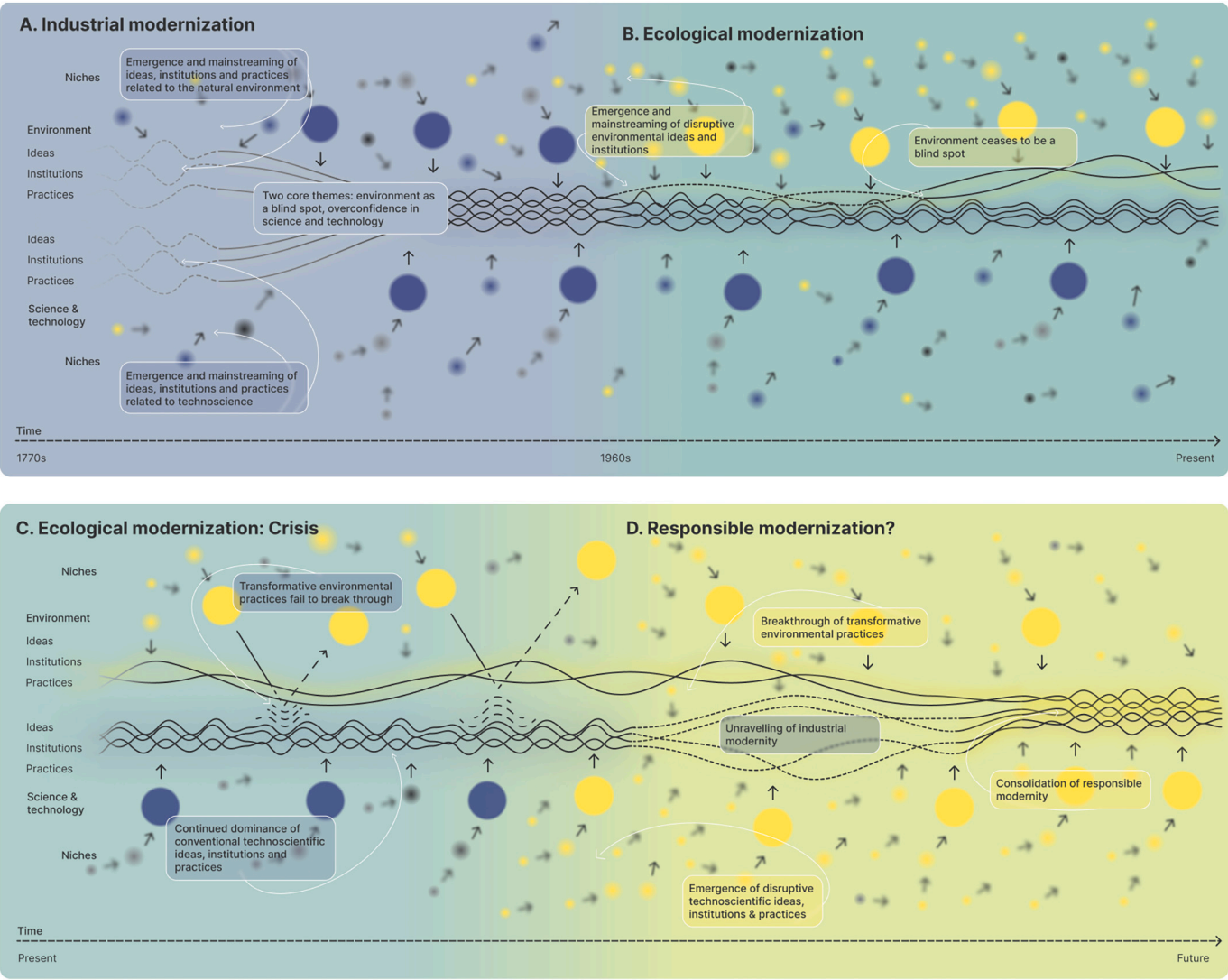


Fig. 5. Three stages of modernization.

modernity. This crisis largely results from the limitations of ecological modernization, where the introduction of new sustainability fixes has not been coupled with a major rethinking of conventional assumptions about technoscience underpinning them. This effectively amounts to a failure to prevent the re-occurrence of various controversial outcomes related to scientific research and technological innovation (see Table 4). As a result, the historical legacy of ideas, institutions and practices related to technoscience is now effectively blocking the translation of unfolding shifts in environmental awareness and institutions into pervasive, durable and transformative environmental practices, e.g. circular economy, absolute reduction of global material footprint, or energy sufficiency (Fig. 5c). This, in turn, results in a potentially explosive situation where increasing environmental degradation is met with a series of ill-controlled technological interventions characterized by increasing speed, scale, scope and uncertainty of their impacts. The situation has prompted a range of responses from continued optimization of industrial modernity (e.g. green growth, Industry 5.0) to backlash against science and technology (e.g. vaccine hesitancy, climate denialism) (Oreskes and Conway, 2010; Decoteau and Sweet, 2024). Insufficiency of the dominant response is also reflected in the continued acceleration of niches focused on radically rethinking nature-society

Table 5
Dominant traits of industrial modernity, alternative principles and niches exemplifying the latter.

	Dominant trait	Alternative principle	Existing niche
Ideas	Instrumental view of nature as a resource to be harnessed by humans for humans	Nature has inherent value and right to exist independently of human perceptions	Deep ecology (Næss, 1973)
	Belief in limitless progress through science	Insofar as science is produced in a social context, it can be captured for malign purposes	Hippocratic Oath for scientists (Popper, 1971)
	Assumption that technologies are inherently neutral means to any goal	The design of technologies embeds the preferences and values of their creators	Value-based engineering (Spiekermann and Winkler, 2022)
Institutions	Prioritization of societal over environmental concerns in institution-building	The design of institutions should seek to overcome anthropocentrism	Providing legal rights to nature (Borrás, 2016)
	Technocratic reasoning and decision-making in policy circles	The public should be involved in decision-making about high-impact technoscientific choices from the outset	Citizens' climate assemblies (KNOCA, 2025)
	Institutions mainly focus on stimulating the volume and speed of innovation	Institutions should address the directionality of innovation	Transformative innovation policy (Schot and Steinmueller, 2018)
Practices	Growing generation of waste and dominance of a throwaway consumer culture	Industrial production focused on maximizing the circularity of resources	Circular economy (Potting et al., 2017)
	Neglect, redefinition or normalization of risks in scientific research	Systematic integration of anticipation, reflexivity and precaution into scientific research	Responsible Research and Innovation (Owen et al., 2012)
	Using new technologies to fix the problems created by previous ones	Technological solutions can avoid the extreme limitations of high- and low-tech approaches	Mid-tech technology development (Kostakis et al., 2023)

relations as well as the recent upsurge of ones challenging the second core theme of industrial modernity – overconfidence in science and technology (see Table 5 for some historical and recent examples).

It remains to be seen whether this crisis will only deepen in the coming decades or whether purposeful action from social movements and policymakers will be able to avoid the reproduction of various recurrent controversial outcomes of industrialization and accelerate the shift to the third phase, tentatively called responsible modernization (Fig. 5d). Since this shift is by no means guaranteed, its exact features cannot be known at the moment. However, one may argue that a major transformation of industrial modernity would require at least three broad changes: 1) adoption of a doctrine of technoscientific realism, i.e. a history-informed understanding of the possibilities and limitations of science and technology with appropriate safeguards to neutralize the latter (Kanger et al., 2023); 2) a more balanced set of innovation policy objectives, aiming for “good life for all within planetary boundaries” (O'Neill et al., 2018); 3) increased emphasis on anticipatory policies aiming for *ex ante* minimization of the risks of basic scientific research and radical technological innovations, e.g. the proposal to extend the notion of precautionary principle to entire technology groups (Markard et al., 2023) such as nanotechnology.

7. Conclusion: A research agenda for studying industrial modernization

This paper has argued that the long-term evolution of macro-level ideas, institutions and practices related to the natural environment, science and technology constitutes a critical yet also somewhat under-conceptualized component in understanding the historical roots of and barriers to the current sustainability crisis. As a response, we have attempted to formulate a conceptual vocabulary for theorizing the process of industrial modernization, entailing the emergence of its traits over a 250-year timespan, recurrent controversial outcomes generated by these traits as well as the internal transformation of industrial modernity resulting from these processes. In particular, the paper posed five research questions and 1) identified 38 core ideas, institutions and practices of industrial modernity (RQ1, Section 4.1); 2) created a timeline of the emergence of the traits and identified two general patterns in their evolution (RQ2, Section 4.2); 3) identified 10 recurrent controversial outcomes produced by interacting traits (RQ3, Section 5); 4) proposed a novel periodization, distinguishing between industrial, ecological and responsible modernization (RQ4, Section 6), and; 5) demonstrated the impacts of the historical legacy of industrial modernity on current sustainability interventions (RQ5, Section 4.2). Our key conclusion is simple: traits that were historically vastly successful in accelerating technoscientific innovation, productivity, economic growth and societal welfare are at least partly maladapted to address the current sustainability pressures. As a result, science and technology now keep intensifying the very sustainability problems they promise to solve. Or to put it more provocatively: if people born in the 20th century attempt to solve the 21st century problems with 19th century assumptions about technoscience, the resurgence of many setbacks known from the history of industrialization should not come as a big surprise. Yet it does, time and again.

Because of the sheer amount and disciplinary fragmentation of different insights on the macro-level features of industrialization, this paper has mainly focused on synthesizing them into a unified analytical framework, making it possible to conceptualize the internal dynamics of industrial modernity as a semi-independent societal selection environment. This has meant emphasizing particular theorizing strategies, mainly the formation of new concepts, relating the concepts to each other as well as dating and periodization. Much more remains to be done in order to develop the conceptual framework offered in this paper into a more ambitious process theory of industrial modernization. In particular, we would highlight four directions for further research:

1. Identification of comparative-historical patterns in the evolution of industrial modernity, combining quantitative and qualitative methods (e.g. text mining, quantitative time-series analysis of existing databases, qualitative narrative explanation based on the synthesis of existing historical literature, case studies). Whereas work on the varieties of capitalism (Hall and Soskice, 2001; Hall and Thelen, 2009) is well established, we currently simply do not know whether the pathways of industrial modernization can also be classified into distinct types based on the combination of particular environmental and technoscientific ideas, institutions and practices. Empirical results from different regions and countries would help to flesh out the ideal type of industrial modernity, increase its geographical sensitivity and provide building blocks for a more nuanced theorization of the emergence, diffusion and linking of various traits of industrial modernity.
2. Although the paper has identified an overarching pattern in the evolution of industrial modernity, much more research is needed on various types of mechanisms shaping this process. In particular, the interplay between three types of mechanisms should be addressed. First, mechanisms that have historically amplified the speed, scale and scope of industrial modernity, enabling its swift expansion around the globe. Possible mechanisms include combinatorial evolution (Arthur, 2009), science-technology feedback (Mokyr, 2002), Schumpeterian growth between innovation and economy (Aghion et al., 2015), reordering of the world through standardization (Bowker and Star, 1999; Immerwahr, 2019), or feedback loops between innovation and military capabilities (Morris, 2014). Second, mechanisms through which the dominant traits of industrial modernity have been contested (e.g. new framings in media, labour strikes), leading to gradual discursive, institutional and practical adjustments (Hård and Jamison, 2005). Third, blocking mechanisms that have favoured the optimization of industrial modernity, thereby delaying and preventing more transformative changes, e.g. the continuous normalization of the risks of new technologies (Fressoz, 2024). Understanding industrial modernity as an outcome of countervailing forces – in other words, as struggle – will allow us to develop a model that foregrounds both power imbalances, and the role of human agency in generating the patterns of industrial modernization.
3. Whereas a tentative attempt has been made to measure the historical legacy of industrial modernity in different countries (Pahker et al., 2024), focus on deep structural constraints is only part of the story for determining the transformative potential of any geographical location. Equal attention should also be paid to the presence of transformative niches in different regions that go beyond palliative techno-fixes or quick but superficial tipping point wins (Otto et al., 2020; Lenton et al., 2022). However, a methodology for identifying niches that systematically problematize different assumptions about environment, science and technology remains to be largely developed (see Morrison et al., 2022, for a promising start). A combined measurement of historical constraints and deep transformative niches could reveal locations most likely to enact the deep sustainability turn.
4. The final strand of work concerns the design of transformative niche clusters, i.e. a set of interlinked niches collectively providing new-to-the-world solutions to some problematic features of industrial modernity. For example, environmental degradation resulting from selective valuation and pricing of nature could be addressed by creating a novel positive feedback loop between individual incentives and ecosystem restoration. This could be hypothetically realized through the combination of automated environmental monitoring, expert-based pricing, and green cryptocurrency into a universal ecocoin, mined for engaging in sustainable practices (e.g. planting trees, giving up the car) (Kanger et al., 2023). This, in turn, can be complemented by a policy mix (Rogge and Reichardt, 2016; Kern et al., 2019) nurturing the growth of different innovations for

incentivising ecosystem restoration while destabilizing currently dominant modes of valuation. In our view the co-evolution between the design of transformative niche clusters and policy mixes supporting them constitutes one of the most exciting future research directions in system innovation.

We would like to end with a brief note on reflexivity and responsibility. Beginning from the 1990s, some social theorists have argued that we have now entered a new era of reflexive modernity (Beck et al., 1994, 2003). Fittingly, the need for more reflexivity is frequently echoed in innovation policy literature (e.g. Weber and Rohracher, 2012; Schot and Steinmueller, 2018; Laatsit et al., 2025). Indeed, reflexivity is ubiquitous in contemporary societies: as evidence on climate change and loss of biodiversity continues to accumulate it has an increasing impact on policymaking, while even the denialist camp has to invest considerable cognitive and political effort into the social construction of ignorance about these crises (Rayner, 2016; Bowden et al., 2021). Yet these two contrasting reactions to the same evidence well demonstrate that increasing awareness of sustainability issues does not necessarily increase the motivation to address them in a constructive manner. It is precisely for this reason that we prefer the notion of responsibility which includes both a normative disposition and an action-oriented component. For breaching the boundary between reckless and responsible modernization requires taking responsibility for one's actions.

CRediT authorship contribution statement

Laur Kanger: Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Aro Velmet:** Writing – original draft, Validation, Supervision, Investigation, Formal analysis, Conceptualization. **Liina Maurer:** Writing – original draft, Validation, Investigation. **Anna Helena Liiv:** Writing – original draft, Validation, Investigation. **Phil Johnstone:** Writing – original draft, Validation, Investigation.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.respol.2026.105625>.

Data availability

The data has been provided in Appendix A

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