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ANNA-KATI PAHKER

Measuring industrial modernity in comparative perspective, 1900–2020

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This dissertation is based on the following four original publications referred to by Roman numerals:

I. Kanger, L., Tinits, P., **Pahker, A.-K**., Orru, K., Tiwari, A. K., Sillak, S., ... & Vaik, K. (2022). Deep Transitions: Towards a comprehensive framework for mapping major continuities and ruptures in industrial modernity. Global Environmental Change, 72, 102447. Copyright Elsevier. https://doi.org/10.1016/j.gloenvcha.2021.102447

II. Kanger, L., Tinits, P., **Pahker, A.-K.**, Orru, K., Velmet, A., Sillak, S., ... & Lauk, K. (2023). Long-term country-level evidence of major but uneven ruptures in the landscape of industrial modernity. Environmental Innovation and Societal Transitions, 48, 100765. Copyright Elsevier. https://doi.org/10.1016/j.eist.2023.100765

III. **Pahker, A.-K**., Kanger, L., & Tinits, P. (2024). Where is the deep sustainability turn most likely to emerge? An Industrial Modernity Index. Technological Forecasting and Social Change, 201, 123227. Copyright Elsevier. https://doi.org/10.1016/j.techfore.2024.123227

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AUTHOR'S CONTRIBUTIONS

The specific methodological contribution of the author is outlined in detail in Section 3.4 My methodological contribution. Here, contributions are overviewed according to the CRediT authorship contribution statement.

STUDY I
"Deep Transitions: Towards a comprehensive framework for mapping major continuities and ruptures in industrial modernity": Investigation, Methodology, Visualisation, Writing – original draft, Writing – review & editing. For writing, my main responsibilities were methods, results, and discussion chapters.

STUDY II
"Long-term country-level evidence of major but uneven ruptures in the landscape of industrial modernity. Environmental Innovation and Societal Transitions": Investigation, Methodology, Visualisation, Writing – original draft, Writing – review & editing. For writing, my main responsibilities were methods, results, and discussion chapters.

STUDY III
"Where is the deep sustainability turn most likely to emerge? An Industrial Modernity Index": Conceptualisation, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualisation, Writing – original draft, Writing – review & editing. For writing, my main responsibilities were introduction, methods, results, and discussion chapters.

STUDY IV
"Research frontiers for multi-system dynamics and deep transitions": Visualisation, Writing – original draft, Writing – review & editing. My main responsibility was visualisation.

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I am delighted to be finally at the point where I am writing this section. Exhilarated even. The work that went into this thesis has been an opportunity for academic and personal growth. I feel a distinct difference that, to me, is an improvement in how I think and see the world. There are many people I would like to thank for their part in my achieving this feat.

My deepest gratitude goes to Laur Kanger for (somewhat reluctantly) accompanying and guiding me on this journey. I am incredibly fortunate to have had a supervisor as involved, attentive, and available as you, Laur. I must say you have, first and foremost, been very agitating yet also fun, helpful, and considerate.

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Having expressed my gratitude, I must also acknowledge the challenges mostly because I thoroughly enjoy whining. As I mentioned, these past years have been challenging and isolating, filled with long work days, uncertainty, conflict, and (self-)doubt. Countless tears have been shed over, out of all the things one can cry about, various Microsoft Word documents. For anyone considering pursuing a PhD, let me offer a word of caution: doing a PhD is a gruelling experience, often described as the best part of an academic career, which is a dubious dichotomy at best. What is more, the act of thinking itself can be rather unpleasant, and to make matters worse, it has led me to grow increasingly pessimistic about the state of the world. While I will discuss potential solutions to the unsustainable trajectory of industrial societies, I remain sceptical about the likelihood of profound change. The path of least resistance often leads to the perpetuation of existing power structures. However, dwelling on such a grim and predictable scenario can lead to a sense of helplessness. Instead, I hope for something very realistic and cool like mass hypnosis that leads us to finally be serious about climate change. Or, if not that, maybe extraterrestrials could visit us again, and this time, instead of building pyramids and whatnot, they would help with something more practical like energy storage capacity. That would be neat, right?

1. INTRODUCTION

"Coal," British economist W. S. Jevons declared in 1865, "stands not beside but entirely above all other commodities. It is the material energy of the country, the universal aid, the factor in everything we do. With coal, almost any feat is possible or easy; without it, we are thrown back into the laborious poverty of early times" (Jevons, 1865: vii). This quote encapsulates the aspirations and anxieties of its era. Amidst the still looming energy scarcity and the lingering spectre of poverty, coal ignited a societal transformation, ushering in an unprecedented surge in productivity, economic expansion, and societal well-being that the world has witnessed since the 19th century (OECD, 2021). However, the very foundations of industrial societies, built on the relentless pursuit of economic growth and fossil fuel-based energy consumption, now pose a significant threat to the planet's sustainability. The notion that our past endeavours to improve our conditions may be hindering our pursuit of a more sustainable future is driving my thesis and its underlying research.

The concept of sustainability first articulated in the 1987 Brundtland Report (United Nations, 1987), entails "meeting the needs of the present without compromising the ability of future generations to meet their own needs." This seminal report introduced a novel perspective on the evolution of industrial societies, diverging from the previous trajectory characterised by unchecked expansion (Meadows et al., 1972). Nevertheless, despite ongoing initiatives to combat climate change, resource depletion, and biodiversity loss (IPBES, 2019; IPCC, 2023), a robust scholarly consensus maintains that industrial societies not only persist on an unsustainable course but have also accelerated their unsustainable practices in recent decades (McNeill & Engelke, 2016; Steffen et al., 2015). This unsustainable trajectory is exemplified by the ceaseless escalation of energy and material consumption (Haas et al., 2020; Haberl et al., 2019) and the persistent transgression of planetary boundaries to fulfil societal demands (Fanning et al., 2022; O'Neill et al., 2018; Richardson et al., 2023).

There is less consensus on the underlying causes and potential solutions to end these trends, as research communities across sub-disciplines of sustainability science tend to focus on different aspects of the problem within specific academic boundaries (Clark & Harley, 2019). Some studies identify global population growth (Vollset et al., 2020) as the underlying issue, while others point to affluent lifestyles (Wiedmann et al., 2020) and capitalism's growth orientation (Hickel et al., 2022a). It follows that proposed solutions range from fundamentally changing our economic system (Feola et al., 2021; Raworth, 2017) to more internationally agreed-upon approaches that sidestep the need to find the root cause and focus only on the material aspects, such as remaking industrial societies' fossil-fuel dependence through rapid decarbonisation (Sustainable Development Solutions Network, 2014; Rockström et al., 2017) and a 100% global shift to renewable energy (Jacobson et al., 2022). At the same time, scholars looking beyond material needs find that we are not necessarily on a one-way street to collapse, as

aspects of industrial societies have already experienced major shifts, such as the rise of environmental values, institutions, and movements (Dietz et al., 2005; Giugni & Grasso, 2015), increasingly stringent environmental policy (Galeotti et al., 2020), and changes in innovation trajectories, such as growth in green patents (Probst et al., 2021). Moreover, it is observed that the most significant obstacles to finding and implementing solutions to the climate crisis are not material but political in nature (Meckling & Karplus, 2023).

In other words, it is evident that historical continuities still characterise some aspects of industrial societies while others are already in transformation. However, research within disciplinary boundaries does not easily allow for a holistic view of these trends. Zooming out could be necessary not only to understand the drivers of unsustainable development better but also to reveal where current solutions could fall short in changing the trajectory of industrial societies.

The research community's efforts to study the various facets of sustainability with different approaches has become increasingly recognised as a field of sustainability science (Clark & Harley, 2019). One of these approaches, sustainability transitions studies, examines the capacity for such trajectory change, or, in other words, a capacity to promote a society-wide transformation to a more sustainable state (Geels, 2005; Grin et al., 2010; Köhler et al., 2019). Transitions research does this by tracing the current challenges' roots to various socio-technical systems (e.g., energy, mobility, and healthcare) underpinning industrial societies (Geels et al., 2017). The dominant framework used in the field, the Multi-level Perspective on socio-technical transitions (Geels, 2005; Grin et al., 2010), theorises system shifts through the interaction of three analytical factors: the stability of the regime shaping the directionality of the system, maturity of the niches promising a new route, and the pressure from the external environment not directly influenced by the system, the landscape.

While the regime and niche levels are subject to extensive research in transitions studies (Köhler et al., 2019), landscape has received less attention. Rip and Kemp first introduced socio-technical landscape as "something around us that we can travel through; and in a metaphorical sense, something that we are part of, that sustains us" (Rip & Kemp, 1998: 334). Building on this, Geels (2005) defined landscape to represent broader social and material structures and processes beyond actors' immediate influence. This conceptualisation, however, leaves the landscape as a residual category that is simultaneously just an exogenous environment to systems (Geels, 2011; Markard & Truffer, 2008) and an umbrella term encompassing a wide variety of highly divergent trends both in scope and speed (van Driel & Schot, 2005). Examples include broad but slow-moving technological, economic, and environmental trends such as globalisation and climate change, as well as shocks such as wars or energy crises. A deeper understanding of landscape processes is only emerging, and even recent literature on the topic does not try to describe landscape processes extensively. Instead, the existing literature on landscape qualitatively characterises a small portion of it (Antadze & McGowan, 2017; Johnstone & McLeish, 2022; Simpson, 2019; Weng et al., 2020) or points to novel research directions, such as the need for

sustainability transitions research to engage in researching the relation between socio-technical systems and capitalism (Feola, 2020) and the regime-landscape dynamics (Geels, 2022).

The recent Deep Transitions (DT) framework (Kanger & Schot, 2019; Kanger, 2022; Schot & Kanger, 2018), to which my thesis contributes, marks the first attempt in transitions research to theorise landscape processes systematically, linking system level dynamics to broad long-term macro-level outcomes, in particular ideas, institutions, and practices related to the environment, science, and technology. The proponents of the framework argue that over the last 250 years, during the First Deep Transition, the simultaneous development of multiple socio-technical systems has shaped many currently taken-for-granted landscape-level assumptions, norms, and practices related to the natural environment, science, and technology, which now keep the systems on an unsustainable path (Kanger & Schot, 2019). Examples include perceiving nature as a resource, regulatory focus on new technologies, not their environmental impact, and increasing energy and material consumption. Kanger and Schot (2019) termed these tendencies industrial modernity. Thus, a fundamental sustainability turn with a similar magnitude as the First Deep Transition, the Second Deep Transition, would require rethinking industrial modernity.

Nevertheless, even in DT research, until now, the focus has not been on building empirical knowledge on industrial modernity but on theory-building through empirical studies on how transitions in single systems have led to transitions in other systems (Kanger & Sillak, 2020; Kanger et al., 2022) and the connections between these (van der Vleuten, 2019), the role of shocks in shaping multi-system transitions (McLeish et al., 2022), governing the Second Deep Transition (Kern et al., 2020), and accelerating it through investments (Penna et al., 2023a). The original framework has, however, made hopeful yet vague claims that ruptures in industrial modernity have been unfolding as a historical undercurrent since the 1960s (Kanger & Schot, 2019). Kanger (2022) has further argued that the particular traits of industrial modernity cannot be expected to be equally present in all locations and that the unevenness of this legacy might diverge considerably in different countries. The latter is significant as country-level constraints imposed by industrial modernity may indicate where the onset of the Second Deep Transition is most likely. Still, these theoretical assumptions remain to be empirically tested.

My thesis and the research it is based on constitute the first attempt to quantitatively measure the evolution and spread of industrial modernity through time and space. As such, my research contributes to the theory of DT framework, transitions studies, and sustainability science by expanding the empirical understanding of the dynamics of landscape processes in shaping sustainability transformations and exploring the implications of industrial modernity for changing the trajectory of industrial societies onto a sustainable path.

My thesis was guided by the following research questions to reach these aspirations:

1. To what extent is it possible to observe continuities and ruptures in industrial modernity in different countries between 1900 and 2020? (**STUDY I** and **STUDY II**)
2. Where is the onset of the Second Deep Transition the most likely? (**STUDY III**)

I approach these research questions through three empirical articles that measure industrial modernity temporally (RQ1) and spatially (RQ2). The first study in my list of publications is a pilot study measuring the continuities and ruptures in industrial modernity regarding the natural environment and technology and innovation in Australia, Germany, and USSR/Russia (**STUDY I**, "Deep Transitions: Towards a comprehensive framework for mapping major continuities and ruptures in industrial modernity"). This was followed by a study that first expanded the list of countries analysed with India and the United States, additionally measured industrial modernity regarding science, and added quantitative measures of the ruptures identified (**STUDY II**, "Long-term country-level evidence of major but uneven ruptures in the landscape of industrial modernity"). In my third publication (**STUDY III**, "Where is a deep sustainability turn most likely to emerge? An Industrial Modernity Index"), I led the development of a novel Industrial Modernity Index measuring the current manifestation of industrial modernity in 63 countries across the globe. Thus, **STUDY I** and **STUDY II** measure the development of industrial societies from 1900 to 2020, and **STUDY III** assesses the current country-level capacities to transform industrial modernity. **STUDY IV** does not deal with the empirics but provides a research agenda for the emergent deep transitions research. My research is a part of the research project "Reshaping Estonian energy, mobility and telecommunications systems on the verge of the Second Deep Transition" (PRG346), and the articles are co-authored with other scholars. I have, therefore, carefully outlined my role in the Author's contribution and Methodological approach chapters.

This thesis is organised as follows. First, in Chapter 2, I provide the theoretical background by overviewing the DT framework to guide the reader in understanding the research gap. I then situate the theoretical construct of industrial modernity within the literature on modernisation and outline how the notion is used in the context of my thesis to answer the research questions posed and contribute to sustainability science and, more specifically, sustainability transitions studies. Next, in Chapter 3, I describe the methodological approach, the operationalisation of industrial modernity, the data selection, and the limitations of my thesis. Then, in Chapter 4, I will present the main findings of my studies regarding the continuities, ruptures, and current state of industrial modernity. In Chapter 5, I discuss these findings in the context of sustainability science, transitions studies, and policymaking. In the concluding chapter, I directly address the research questions, followed by a final chapter summarising the research in Estonian.

2. THEORETICAL BACKGROUND

2.1 Sustainability transitions studies

Given its focus on examining the issue of (un)sustainable development, my thesis contributes to the discipline of sustainability science. More specifically, however, my thesis draws upon the theories and methods of sustainability transitions studies. This relatively young research field has experienced rapid growth over the past decade and has become increasingly integrated into established disciplines (Köhler et al., 2019). Moreover, the topic and research of sustainability transitions have become more politically relevant than ever, as they are now part of the OECD guidelines for managing societal transformations to sustainability (OECD, 2023), and the field has provided significant input to the Intergovernmental Panel on Climate Change's (IPCC, 2019; 2023) landmark reports in the context of accelerating climate action. Additionally, the concept of sustainability transitions is becoming increasingly institutionalised, as exemplified by its inclusion as one of the key components of the European Environmental Agency's (EEA, 2023) main operational structures.

Transitions research analyses the prospects of deep transformative change by focusing on multi-level, evolutionary processes at the level of socio-technical systems fulfilling a specific societal function such as energy, mobility, or healthcare. These systems are made up of actors, technologies, and institutions and allow for producing, distributing, and consuming goods and services, thus forming "the material backbone of modern civilisation" (Schot & Kanger, 2018: 1045). Within the field, a prominent framework used to understand sustainability transitions is the Multi-Level Perspective (MLP). The framework enables the analysis of transitions across three analytical levels: niches, regime, and landscape (Geels, 2005; Grin et al., 2010).

According to Geels & Schot (2007), niches are the radical technological or social innovations – "hopeful monstrosities" as Mokyr (1990: 291) defines them surrounded by actors that initially develop the innovation in an environment not affected by the market forces. The regime is the ruleset that creates the status quo and gives the currently dominant system a specific directionality by guiding the perceptions and actions of incumbent actors (Schot et al., 2016). Lastly, the landscape is somewhat of a residual category as it is often described as just an exogenous environment that does not fit either the niches or the regime and creates pressure on the system that cannot be directly affected by niche or regime actors (e.g., shocks such as wars or long-term trends and processes such as climate change and individualisation) (Geels et al., 2017). According to the MLP framework, system change depends on how mature the niches are and how stable the regime is when landscape pressure occurs (Geels, 2005). Furthermore, the pathway that the transitions will take depends on the dynamics between three factors at the outset of the transition (Geels & Schot, 2007). For example, Geels (2006) found that the landscape pressure that came with the scientific understanding of bacteria changed the perception of waste problems in The Netherlands during the

19th century, which, in turn, pressured the dominant cesspool regime until the integrated sewer systems niche matured enough and became central to the system of waste management. According to Geels and Schot (2007), this socio-technical transition exemplifies a transformation path characterised by incremental adjustments within the established regime rules, wherein landscape developments play a pivotal role in catalysing change.

Transitions studies have generally researched developments in single systems, with a dominant focus on niche-regime interactions (e.g., Hess, 2016; Kivimaa, 2014; Smith, 2007). In recent years, empirical work has increasingly been focusing on multi-system interactions (e.g., Andersen et al., 2023; Löhr & Chlebna, 2023; Ohlendorf et al., 2023) as there is an inherent interconnectedness created by the mutually reinforcing developments in these systems (Geels, 2007; Schot & Kanger 2018). Landscape, however, is an outsider by definition and in literature, with only a few recent exceptions aiming to describe a part of landscape developments qualitatively. Examples of this include analysing regime-landscape interactions (Weng et al., 2020) or the role of "moral entrepreneurs" (Antadze & McGowan, 2017) and shocks (Johnstone & McLeish, 2022; Simpson, 2019) in shaping landscape developments. Nonetheless, my colleagues and I (**STUDY IV**) argue that the landscape can shape the broader context of multiple systems to be less or more favourable for sustainability transitions. Consequently, this research gap can hinder our understanding of accelerating transitions during a time when the speed of climate action is of paramount importance (IPCC, 2023).

The recent Deep Transitions (DT) framework, as initially proposed by Schot and Kanger (2018), subsequently expanded upon by Kanger and Schot (2019), and further refined by Kanger (2022), constitutes the first attempt in transitions research to comprehensively theorise landscape processes, as well as the interactions between socio-technical systems and the landscape itself. In addition to the 'fundamentally socio-technical' (Kanger & Schot, 2019: 8) framing of the DT approach, the framework relies on a neo-schumpeterian version of long wave theory (Freeman & Louçã, 2001) and synthesises insights from industrialisation and modernisation literature (Beck, 1992; Stearns, 2013). More precisely, Schot and Kanger (2018) propose that beginning from the late 18th century, multi-system interactions have catalysed the emergence of five increasingly global "great surges of development," each spanning approximately 40-60 years. Perez (2002) identified these surges as The Industrial Revolution (1771), The Age of Steam and Railways (1829), The Age of Steel, Electricity, and Heavy Engineering (1875), The Age of Oil, the Automobile, and Mass Production (1908), and The Age of Information and Telecommunications (1971). The proponents of the DT framework argue that, on the one hand, this very development has led to significant increases in life expectancy and societal welfare. On the other hand, it has also created an unsustainable trajectory of environmental degradation. The DT framework thus urges a shift of comparable magnitude – a Second Deep Transition – to address these issues.

The concept of a Second Deep Transition, introduced by Schot and Kanger (2018), suggests a fundamental transformation of the core structures and processes

that define industrial societies. The language surrounding the Second Deep Transition is intentionally broad. There is no single, predefined Second Deep Transition unfolding in a strictly predetermined and inevitable direction. Rather, it represents an ongoing discussion, or a power struggle, between different narratives about how to guide industrial societies towards a better, more sustainable future. While potential pathways can be envisioned based on current trends, the actual pathway(s) that industrial societies will take is(are) yet to be determined (Kanger & Schot, 2019). Moreover, the notions of "better" and "more sustainable" are also open to interpretation. While the Brundtland Report's definition of sustainability emphasises meeting the needs of future generations, the specific implications of this definition remain a topic of ongoing debate. Thus, the DT framework does not prescribe a specific form for the Second Deep Transition. Instead, it underscores the critical need for large-scale transformations if industrial societies are to effectively address the multifaceted sustainability challenges they face and that conscious effort is needed for such change, regardless of the (agreed-upon) direction.

While Schot and Kanger (2018) formulated the patterns and mechanisms of how multi-system interactions lead to great surges of development, Kanger and Schot (2019) focused on the continuities termed industrial modernity that have accumulated through successive surges of development over the last 250 years during the First Deep Transition.

2.2 Industrial modernity

2.2.1 Modernity

Before getting to the core theoretical construct of my thesis, I will broadly discuss the diverse theoretical approaches to modernity within sociology and their relation to the DT approach. This overview will serve to situate the notion of industrial modernity within the broad and well-established literature on modernity and modernisation. It will also highlight how the socio-technical approach within the DT framework is utilised to provide a unique perspective on modernisation and industrial societies through the lens of environment, science, and technology.

The concept of modernity, characterised by rationalisation, democratisation, individualism, growing eminence of scientific thinking, and rapid technological development, emerged alongside sociology itself, following the transformative events of the Industrial Revolution, the French Revolution, and the Enlightenment (Giddens & Sutton, 2021: 194). In essence, modernity signifies the distinct historical period, modes of existence, social practices, and societal structures that succeeded the agrarian era, marking a transition generally placed around the late 18th or 19th century. Theories of modernity can be broadly categorised into cultural and epistemological theories (e.g., Habermas, Hegel, Nietzsche, and Heidegger), which focus on premodern and modern cultural forms and modes of knowledge, and institutional theories (e.g., Weber, Marx, and Durkheim), which examine key structural features of modern societies and their transitions (Brey,

2003). As my thesis is focusing on ideation, institutions, and practices, I bridge the two approaches to modernity for a more holistic view.

Hall et al. (1992: 2), echoing Giddens (1992), identify key institutions of modernity: the nation-state and international system of states; a dynamic and expansionist capitalist economic order based on private property; industrialism; large-scale administrative and bureaucratic systems; dominant secular, materialist, rationalist, and individualist cultural values; and the separation of 'private' and 'public' spheres. My thesis focuses specifically on industrialism as a distinct pillar of modernity. This situates my analysis in the 20th century, when the social, cultural, economic, and technological changes associated with industrialism began to spread beyond Europe (Stearns, 2013).

While painting with broad strokes allows to characterise modernity in a specific manner, the literature does not see modernisation as a uniform process. Some detect ruptures in the fabric of modernity and posit new postmodern societal formations such as Bell's (1973) post-industrialisation or Castells' (2000) network society. In the same vein, postcolonial critiques of modernity offer important counter-narratives to the dominant Western-centric understanding of this concept. Postmodern theorists argue that modernity's emphasis on rationality, progress, and universal truths has led to fragmentation of knowledge and a loss of meaning in contemporary society (Lyotard, 1984; Baudrillard, 1994). Postcolonial scholars critique modernity's complicity in colonial projects and its universalising tendencies that often obscured the exploitation and subjugation of non-Western cultures (Said, 1978; Spivak, 1988). These critiques challenge the notion of a single, linear trajectory of modernity and underscore the importance of diverse experiences and perspectives. The proponents of the DT approach, however, while acknowledging these critiques, do not envision an entirely new societal structure. Instead, they position their theory in the modernity versus postmodernity debate as "modernity transformed but not transcended" (Kanger & Schot, 2019: 8). As my thesis compares the manifestation of industrial modernity in various countries, I will remain empirically attentive to country-specific differences in industrialisation to employ the postcolonial critiques.

A further criticism of modernity itself is its continued contribution to environmental degradation. This issue is frequently discussed in modernisation literature within the framework of the nature-society dichotomy, a concept rooted in Judeo-Christian philosophy that positions humans as separate from and superior to nature (Adas, 1989: 210). This dualism, emphasised by scholars like Lyotard (1984), Bauman (1987), and Gellner (1988), is considered a root cause of the current environmental crisis (Lamba, 2010). To address this crisis, some propose transforming modernity. Giddens (1992) links environmental degradation directly to industrialism and suggests 'remaking technology' into a more humanised form. Beck (1992) advocates for a 'reflexive modernity' that acknowledges environmental risks and takes proactive steps to mitigate them. Others, like proponents of ecological modernisation theory, believe societies can modernise while addressing environmental challenges through the application of science and

technology by institutions like governments and markets (Jänicke, 1984; Spaargaren & Mol, 1992; Mol et al., 2020). This approach calls for a giving the environment a central position in the economy, or "ecologising the economy" as termed by Hubler (1982), by introducing institutional changes such as the implementation lifecycle analysis, environmental auditing and reporting (Mol et al., 2020). However, the foundation of this theory has been heavily criticised (Hickel & Kallis, 2020; Leipold, 2021; see Section 5.1.2 for a further discussion). The DT approach aligns more closely with the views of Giddens and Beck, calling for rethinking the problematic traits of industrial modernity (Kanger & Schot, 2019).

The most significant distinction of the DT approach from other industrialisation and modernisation theories lies in its socio-technical nature. Schot and Kanger (2018) utilise this socio-technical aspect to differentiate the DT framework from macro-historical perspectives like Polanyi's (1944; 2001) Great Transformation narrative or Wallerstein's (1989) interpretation of the industrial revolution as a byproduct of capitalism. While many scholars discuss "industrial capitalism" and some even consider the two inseparable (Patnaik, 2023: 40), the DT approach allows to disentangle industrialism by focusing on modern societies' relationships with the environment, science, technology, and innovation. This separation is crucial. Without it, the distinct mechanisms of industrialism tend to be overshadowed by its capitalist aspects, a frequent criticism of Marxist perspectives (Giddens, 1991: 15). Kanger and Schot (2019: 4) articulate this, stating that industrial modernity constitutes a "selection environment" with distinct characteristics and internal dynamics, operating alongside but not solely determined by "economic," "political," or "cultural" factors. Thus, by employing the notion of industrial modernity, my thesis highlights industrialism as a relatively independent force within broader societal developments.

2.2.2 Definition of industrial modernity

In their original conceptualisation, Kanger and Schot (2019) described industrial modernity as a macro-level selection environment embracing the traits of industrialisation covering multiple surges of development "having such a wide scope that they have come to characterise almost any socio-technical system in any industrial society" (Kanger & Schot, 2019: 10).[1] The list of traits included 17 'beliefs and guiding rules' manifesting themselves in 14 'long-term trends' and eight 'persistent problems' of industrial societies (Kanger and Schot, 2019: 12), covering at least two great surges of development. As indicated by the mention of 'persistent problems', Kanger and Schot (2019) underline that some traits of

[1] I use the notion of industrial modernity and the related traits in all three studies in my list of publications as an ideal type, as described in **STUDY I**. This line of thinking is derived from Gerring (2012: 426), who defines an ideal type as "a collection of attributes that is maximal in that it includes all non-idiosyncratic characteristics that together define the concept in its purest, most ideal form." This means that there may not be an exact real-world manifestation of the traits of industrial modernity; instead, these traits are used as empirical tools that approximate real, existing entities.

industrial modernity have become unfit for the challenges industrial societies are currently facing and may thus need to be redesigned.

The genesis of these traits and the accompanying issues is exemplified by the idea that implementing (novel) technologies is inherently neutral means to any goal. The upturn of this rule can be traced back to the late 19th century when technology or "the machine" came to be seen as the "unfolding of rationality", as an idea of technological neutrality came to be with people misusing the technology regarded as standing in the way of the solution (Nye, 2006: 22). Regardless of some critics making being a machine operator less than being an artisan (Carlyle, 1842), those glorifying machine tools became more plentiful. For example, James Nasmyth, the developer of the steam hammer, signified the upper hand a machine has over a human by saying that the machine "never got drunk; their hands never shook from excess; they were never absent from work; they did not strike for wages; they were unfailing in their accuracy and regularity" (Rolt, 1965: 113). Adas (1989: 409) describes how the father of mass production, Henry Ford, "was widely regarded as the prophet of a new age of 'heroic optimism,' in which science and invention were hailed as the key to American prosperity and the best solution for social ills." Even though the outcomes of technological innovation and the course it might take in the future were (and are) primarily considered unpredictable (Mokyr, 1990: 529; Nye 2006, 36), the idea of superiority and the promise for good still lingered. Now, however, the very same idea contributes to unsustainable development through validating "techno-fixes" or counter-technologies (e.g., electric cars or the need for air-purifying technologies in production) that are aimed at neutralising or "solving" (environmental) problems caused by other technologies (Huesmann & Huesmann, 2011: 100), creating an infinite loop without providing an actual solution.

Thus, as proposed, the original conceptualisation introduced a comprehensive and helpful umbrella term for the developments related to industrialisation and a set list of traits – some of which are unfit for current times – that could be observed through time and space. However, despite the authors' emphasis on the unique nature of industrial modernisation within the broader modernisation discourse, the original conceptualisation and the DT framework itself have faced criticism. Specifically, critics argue that the framework's focus on industrial modernity overlooks crucial socio-economic factors such as marketisation, financialisation, income stagnation, rising debt, individualisation, and lifestyle fragmentation (Geels 2024: 119; Kemp et al., 2022). Additionally, Kemp et al. (2022) point out the framework's deterministic consolidation of industrial modernity traits and its failure to account for the diverse trajectories of Deep Transitions. I acknowledge the significance of these criticisms, particularly the interplay between different aspects of modernity, which could substantially impact the society-wide transition towards sustainability. Nevertheless, my thesis prioritises a focused understanding of industrialism before delving into broader dynamics (for reasoning, see Section 2.2.1). The empirical questions of determinism and dominant directionalities raised by Kemp et al. (2022) will be directly addressed in my research through empirical testing of the DT framework's claims. This will

involve examining the prevalence of industrial modernity traits proposed by Kanger and Schot (2019) in countries with diverse socio-economic and cultural contexts (see Section 3.3.5). Consequently, the original conceptualisation remains a valuable tool for my thesis, although its descriptive nature requires refinement to highlight its distinct features. Additionally, it presents challenges in terms of practical application and empirical validation.

To make the concept less ambiguous, in **STUDY I**, my co-authors and I first argued that the natural environment, along with science and technology, should be made more central to the analytical scheme. Emphasising the three domains – natural environment, science, and technology/innovation – reinforces the conceptual foundation of industrial modernity in two ways. First, it brings the core of the industrialisation process to centre stage as the production of scientific knowledge became fundamentally intertwined with technology through the mechanisation of labour during the early modern period (Mesoudi et al., 2013: 212). Furthermore, the focus on technoscience allowed us to highlight better the socio-technical nature of industrial modernity stressed by the authors of the framework (Kanger & Schot, 2019: 8) and distinguish it clearly from other formulations of modernity emphasising the economic, political, social, or cultural dimensions.

Additionally, it reinforced the central role of the natural environment evident in the original list of traits (e.g., essential traits like *Instrumental view of nature as a resource to be harnessed and manipulated by humans for humans,* arguably shaping the First Deep Transition as a whole). This is a particularly significant point as, while it might seem intuitive that the ecological domain is at the core of transitions studies, recent literature has highlighted its absence (Ollivier et al., 2018; Patterson et al., 2017). Examples of trying to overcome this shortcoming include the development of the eco-socio-technical approach (Aps et al., 2015), acknowledgement of the intermediation of ecology in transition processes (Soberón et al., 2022), the recognition of ecology's role in the agri-food system (Vermunt et al., 2020), and the attempt to build bridges between socio-technical and socio-ecological systems literature (Wesselink et al., 2020). Including the natural environment within the conceptual schema of industrial modernity can be considered a continuation of these efforts.

Second, based on Kanger and Schot (2019), in **STUDY I** we further organised the traits belonging to three dimensions: ideas, institutions, and practices. This categorisation was needed as the DT framework sees beliefs and rules as the underlying drivers generating various trends and persistent problems (Kanger and Schot, 2019: 10). Furthermore, the framework stresses two-way interaction between rules and socio-technical systems (Schot & Kanger, 2018: 9). Our conceptualisation thus assists in negating the perceived causal primacy of rules by making a clear distinction between actors' beliefs (ideas), rules guiding their actions (institutions), and actual behaviour (practices) (see **STUDY I** for a more detailed rationale). Table 1 overviews the conceptual schema along with examples of traits.

Table 1. Selected traits of industrial modernity (based on **STUDY I**)

	Environment	**Science**	**Technology/ innovation**
Ideas	Instrumental view of nature as a resource to be harnessed and manipulated by humans for humans	Belief in limitless societal progress through the application of science	The assumption that technologies are inherently neutral means to any goal
Institutions	Preoccupation with socio-economic indicators (e.g. economic growth and labour productivity) for guiding development	Science without limits, i.e. relative lack of regulation of the direction of scientific research	Regulatory emphasis on stimulating the volume and speed of new technologies, far less stress placed on guiding their direction of evolution
Practices	Increasing amounts of waste generation with fairly little attention to reusing or recycling	Increasing the use of science as an input to engineering	Techno-fixes: repeated attempts to solve problems created by existing technologies through the introduction of new and more complex technologies

Note. While **STUDY I** divided the traits of industrial modernity into three domains – environment, science, and technology/innovation it only measured traits in the environmental and technology/innovation dimensions. **STUDY II** measured traits in all three dimensions, while **STUDY III** combined the dimensions of science and technology/innovation.

2.2.3 Historical evolution of industrial modernity

Schot and Kanger (2019) claim that industrial modernity may already be undergoing a transformative process by proposing that the start of the Second Deep Transition can be traced back to the 1960s. This proposition is undoubtedly optimistic during times when climate doom and gloom narratives, exemplified in, for instance, the Great Acceleration thesis (McNeill & Engelke, 2016; Steffen et al., 2015) or socio-metabolism approaches (Haas et al., 2020; Haberl et al., 2020), tend to dominate the collective consciousness. However, while equally hopeful and pertinent, it is a vague theoretical claim. The conceptual schema developed in **STUDY I** allows for the viewing of developments regarding industrial modernity in the domains of the natural environment, science, and technology/innovation. It includes mutually supporting foundational beliefs and assumptions (ideas), formal and informal rules (institutions), and characteristic behaviour (practices). This conceptualisation, in turn, allows the analysis of the continuities and ruptures in industrial modernity in those dimensions and domains to answer RQ1 in **STUDIES I** and **II**.

2.2.4 Spatial distribution of industrial modernity

The initial conceptualisation of industrial modernity proposed by Kanger and Schot (2019) was further developed by Kanger (2022), who proposed that the theoretical concept can be viewed as a socio-material landscape consisting of five layers left by each great surge of development. According to Kanger (2022), the embeddedness of various traits introduced during particular surges is influenced by location-specific factors. This leads to notable variations in how these traits are integrated into different societies over time. For instance, location-based differences can be observed in the extent to which societal progress is prioritised compared to environmental health, the level of support for technocratic policy-making, and the utilisation of natural resources. However, these claims also remain to be empirically tested.

To approach this goal in **STUDY III**, my co-authors and I used the schema developed in **STUDY I** to conceptualise the "thickness" of the socio-material landscape in a specific location (Figure 1). The schema was revised to better fit the task by proposing a merged domain of technoscience. This was done for both practical and theoretical reasons. First, it can be observed that industrial modernity underwent some internal rearrangement regarding the domains of science and technology starting from the late 19th century. During the 20th century, scientists and advanced laboratories became integral to industrial firms, reinforcing the convergence by making science the knowing and technology the doing in harnessing the natural world (Adas, 1989: 137, 142; McClellan & Dorn, 2016: 437). Given these historical accounts and the objective of **STUDY III** being to measure the current makeup of the layer of industrial modernity, it was logical to merge the two domains in the conceptual schema. Second, the merged schema also works better with the restrictions posed by data availability regarding

ideation (see 3.2 Methods and data selection). Finally, the two-domain conceptualisation underscores the two broad tendencies in the original list of traits of industrial modernity highlighted in **STUDY I**: "1) treating the environment as a blind spot, which often results in neglecting it in policy-making, production, and consumption; and 2) being overconfident in science, technology, and innovation which has historically resulted in a constant overestimation of their promises, underestimation of their perils, and misspecification of their impacts" (**STUDY I**: 3–4).

This approach led to a conceptualisation of industrial modernity where, in a given time, the compound ideas, institutions, and practices regarding environment and technoscience could be understood as the "thickness" of the layer of industrial modernity. Based on this notion and the theory of spatial dynamics of industrial modernity (Kanger, 2022), a thicker layer of industrial modernity in a specific place can indicate higher structural constraints associated with the First Deep Transition. These constraints are understood as various ideational, institutional, and practice-related factors (e.g., populations' environmental values, the orientation of innovative activities, and energy mix, see Table 1) that could be limiting countries' capacity for a deep sustainability turn. It follows that more of these restrictions make enacting a major transformative change on the scale of the Second Deep Transition more challenging. These insights contributed to answering RQ2, which explores the onset of the Second Deep Transition.

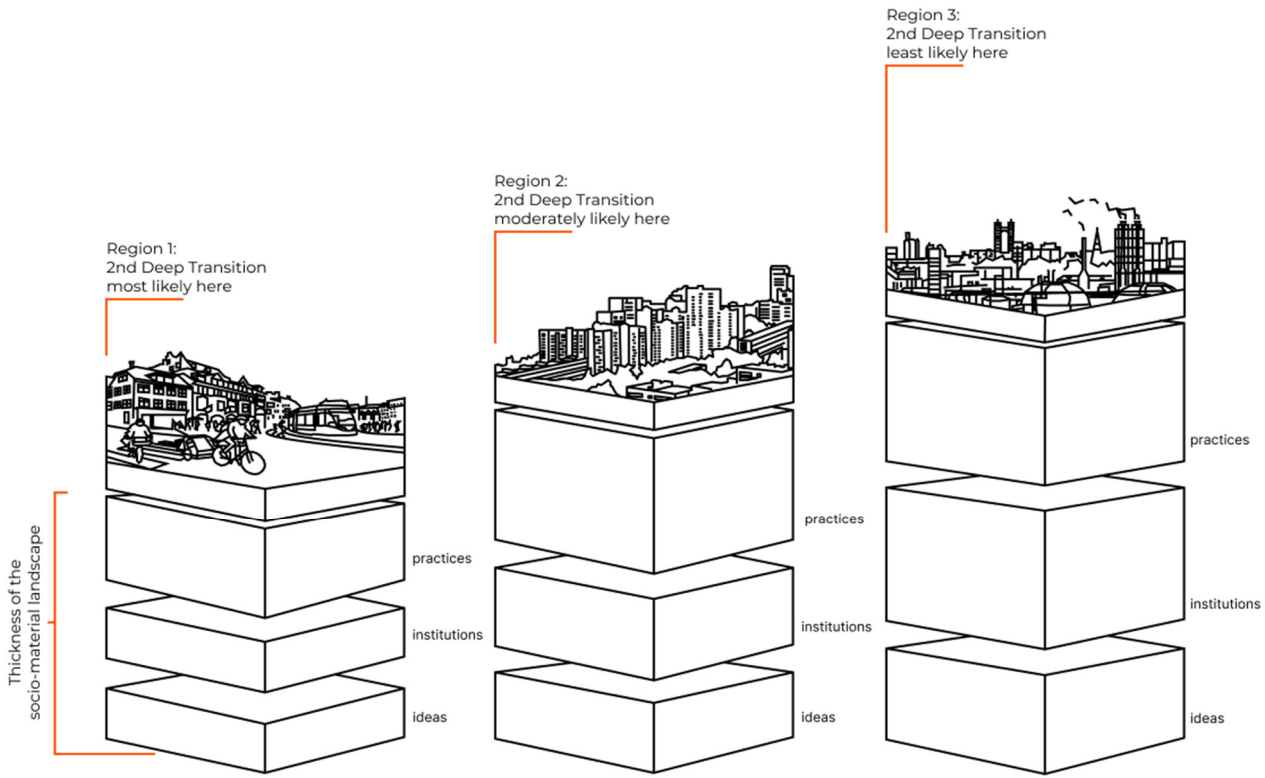

Figure 1. The socio-material landscape of industrial modernity (**STUDY III**: 3)

3. METHODOLOGICAL APPROACH

In this chapter, I will describe the methodological approach taken in my thesis to answer the research questions posed in the introductory chapter. Various quantitative methods were used depending on the studies' aims and the data used. The same or similar operationalisation rationale was used in all three empirical studies in my list of publications. However, it is important to note that the aims of **STUDIES I** and **II** differed from that of **STUDY III.** While the former sought to identify historical continuities and ruptures within industrial modernity, the latter aimed to measure the current makeup of the socio-material layer of industrial modernity. Consequently, the methodological approaches employed, and the data used to achieve these distinct objectives diverged to an extent. In this chapter, my approach will be to overview the methodological approaches taken and direct the reader to the original sources for detailed accounts. This chapter is structured as follows. First, I will outline the general considerations for measuring industrial modernity. Subsequently, I will detail the steps involved in operationalisation. Next, I will provide an overview of the methods used and data selection. I will then highlight my specific methodological contributions to the three studies, acknowledging the collaborative nature of this research. Finally, I will discuss the limitations of the three empirical studies.

3.1 General considerations

In all three empirical studies within my list of publications, the primary approach involved quantifying selected traits of industrial modernity. This process included developing 20 indicators (not including the alternative indicators developed for **STUDY II**; see Table 2 and Table 4 for an overview), all of which demanded multiple steps. A detailed description of these steps is beyond the scope of this thesis, as reproducibility requires a level of detail that would be excessive here. Instead, I will focus on the research design and more general considerations, referring back to the studies themselves for the detailed methodological steps.

A quantitative methodology was best suited to the objectives of my thesis, as it facilitated the examination of substantial datasets from multiple countries within a manageable timeframe, thereby enabling us to test the theoretical assertions of the DT framework. Additionally, we incorporated secondary sources such as historical and contemporary studies. These sources served a dual purpose: providing qualitative explanations for our quantitative findings and contextualising them, as the quantitative approach, while adept at discerning patterns in historical and time series data, can occasionally lack detailed insights (Hudson & Ishizu, 2016: 7, 144). The selection of specific methods used discussed in Section 3.3 was data driven. We presented the data per country (see Section 3.5 for a discussion on this approach).

The list of industrial modernity traits proposed by Kanger and Schot (2019) provided an initial framework for what *should* be measured. However, it quickly

became evident that a discrepancy existed between what *should* be measured and what *could* be measured, primarily due to limitations in secondary data availability. There is a scarcity of databases encompassing the traits of industrial modernity across the desired timeframe, particularly for the ideational and institutional dimensions. The World Values Survey (WVS) stands as the optimal data source for the ideational dimension, which gauges shifts in values; however, its records only extend back to the 1980s. This limitation did not hinder the measurement of the current state of industrial modernity (**STUDY III**); yet, the timeframe proved insufficient for analysing the evolution of industrial modernity (**STUDIES I-II**). Similarly, certain databases suitable for the institutional dimension (e.g., The Manifesto Project, V-dem) either concentrate on the same timeframe as the WVS, lack coverage in the Global South, or simply do not contain data pertinent to the measured traits of industrial modernity. Consequently, we utilised existing databases wherever possible and developed custom (text mining) indicators to bridge the gaps caused by the lack of longitudinal ideational and institutional data. Not only did this step create novel primary measurements, but it is also *the* step that allowed us to create the desired holistic view of the evolution of industrialism and thus represents an important methodological contribution of my thesis.

The selection protocol for databases and digitised newspaper data used for text mining involved striking a balance among availability, potential content bias (as evaluated by expert historians), and the temporal scope of the data source. Specifically for databases, our primary consideration was always large, reputable databases frequently used within the academic community, followed by smaller, country-specific data sources. This approach generally ensured the collection of data that was as consistent as possible, thereby enhancing the robustness of our measurements. When it came to newspaper data, we prioritised larger national newspapers with long histories to ensure continuous coverage from a single source for as long as possible. Only when there were caps in availability did we consider publications with smaller readerships.

3.2 Operationalising industrial modernity

We carried out the operationalisation of industrial modernity in three phases. In the first phase, we rearranged the traits of industrial modernity based on their general theme to three domains: the environment, science, and technology/innovation. We additionally articulated the traits into three dimensions – ideas, institutions, and practices – leaving us with a 3*3 matrix conceptualisation of the theoretical notion (see 2.2.2 Definition of industrial modernity for the rationale). In the second phase, I carried out a scoping review of potentially suitable databases containing data on environmental, scientific and technological ideas, institutions and practices to assess the traits that should be measured vs. traits that could be measured. This phase where we identified what could *not* be measured, mainly the evolution of the traits in the ideational dimension and, to a certain extent, the institutional dimension (i.e., measuring technocracy in **STUDY II**). This led us to the third phase, which was developing the specific indicators,

including developing text-mining indicators to overcome discrepancies in the ideational and institutional dimensions, as well as constructing indicators based on time series data. For **STUDY III**, this phase included the development and construction of the composite indicator. By doing so, we could measure at least one characteristic of industrial modernity for each dimension and domain (see Table 2 for the traits measured in **STUDIES I** and **II** and Table 4 for **STUDY III**).

3.3 Methods and data selection

STUDY I is considered the pilot **STUDY**; this is where we introduced the multi-dimension and multi-domain approach to measuring industrial modernity. We combined text mining and time series analysis to compile time series for each dimension in the domains of environment and technology/innovation (Table 2). **STUDY II** aimed to further detect historical continuities in industrial modernity by expanding the multi-dimension and multi-domain approach introduced in **STUDY I** by measuring traits in the domain of science. **STUDY II** also provided alternative measurements for each trait to check the descriptive accuracy of the time series. The alternative measurement involved using a different dataset (where possible) or other analysis techniques and thresholds if the underlying dataset remained the same (see Appendices A-C in **STUDY II** for a detailed overview). **STUDY II** additionally introduced quantitative thresholds for identifying breaks in the evolution of industrial modernity (see Section 3.3.3). **STUDY III** again applied the multi-dimension and multi-domain schema (Table 4) to introduce a novel composite indicator for comparing the historical legacy of industrial modernity in 63 geographically diverse countries (refer to Section 3.3.5 Country selection for the selection rationale) across the Global North/South divide (see Figure 2). Using the dimensions of industrial modernity, the indicator allows for the assessment of possible future pathways (as the measures of ideas and institutions describe the possible aspirations of the country) and the current behaviour (practices). The index allows for country-level ranking and comparison according to each dimension and domain, revealing both the opportunities to transform industrial modernity and possible hindrances (see 3.3.4 Composite indicator for an overview of the index construction).

3.3.1 Text mining

Text mining allows for analysing the prevalence of a particular discourse by tracking the frequency of the keywords associated with the topic within the corpus. **STUDIES I** and **II** operationalised the traits of industrial modernity through the text mining of digitised newspaper and other media outlet articles, more precisely, keyword frequency analysis (cf. Lansdall-Welfare et al., 2017; Michel et al., 2011) and topic modelling (Boyd-Graber et al., 2017). We additionally measured the sentiment in the text snippets compared to the baseline levels within the entire corpus in the countries' news media (see Table 2). The

detailed workflow based on the current best practices for text mining is available in Appendix C in **STUDY I** and Appendices A and B in **STUDY II**.[2] I discuss the limitations of using text mining in Section 3.4 Limitations. Text mining was applied in **STUDIES I** and **II** to measure ideational and, to an extent, institutional change due to sparsities detected in the second operationalisation phase. In both studies, text mining was used to measure the prevalence and sentiment of environmental, science, and technology-related discourses. In **STUDY II**, text mining was also used to assess the prevalence of technocratic decision-making (for more details, see Table 2; for limitations of this approach, see Section 3.4). Table 2 overviews the traits measured, the indicators, their interpretations, and the data sources used, including the specific newspapers from each country analysed.

[2] In the interest of maintaining focus on the more general methodological considerations and research design (see Section 3.1), I opted not to provide an exploration of the text mining workflow within my thesis as it was not a part of my methodological contribution (see Section 3.4 My methodological contribution).

Table 2. Operationalisation of industrial modernity in **STUDIES I** and **II**

Dimension ↓	**Domain →**	**Natural environment**	**Science**	**Technology & innovation**
Ideas	**Trait**	**STUDIES I–II** Separation of nature and society, placing primary emphasis on the latter in public discourse	**STUDY II** Belief in limitless progress through the application of science	**STUDIES I–II** Belief in limitless progress through the application of technology
	Indicator	The proportion of keywords denoting 'technology' vs. 'environment' in newspapers and journals	Sentiment of text excerpts containing keywords denoting 'science', 'science AND technology', 'science AND environment' vs. average sentiment in country's newspapers and journals	The sentiment of text excerpts containing keywords denoting 'technology' or 'technology' and 'environment' vs. the average sentiment in newspapers and journals
	Interpretation	Discourse on technology was associated with continuity in industrial modernity (reflecting its status as a valued domain), whereas a rise in environmental discourse would indicate a possible rupture (increasing attention to environmental concerns)	The higher-than-average sentiment toward science was associated with industrial modernity (reflecting optimism in scientific advances), whereas a comparatively lower sentiment of 'science-environment' would indicate a possible rupture (doubts about the possibility that science will provide solutions to all environmental challenges)	The higher-than-average sentiment toward technology was associated with continuity in industrial modernity (reflecting techno-optimism), whereas a comparatively lower sentiment of 'technology- environment' would indicate a possible rupture (doubts about the possibility of finding an easy techno-fix to major environmental challenges)
	Data	Australia: Sydney Morning Herald (1900–1954, 1996–2020), Canberra Times (1926–2020), The Age (1996–2020) Germany: Hamburger Allgemeine (1900–1945), Altonaer Nachrichten (1900–1941), Berliner Tageblatt (1900–1939), Hamburger Nachrichten (1900–1939), Zeit (1946–2019), Spiegel (1947–2018) India: The Times of India (1900–2020) USA: New York Times (1900–2020) USSR/Russia: Izvestia (1917–1991, 1995–2001), Pravda (1924–1978), Lenta.ru (1999–2019)		

Dimension ↓	Domain →	Natural environment	Science	Technology & innovation
Institutions	**Trait**	**STUDIES I–II** Prioritisation of societal over environmental concerns in institutional design (i.e., formal rules, legal and regulatory provisions)	**STUDY II** The dominance of technocratic reasoning and decision-making in policy circles	**STUDIES I–II** Largely reactive approach: institutions are mainly directed at regulating the consequences of technological innovation
	Indicators	A. **STUDIES I–II** Country membership in major international intellectual property-related treaties vs. environmental treaties, number of national environmental regulations B. **STUDY I** The themes of technology/growth in party platforms mostly dominate over environment/anti-growth and sustainability (post-WWII era)	The proportion of keywords denoting 'technocratic' discourse in the country's newspaper and journal articles mentioning policymaking vs. the country's score on the Participatory Democracy Index (PDI)	The relative share of the country's reactive, conservation-oriented, and proactive environmental regulations
	Interpretations	A. **STUDIES I–II** Intellectual property-related treaties were associated with continuity in industrial modernity (importance of regulating technological innovation), whereas the rise of environmental institutions would indicate a possible rupture (institutionalisation of environmental concerns)	Changes in the position of the two scores relative to each other were interpreted as one or the other being the dominant approach to policy-making: a change where technocratic discourse increased while the Participatory Democracy Index (PDI) score remained stable or decreased was associated with industrial modernity, whereas the opposite would indicate a possible rupture (involving citizens more in the decision-making)	Reactive and conservation-oriented regulations were associated with continuity in industrial modernity (addressing already occurred impacts or preventing the known impacts from spreading elsewhere), whereas proactive regulations would indicate a possible rupture (regulatory stress on anticipation)

Dimension ↓	Domain →	Natural environment	Science	Technology & innovation
		B. **STUDY II** Technology and growth-related themes were associated with continuity in industrial modernity (reflecting the importance of technology and technology-led growth), whereas the rise in environmental protection, anti-growth, and sustainability themes would indicate a possible rupture (increasing emphasis on alternative foci of policymaking)		
	Data	WIPOLex (intellectual property-related treaties), ECOLEX (environmental treaties and regulations), Manifesto (party platforms)	See 'Ideas' for textual sources; V-Dem (participatory democracy)	ECOLEX (environmental regulations)
Practices	**Trait**	**STUDIES I–II** Specific socio-metabolic profile: 'mineral', fossil fuel-based, and linear economy	**STUDY II** Sporadic and unsystematic application of precautionary principles to prevent the ethical, social and environmental risks involved in basic scientific research	**STUDIES I–II** The overall directionality of innovative activities and the actual use of technology is largely indifferent to environmental concerns
	Indicator	Share of fossil fuel vs. renewable energy production per capita in the country's energy mix	Share of scientific publications tagged with 'sustainability AND engineering' from the country's total engineering publications	Share and per capita count of green patents from the country's overall patents per capita

Dimension ↓	Domain →	Natural environment	Science	Technology & innovation
	Interpretation	The absolute increase in energy production and a large share of fossil fuels were associated with continuity in industrial modernity (typical socio-metabolic profile of industrial societies), whereas a rise in the share of renewables would indicate a possible rupture (changing resource base of societies)	An increase in the number of engineering publications was associated with industrial modernity, whereas a rise in the share of publications mentioning sustainability would indicate a possible rupture (a new direction in the engineering science)	An absolute increase in the number of patents was associated with continuity in industrial modernity (continued emphasis on technological innovation), whereas rise in the share and per capita count of green patents would indicate a possible rupture (changing direction of innovative activities)
	Data	Etemad and Luciani (1991), 1900–1980, and U.S. Energy Information Administration, 1980–2016, made available by The Shift Project; Maddison Project Database (2020) and Gapminder (population)	Microsoft Academic	PATSTAT (patents), Maddison Project Database (2020) and Gapminder (population)

3.3.2 Time series analysis

For most traits of industrial modernity measured, we used time series data, which enabled us to not only identify trends over time but also measure a particular phenomenon at a specific period of interest.

In **STUDIES I** and **II**, for the institutional dimension, we utilised several resources. Namely, we used WIPO Lex, a database comprising treaties related to intellectual property (WIPO, n.d.). ECOLEX, gathering data on environmental treaties and regulations (ECOLEX, n.d.). The Manifesto Project database analysing political party platforms (Volkens et al., 2021) and lastly, V-Dem providing data on participatory democracy (Coppedge et al., 2021). In the practices dimension, we used data made available by The Shift Project (The Shift Dataportal, n.d.), combining Etemad and Luciani (1991) and U.S. Energy Information Administration data on energy production, Microsoft Academic data (Microsoft Research, n.d.) on engineering publications, and PATSTAT (2020 Spring Edition) data on patenting (see Table 3 for descriptions). Where mentioned, **STUDIES I** and **II** used population estimates from the Maddison Project Database (Bolt & Van Zanden, 2020). We complemented the Maddison Project Database estimates with data from Gapminder (Gapminder, n.d.). We used these sources for population data as these cover the timeframe of our interest. Table 2 overviews the indicators constructed using these data sources and their interpretation along with the traits of industrial modernity measured.

Table 3. Databases used in **STUDIES I-III**

Database	Description	Used in
WIPO Lex	WIPO (n.d.) describes the WIPO Lex as an extensive database that encompasses international intellectual property laws from approximately 200 jurisdictions.	**STUDIES I** and **II**
ECOLEX	ECOLEX is a globally accessible environmental law information service under the joint operation of the Food and Agriculture Organization of the United Nations, the International Union for Conservation of Nature, and the United Nations Environment Programme (ECOLEX, n.d.).	**STUDIES I–III**
The Manifesto Project Database	The Manifesto Project Database represents a comprehensive database encapsulating political manifestos and electoral performance (Volkens et al., 2021).	**STUDIES I** and **II**
V-Dem	V-Dem offers a multidimensional and disaggregated dataset that encapsulates the intricate nature of the concept of democracy as a system of governance that transcends the mere existence of elections (Coppedge et al., 2021).	**STUDY II**
The Shift Project	The Shift Project is a French think tank that advocates for the transition to a post-carbon economy (The Shift Dataportal, n.d.). The energy production data used in **STUDIES I** and **II** consist of data collected by Etemad and Luciani (1991) for the years 1900–1980 and U.S. Energy Information for the rest of the observation period.	**STUDIES I** and **II**
The Maddison Project Database	The project draws upon the initial dataset assembled by economist Angus Maddison to refine or rectify the historical economic data based on updated information (Bolt & Van Zanden, 2020). Data pertaining to population, gross domestic product (GDP), and per capita GDP are presented by country, small country groupings, regions, and the world, with a historical scope extending back to the Roman era.	**STUDIES I** and **II**
The Gapminder Foundation Database	The Gapminder Foundation serves as a non-profit organization dedicated to fostering sustainable global development and the attainment of the United Nations Millennium Development Goals (Gapminder, n.d.). Its database contains pertinent information pertaining to	**STUDIES I** and **II**

Database	Description	Used in
	social, economic, and environmental development occurring at local, national, and global levels.	
Microsoft Academic	Microsoft Academic search engine and database identify and catalogue authors, institutions, keywords, and scientific journals, and subsequently makes the compiled dataset accessible as open data (Microsoft Research, n.d). The search engine indexes in excess of 260 million publications, of which 88 million constitute journal articles.	**STUDY II**
PATSTAT	PATSTAT database encompasses bibliographical and legal event patent data procured from industrialised and developing nations. This data is extracted from the repositories of the European Patent Office.	**STUDIES I–III**
World Values Survey	The World Values Survey is an international research endeavour that examines the values and beliefs held by individuals, as well as their stability or transformation over time (Haerpfer et al., 2020). It investigates the influence these values and beliefs exert on the societal and political development of various nations worldwide.	**STUDY III**
Global Material Flows Database	The Global Material Flows Database serves as a repository of data that aids governments, policy analysts, and other concerned entities in comprehending and tracing the connections between economic progress and the consumption of raw materials (UNEP, 2016).	**STUDY III**
FAOSTAT	The Food and Agriculture Organization's statistical database, known as FAOSTAT, encompasses a comprehensive range of interconnected sections (FAO, 2020). These sections include agricultural production, trade, consumption of agricultural products, agricultural prices, resources, employees, forestry, and fishery.	**STUDY III**
Web of Science	The Web of Science Core Collection encompasses bibliographic records of scholarly articles drawn from the most impactful journals worldwide—inclusive of open access journals—as well as conference proceedings and comprehensive books (WoS, n.d.). The coverage of certain titles extends back to the year 1900, providing a rich historical archive.	**STUDY III**

Our choice of analysis and visualisation methods was data-driven. We utilised the generalised additive model for most time series created to smooth the time series data and manage missing data points or outliers. For intellectual property rights and environmental treaties data, we calculated the cumulative proportion of treaties joined by each country and presented the changes in this proportion over time. For energy production data, we calculated the share of each energy source from the total energy production at the given time and presented the data using stacked area charts to visualize the different proportions. In **STUDY I**, a more detailed account of the methods used and the related methodological choices are available in Section 3, "Data sources and methods," and Appendices A-C. For a discussion of these choices in **STUDY II**, refer to Section 3, Research design and methods, and Appendices A-C.

STUDY III similarly utilised time series data. In the ideational dimension, we used items from the WVS (Haerpfer et al., 2020). In the institutional dimension, we combined Global Innovation Index (WIPO, 2022) and Environmental Performance Index (EPI, 2022) data to assess the quality of environmental regulations. We also utilised the indicator we constructed for the purposes of **STUDIES I** and **II** based on environmental regulation data from ECOLEX in this dimension. In the practices dimension, we used data from the International Energy Agency (IEA, 2020) to estimate the share of fossil fuels from the Total Energy Supply, Global Material Flows Database (UNEP, 2016) data on Direct Material Input, land use data from the FAOSTAT (FAO, 2020), country-specific data sources on vehicles (see Table B2 in Appendix B of **STUDY III** for a complete list of sources), Web of Science data (WoS, n.d.) on scientific publications and PATSTAT (PATSTAT, version 2020a) data on patenting (see Table 3 for descriptions). In **STUDY III**, we used population data from the United Nations for the per capita measurements. We used the most recent data available for all data sources. Where there were significant fluctuations in the annual data, we combined data from multiple recent years for a median estimate. The latter includes data on environmental regulations, scientific publications, and patenting. The specific years and periods used, the indicators constructed, their interpretations, and the traits of industrial modernity measured are available in Table 4. For a more detailed overview of operationalisation and indicator calculation, see Section 3. Methods and data in **STUDY III**. I overview the composite indicator construction in Section 3.3.4 Composite indicator.

Table 4. Operationalisation of industrial modernity in **STUDY III** (based on **STUDY III**)

Dimension ↓	**Domain →**	**Natural environment (ENV)**	**Science, technology, and innovation (STI)**
Ideas	**Trait**	Instrumental view of nature	Highly exaggerated beliefs about the societal impacts of science and technology
	Indicator	Share of respondents prioritising economic growth and more jobs over protecting the environment	Share of respondents giving extreme answers ("Strongly disagree", "Strongly agree") with the statement "Science and technology are making our lives healthier, easier, and more comfortable"
	Interpretation	A higher share of respondents choosing economic growth and more jobs even if the environment suffers was interpreted to be characteristic of industrial modernity (reflecting the instrumental view of nature) and thus was interpreted as more industrial modernity.	The extent to which respondents held extreme views on the potential of science and technology was interpreted as indicative of industrial modernity. A relatively higher share of respondents who held dystopian (i.e., dismissive) and utopian (i.e., uncritical) views on the potential of science and technology was interpreted as characteristic of industrial modernity.
	Data	World Values Survey, 6th (2010-2014) and 7th wave (2017-2020)	
Institutions	**Trait**	Prioritisation of societal over environmental concerns in institutional design	Institutions are mainly directed at regulating the consequences of technological innovation
	Indicator	The relative performance of the country's innovation-supporting vs. environmental institutions	The share of the country's environmental regulations that are not proactive from overall environmental regulations

Dimension ↓	Domain →	Natural environment (ENV)	Science, technology, and innovation (STI)
	Interpretation	An institutional design where innovation-supporting institutions outperform environmental institutions and/or the latter are of low quality was interpreted to be characteristic of industrial modernity.	The share of non-proactive regulations (addressing already occurred impacts or preventing the known impacts from spreading elsewhere) was associated with industrial modernity.
	Data	Global Innovation Index (GII), Environmental Performance Index (EPI) (2022)	ECOLEX (2007-2017)
Practices	**Trait**	Specific socio-metabolic profile: 'mineral', fossil fuel-based and linear economy	The overall directionality of innovative activities and the actual use of technology is largely indifferent to environmental concerns
	Indicators	**A.** Share of fossil fuels from the country's Total Energy Supply (TES) **B.** Direct material input (domestic extraction and import, DMI) per capita	**A.** Share of agricultural land not under organic agriculture from total agricultural land **B.** Number of motor vehicles per capita **C.** The geometric mean of the share of non-sustainability-related publications of total publications and non-sustainability-related publications per capita **D.** The geometric mean of the share of patents not related to climate change mitigation technologies (CCMT) of total patents and non-CCMT related patents per capita
	Interpretations	**A.** A higher share of fossil fuels in the TES was interpreted to be characteristic of industrial modernity. **B.** Higher DMI per capita was interpreted to be associated with industrial modernity.	**A.** A higher share of agricultural land was interpreted to indicate intensive agricultural practices associated with industrial modernity. **B.** A higher number of vehicles per capita was interpreted as the use of technology indifferent to environmental concerns.

Dimension ↓	Domain →	Natural environment (ENV)	Science, technology, and innovation (STI)
			C. A higher combined share and per capita measure of non-sustainability-related publications was understood as a measure of scientific research not concerned with the environment. **D.** A higher combined share and per capita measure of non-CCMT patents was understood as a measure of innovative activities not concerned with the environment.
	Data	**A.** Fossil fuels in TES: International Energy Agency (2020) **B.** DMI per capita: Global Material Flows Database (2015), United Nations (population)	**A.** Land use: FAO (2019) **B.** Vehicles per capita: various country-level sources, last available year, United Nations (population) **C.** Scientific publications: Web of Science (2014-2018), United Nations (population) **D.** Patents: PATSTAT (2007-2017), United Nations (population)

3.3.3 Ruptures

In **STUDY I**, we identified three types of ruptures in industrial modernity:

- slow-moving changes in the time series data trends, such as constant discourse on the topic of the natural environment but a change in the discussion sentiment;
- the emergence of a new trend, for example, the emergence and ratification of environmental treaties,
- and the sharp acceleration of a new trend, such as the acceleration of the number of green patents per capita in a particular country.

In **STUDY II**, we furthered the approach of **STUDY I** by formally defining eight changepoints detected based on the visual inspection of the time series. The eight changepoints included three from the ideational dimension, two from the institutional dimension, and three from the practice-related dimension. Table 5 overviews these (for a more detailed account, see Appendix E in **STUDY II**). Although the general strategy was to rely on data-driven analysis, supporting evidence from existing literature and the expert judgement of the research team to determine substantive ruptures (for a more detailed explanation, see Appendix E in **STUDY II**). I will examine the ruptures in context in Section 4.1 The continuities and ruptures.

Table 5. The types of ruptures detected in the related time series (based on **STUDY II**)

Type of rupture	Time series	Detection method
The onset of rapid growth	Frequency of environment-related keywords	Testing for multiple structural breaks (Bai & Perron, 1998, 2003): acceleration of continuous growth
	Growth in patents related to climate change mitigation technologies	
Trends reaching a certain threshold (used for more gradual or just emerging trends)	Sentiment of the environmental discourse	Sentiment crossing the baseline of the text corpus, going from positive to negative
	Proactive environmental regulations	The proportion of proactive environmental regulations crossing the 16.7% threshold (Rogers, 2003)
	Renewable energy	Primary energy production crosses the 16.7% threshold (Yang et al., 2020)
	Sustainability-oriented engineering publications	Emergence

Type of rupture	Time series	Detection method
The reversal in the mutual relation of two trends*	Sentiment towards science and technology	Comparing the LOESS model fits for the z-scores of the sentiment towards science to that of technology: technology and innovation surpassing science
	Adoption of major environmental treaties	Using Normal Reference Distribution: conditional density of environmental treaties exceeding 50% for at least five consecutive years (Scott, 1992)

Note. *While this approach was also potentially applicable to technocratic vs. participatory institutions, we did not find any discontinuities here.

3.3.4 Composite indicator

In **STUDY III**, we combined the measurements of the traits of industrial modernity into a novel composite indicator – the Industrial Modernity Index (IMI). Composite indicators combine a number of individual indicators and are frequently used for summarising complex and multi-dimensional issues (Freudenberg, 2003; OECD, 2008). Similarly to **STUDIES I–II**, the IMI conceptualises industrial modernity, distinguishing between three dimensions (ideas, institutions, and practices). However, for substantial and practical considerations, we combined the domains of science and technology/innovation (see Section 2.2.3 for the rationale). The 3*2 matrix conceptualisation allowed us to obtain dimension and domain scores in addition to the final aggregate.

The IMI construction follows the composite indicator construction steps proposed by the Organisation for Economic Co-operation and Development (OECD, 2008). Table 6 outlines the OECD guidelines, the steps taken to construct the IMI, and the rationale behind these steps (a more detailed account is available in Section 3. Methods and data in **STUDY III**). Additionally, we assigned the countries studied into clusters using k-means clustering (Hartigan & Wong, 1979) based on the more restricting dimensions for each country, i.e., dimensions contributing the most to the country's IMI score, thereby hindering its potential for major transformative change. A country scoring 100 would signify the highest level of structural constraints, indicating a lower likelihood for a country to implement a deep sustainability turn. Conversely, a country scoring 0 would represent the fewest constraints, suggesting a greater chance for a country to undertake a deep sustainability turn.

Table 6. The IMI construction following the OECD (2008) guidelines

	Steps for constructing composite indicators	**The IMI**
1	Deciding on a theoretical framework to guide the selection and combination of variables to be measured	DT framework and the notion of industrial modernity, which combines multiple dimensions (ideas, institutions, practices) and domains (natural environment, technoscience). These dimensions and domains constituted the underlying scheme for the IMI.
2	Selecting indicators that are analytically sound, relevant to the phenomenon being measured, and covering a number of countries fitting to the aim of the composite indicator. Accounting for the relationship between the indicators.	Balancing between what should be measured and what could be measured, we chose ten indicators measuring six traits of industrial modernity. We analysed data from 63 countries (see s Section 3.3.5 Country selection for country selection principles). We accounted for the relationship between indicators using Spearman's rank correlation coefficients and excluded indicators with a strong positive relationship measuring the same trait.
3	Imputing for missing data to achieve a complete dataset	As **STUDY III** was the first time presenting the IMI, we did not impute for missing data but limited our country coverage to the number of countries where a complete dataset was available (N = 63).
4	Analysing the overall structure of dataset to find the underlying scheme for the composite indicator	We used the conceptual schema of industrial modernity introduced in **STUDIES I-II**; thus, the IMI is a theory-driven composite indicator.
5	Normalising data to render the variables comparable	We distinguished between two types of indicators in constructing the IMI: those with logical and theoretically justifiable maximum/minimum values and a natural range [0, 100] suitable for composite indicator construction, and those either without justifiable maximum/minimum values or with an incomparable range. The first group we left as is, and the second we normalised using log-transformation, z-scores, and min-max transformation.

	Steps for constructing composite indicators	The IMI
6	Weighing and aggregating the data along the lines of the theoretical framework chosen in the first step	As the DT framework does not deem any single trait of industrial modernity more significant than the other, we assigned all the indicators, dimensions, and domains equal weight. The weight of each indicator was based on the number of indicators measuring the same trait; e.g., if two indicators measure the same trait, they each receive a weight of 0.5. Each dimension received a weight of 0.33, as there were three dimensions. Each domain had a weight of 0.5, as there were two domains. We used additive aggregation as the indicators, dimensions, and domains were allowed to compensate for one another fully.
7	Assessing the robustness of the composite indicator in terms of the normalisation scheme, the imputation of missing data, the choice of weights, and the aggregation method	We performed an analysis of sensitivity to removing indicators and aggregates and an uncertainty analysis of the chosen normalisation scheme (see Appendix C in **STUDY III** for more details). We did not assess robustness to imputation as we used a complete dataset; the choice of weight and aggregation methods, as the underlying theoretical framework defined these, and changing them would not be in accordance with the framework.
8	Demonstrating what makes a country perform well or badly	We both showed and described the overall country ranking as well as performance per each dimension and domain (see Section 4.2).
9	Comparing the composite indicator with other relevant composites or simple indicators	We compared the IMI with the Gini index, Social-environmental index, Ecological footprint, per capita GDP, Sustainable Development Index, and Human Development Index (see Section 4.2).
10	Visualising the results	We visualised the results using maps and custom country profiles (see Section 4.2).

3.3.5 Country selection

STUDIES I–III had to balance data availability restrictions and achieving diversity[3] in the range of countries included in the analysis. Text mining data presented the primary restriction for **STUDIES I** and **II** because only a limited set of historical newspapers were digitised and available to us. Moreover, applying text mining requires a certain level of language proficiency, thus limiting us to the project teams' language skills (see Section 3.4 for further discussion of these issues). Despite these limitations, we could analyse data from a satisfactory range of countries. **STUDY I** analysed data from Australia, Germany, and the USSR/ Russia and **STUDY II** broadened the scope of **STUDY I** by introducing two additional G20 countries: India and the United States of America. Table 7 provides a comparative diversity assessment of the five countries.

[3] Our assumption here was that if countries with very different profiles display similar historical trends regarding the emergence and development of industrial modernity, then the empirical relevance of the concept can be validated.

Table 7. Comparison of countries included in **STUDIES I–II** (**STUDY II**: 4)

	Australia	**Germany**	**India**	**USA**	**USSR/Russia**
Total population in thousands (% share of the global population)[1]	25 500 (0.33)	83 784 (1.07)	1 380 004 (17.7)	331 003 (4.25)	145 934 (1.87)
GDP in trillion current US$ (% share of global GDP)[2]	1.33 (1.57)	3.85 (4.55)	2.62 (3.1)	20.94 (24.75)	1.48 (1.75)
Total primary energy production in EJ (% of global production)[3]	9.11 (2.95)	4.8 (0.74)	18.09 (2.79)	107.48 (16.6)	68.14 (10.52)
Economy[4]	Liberal market economy	Coordinated market economy	Statist market economy	Liberal market economy	Planned economy shifting to patrimonial market economy
Polity[5]	Liberal democracy	Liberal democracy	Liberal democracy	Liberal democracy	Communist ideocracy shifting to electoral autocracy
Culture[6]	Secular/ self-expression	Secular/ self-expression	Traditional/ survival	Secular/ self-expression	Secular/survival
Time of industrialization[7]	Second phase	First phase	Third phase	First phase	Second phase

[1] Data source: UN (2022). Shares are rounded to two decimal points.
[2] Data source: World Bank (2022). Shares are rounded to two decimal points.
[3] Data source: EIA (2022). Shares are rounded to two decimal points.
[4] Based on an expanded Varieties of Capitalism typology, which includes emerging economies (Schedelik et al., 2021). Classification refers to the type dominant for most of the observation period.
[5] Based on Kailitz's typology of political regimes (Kailitz, 2013). Classification refers to the type dominant for most of the observation period.
[6] Data source: The Inglehart-Welzel World Cultural Map (2020)
[7] Based on Stearns's (2013) periodisation: 1) first phase, 1760-1880; 2) second phase, 1880-1950; 3) third phase, 1950-2000s.

For the composite indicator construction in **STUDY III**, we only included countries where complete data for the most recent period could be obtained, with the WVS essentially defining the achieved coverage. As such, **STUDY III** includes 63 countries with a good spectrum of diversity in geography and national income (Figure 2).

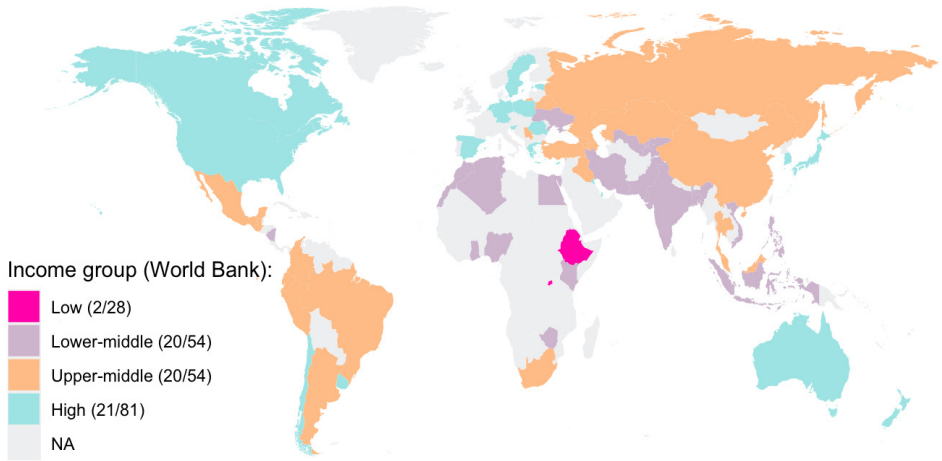

Figure 2. World Bank income estimates for countries included in **STUDY III**
Note. For the current 2023 fiscal year, low-income economies are defined as those with a GNI per capita lower than $1,086, lower-middle-income economies between $1,086 and $4,255; upper-middle-income economies between $4,256 and $13,205; high-income economies with a GNI per capita of $13,205 or more. On the legend, the numbers in the brackets signify the number of countries in our sample vs the group size. NA represents countries not studied. Data source: https://datahelpdesk.worldbank.org/.

3.4 My methodological contribution

Having overviewed the general methodological steps taken in each study in my list of publications, I will now elaborate on my methodological contribution specifically. Table 8 describes the contributions in the context of **STUDIES I–III**[4]. My general contribution to the published manuscripts is available in the List of original publications.

[4] Since **STUDY IV** is a perspective paper, it is not included here.

Table 8. My methodological contribution to **STUDIES I–III**

Contributions	**STUDY I**	**STUDY II**	**STUDY III**
Conducting a scoping review to identify potential data sources	General web search for available databases as well as going through the literature to identify databases used by other studies in related fields		
Operationalising industrial modernity	Participated in constructing the multi-dimension and multi-domain approach to measure industrial modernity and operationalising specific traits		
Constructing time-series data-based indicators	Constructed indicators for measuring the trait *Prioritisation of societal over environmental concerns in institutional design* in the institutional dimension and the trait *Specific socio-metabolic profile: 'mineral', fossil fuel-based, and linear economy* in the dimension of practices (**STUDIES I-II),** patenting activity for the measurement of the trait *The overall directionality of innovative activities and the actual use of technology is largely indifferent to environmental concerns* in the dimension of practices and the time series analysis using the Participatory Democracy Index for the measurement of the trait *Dominance of technocratic reasoning and decision-making in policy circles* (**STUDY II**). I lead the development of all indicators constructed **in STUDY III**		
Categorising data for analysis	Categorised the keywords and described the categories for the measurement of the trait *Largely reactive approach: institutions are mainly directed to regulating the consequences of technological innovation* in the institutional dimension		
Compilation of relevant data conducting time-series analysis	Gathered, cleaned, and compounded data for analysis based on the indicator construction rationale developed for the traits mentioned. I also conducted the analysis to create the respective time series		Analyses for the IMI construc-tion and validation (see Table 4 for an overview) and the calcu-lations for the final aggregates

Contributions	**STUDY I**	**STUDY II**	**STUDY III**
Explaining the quantitative findings	Contributed to the collaborative process of explaining the quantitative time series in all five countries analysed		Responsible for explaining all findings
Identification of structural breaks in the time series to detect potential ruptures	–	The analysis for the frequency of environment-related keywords and growth in patents related to climate change mitigation techno-logies (see Table 4). I additionally contributed to finding suitable techniques for identifying breaks in the other time series	–
Conceptualisation and construction of the composite indicator	–	–	Collaborative process on deciding on the IMI structure, the choice of weights, norma-lisation, and aggregation

Note. – Does not apply.

3.5 Limitations

Measuring a novel theoretical concept comes with limitations, which can be classified into three categories: limitations regarding operationalisation, data availability, and methods applied.[5] In this section, I will overview the more significant limitations regarding each category.

First, subjectivity remains inherent to indicator selection. To address this, we conducted an exhaustive search for databases containing relevant information on the traits of industrial modernity (see Section 3.1 for an overview). Additionally, we introduced alternative measures for each indicator in **STUDY II**. Table 9 details these alternatives, as well as other approaches considered but ultimately not used, for transparency. In retrospect, I recognise there were also alternatives that we simply did not think of or consider at the time. For example, for measuring if the societal is prioritised over environmental concerns in institutional design, assessing the size of environmental against other government institutions using staff and budget measures and year of establishment could be possible. This would be particularly relevant for **STUDY III** since the composite indicator measured the current makeup of industrial modernity and would not demand collecting historical data. Additionally, evaluating national policies on waste management, wastewater treatment, and pollution reduction could provide further insights. For measuring technocracy, similar indicators could be constructed based on the size and year of establishment of technical universities or relative size of government institutions per capita. While some of these alternatives might have been preferable, data availability constraints often limited their use, as illustrated in Table 9. Nevertheless, future research on industrial modernity should revisit the metrics chosen, as the examples provided highlight the potential for further refinement. Allocating more resources for historical data collection and conducting updated database searches as new resources become available could also improve operationalisation.

[5] The inventory is available in Appendix B of **STUDY I**, and many of the limitations described also apply to **STUDIES II** and **III**.

Table 9. Examples of the alternative approaches to measuring industrial modernity, considered but not utilised in the research

Traits of industrial modernity	Alternative approach	Applicable	Reason for not using
Separation of nature and society, placing primary emphasis on the latter in public discourse; Belief in limitless progress through the application of science; Belief in limitless progress through the application of technology	Measuring change in ideation and values based on survey data	**STUDIES I–II**	Data not available for most of the observation period
	Using articles as a unit of analysis instead of recognised tokens	**STUDIES I–II**	Produced similar results to the approach chosen; data availability limitations for the countries analysed. See Appendix B2 in **STUDY** II for the analysis
	Using various "off-the-shelf" lexicons	**STUDIES I–II**	Produced similar results to the approach chosen; however, the literature supports constructing own lexicons as these produce the best results (Chan et al., 2021). See Appendix B3 in **STUDY II** for the analysis and a further discussion
Belief in limitless progress through the application of technology	Measuring the sentiment of mentions of specific technologies	**STUDIES I–II**	Initial tests that resulted in similar results to the more general keywords used; out of scope as the approach would call for the development of a novel methodology
Prioritisation of societal over environmental concerns in institutional design (i.e., formal rules, legal and regulatory provisions)	Assessing the balance between techno-economic and sustainability-oriented policy positions based on coverage in party platforms	**STUDIES I–III**	Data not available for most of the observation period and for all countries analysed. See Appendix C3 in **STUDY II** for the analysis and a further discussion. The indicator was eliminated from STUDY III as it showed strong correlation with another indicator. See Appendix C in **STUDY III** for the analysis.

Traits of industrial modernity	Alternative approach	Applicable	Reason for not using
	Using different thresholds for which environmental and intellectual property related treaties are considered major	**STUDIES I–II**	Same or similar patterns still present. See Appendix C1 in **STUDY II** for the analysis and a further discussion
The dominance of technocratic reasoning and decision-making in policy circles	Using a text mining only approach to measuring technocracy	**STUDIES I–II**	Strong bias likely for authoritarian and colonial countries. See Appendix C2 in **STUDY II** for the analysis and a further discussion
Specific socio-metabolic profile: 'mineral', fossil fuel-based, and linear economy	Assessing the direct material input in each country	**STUDIES I–II**	Data not available for most of the observation period and/or for all countries in the sample
	Assessing circular economy statistics	**STUDIES I–III**	Data not available for most of the observation period and/or for all countries in the sample
	Assessing resource productivity statistics	**STUDIES I–III**	Data not available for most of the observation period and/or for all countries in the sample
	Assessing material stocks and flows	**STUDIES I–III**	Historical disaggregated country-level data not available
Sporadic and unsystematic application of precautionary principles to prevent the ethical, social and environmental risks involved in basic scientific research	Using different confidence thresholds of the used tag associations	**STUDY II**	Did not affect the results. See Appendix D2 in **STUDY II** for the analysis and a further discussion
	Assessing funding allocated to research applying the precautionary principle	**STUDY II**	Data not available

Traits of industrial modernity	Alternative approach	Applicable	Reason for not using
The overall directionality of innovative activities and the actual use of technology is largely indifferent to environmental concerns	Using another patent database	**STUDIES I–III**	PATSTAT is widely recognised as the most comprehensive patent database
	Using another inventory to detect green patents, such as the IPC Green inventory	**STUDIES I–III**	IPC Green Inventory has a greater chance of resulting in false hits, i.e. the inclusion of many non-green patents (Veefkind et al., 2012). See Appendix D3 in **STUDY II** for the analysis and a further discussion
	Assessing data on electric vehicles	**STUDY III**	Data not available for most countries analysed; initial tests showed strong correlations with green patenting. See Appendix C in **STUDY III** for the analysis

Second, the lack of longitudinal data and limitations regarding country coverage beyond the Global North significantly affected country selection (see Section 3.3.5). The former was especially apparent for measuring the traits in the ideational dimension in **STUDIES I** and **II**. As I explained in the operationalisation section of this chapter (3.2 Operationalising industrial modernity), no longitudinal (1900-2020), survey data was available to measure the traits in the ideational dimension, so we applied text mining in **STUDIES I** and **II**. We additionally applied text mining in the institutional dimension to measure the extent of technocratic reasoning in **STUDY II**. There are two major considerations for using text mining, and the effect of these diverges depending on whether it is applied to the ideational or institutional dimension. Media discourse is not a direct measurement of public opinion. However, Neresini and Lorenzetsini (2016) show that it can be used as a proxy for public opinion, as the results of media discourse analysis using text mining tend to correlate highly with survey data on the same phenomena. This proxy relationship may not be as straightforward in authoritarian and colonial countries. Instead, here, media discourse tends to reflect the officially approved ideology of the ruling elite (McQuail & Deuze, 2020; Siebert et al., 1956). Nevertheless, as the general public was not included in decision-making, it can be argued that the ruling elite's views were the most impactful as these ideas contributed to societal outcomes.

Additional caution should be applied for the measurement of technocratic reasoning in policy circles in the institutional dimension as the bias in the contents of newspapers can considerably change the results, especially during an authoritarian rule, when official rhetoric about institutions might diverge substantially from actual institutional changes (see Section 2. Theoretical framework: Industrial modernity and 3.1. Ideas in **STUDY I** for a detailed discussion). For this reason, comparing the shares of technocratic discourse across different countries might not be meaningful. To combat this limitation, we took a modified approach accounting for the country-level differences and juxtaposed text mining data on technocracy to time series data on citizen participation levels (see Table 2 or Appendix C2 in **STUDY II** for a more detailed account). Although this approach was less than ideal, we faced a choice between measuring imperfectly or not measuring at all. We opted for the former while recognising its limitations, including those related to results and their interpretations.

The other aspect of data availability, limitations regarding country coverage, also affected the three studies. In **STUDIES I** and **II**, due to the above-described lack of longitudinal data, text mining newspaper data limited us to languages our team had proficiency in. To ensure this limitation would not skew our results too much, we aimed to find a balance between data availability for text mining and between-country differences (see Section 3.3.5). While we did reach a defensible variety of countries, a more diverse selection, especially regarding the Global South, could lead to an improved understanding of industrial modernity. However, it should also be noted that this increased diversity can be challenging to achieve, as Beach and Hanlon (2023) report historical newspaper data to be particularly sparse in developing countries.

Beyond text mining, this tendency for sparseness was also apparent in measuring the current layer of industrial modernity in **STUDY III**. While more data was available for the last decade, diversity remained a limitation here too, as the databases available to us containing relevant information (e.g., the WVS, the Manifesto Project, and IEA data on electric vehicles) are largely Eurocentric. Examples of trying to overcome this include using data from two WVS waves in the ideational dimension, constructing an indicator using two other composite indicators in the institutional dimension, and across all three dimensions, successful efforts were made to ensure coverage of the two main themes of industrial modernity.

Furthermore, as discussed in **STUDY III**, while choosing a country as the main unit of analysis is conventional, it does introduce a problem known as "methodological nationalism" (Beck, 2007; Wimmer & Glick Schiller, 2002). This is especially significant for sustainability issues as these tend to be driven by processes beyond a single nation-state. Similarly, the solutions can be governed by transnational actors and institutions (Truffer et al., 2015). While we acknowledge the critique of methodological nationalism is valid, we did not find a reasonable way to measure the traits of industrial modernity on the scale of regions or even more granularly because, to our knowledge, such data does not exist.

The last general limitation of the three studies is a combination of method-specific limitations (specific limitations and ways of approaching them are discussed in Appendix B in **STUDY I**, throughout the Appendices of **STUDY II** and Section 5. Conclusion of **STUDY III**). For text mining, these included access to digitised newspaper data, possible source biases of newspapers and magazines, words' changing meaning and tonality over time, and the difficulty of establishing the ground truth for the algorithms applied. For other data, examples of limitations we considered are intercoder reliability (the Manifesto Project database), low data coverage for a specific period and often missing location data (PATSTAT), the subjectivity that comes with any data classification (ECOLEX, PATSTAT), normalisation and aggregation methods applied, and taking the country as the unit of analysis. Where possible, we tried and found applicable solutions, for example, discussing the source selection with expert historians to reduce biases, using database-specific techniques to minimise inconsistencies, or introducing a whole set of alternative measures to cross-validate our results.

For **STUDIES I** and **II**, a notable limitation pertains to the sequential mixed methods design utilised. Our approach involved supplementing quantitative methods such as text mining, time series analysis, and detecting ruptures in quantitative data with qualitative approaches like historical account examination and expert consultation. While this conversational method (Teddlie & Tashakkori, 2006) allowed us to validate quantitative findings with qualitative data, a concurrent collection of qualitative measures could offer a more robust approach. This would enable the quantification of qualitative data, facilitating a direct comparison with quantitative results (cf. Halevi Hochwald et al., 2023). Although beyond the scope of this thesis, future research could benefit from this approach

as it has the potential to increase the transparency of the analysis process and better employ the advantages of both types of research.

For **STUDY III** specifically, a major methodology-related limitation is that we did not find a reasonable way to validate whether the composite indicator indeed measures what it was intended to measure. For one, as the aim of this study was to find where there are the least structural constraints to enacting the Second Deep Transition, it is clear that it can be difficult to measure something that does not exist or barely exists. It is similarly challenging to validate the success of such measurement within the scope of one empirical study. Thus, we suggest further research in this area, for example, by conducting comparative country-based case studies to assess our results.

Ultimately, I must admit to being a mere mortal.[6] All areas we gathered information from – be it the change in the public option, environmental regulations, energy production, or patenting – have their best practices. Or, as Clark and Harley (2019) put it, the research domains that contain information on sustainability-related issues tend to be ruled as "island empires with mutually incomprehensible jargon, isolated publication venues, and idiosyncratic case studies" (Clark & Harley, 2019: 4). The research underlying my thesis, however, represents an attempt to build bridges to overcome this and gain a comprehensive understanding of industrialisation-related developments. While not experts in each field of research, we aimed for our approaches to be defensible and executed to the best of our knowledge with clearly stated limitations. During the research process, my co-authors and I included the expertise we lacked by consulting with the people working on these topics or handling the databases we utilised. We validated our results with existing accounts and included experts in the process of analysis and interpretation. Still, it is possible that different choices could have been made to analyse the data in all the papers in my list of publications. Nevertheless, I urge the reader to consider the value of the whole, the sum of the parts, and not only the parts themselves, as this makes measuring industrial modernity valuable.

[6] Although I believe that this notion applies to my co-authors as well, there seems to be an internal disagreement concerning this matter among us, as Laur Kanger does not agree that it applies to him.

4. FINDINGS

The following sections summarise the main findings of the three studies. The sections are organised according to the research questions. First, the results presented assess the continuities and discontinuities (ruptures) of industrial modernity between 1900–2020. Second, the current state of industrial modernity is evaluated in 63 countries across the globe.

The most significant findings of the three empirical studies in my list of publications were the following:

1. The evolution of industrial modernity between 1900–2020 was generally uniform in countries with diverse income levels, social structures, populations, energy consumption, and timing of industrialisation (**STUDIES I–II**).
2. Several traits describing the ideation, institutional approach, and practices characteristic of industrial modernity display ruptures starting from the 1960s. However, this is not true of all traits measured, in particular the traits related to technoscience (**STUDY II**). Furthermore, most ruptures in the practice-related dimension were just emergent. Measuring the current state of industrial modernity further confirmed these findings (**STUDY III**).
3. There were substantial differences in the manifestation of the traits of industrial modernity and, thus, the capacity to enact transformative change, regardless of the development level of the country (**STUDY III**).
4. The dimension of practices posed the highest structural restrictions to transformative change necessary for the Second Deep Transition, although the institutional dimension also proved problematic (**STUDY III**).

Next, I will overview these findings in more detail.

4.1 The continuities and ruptures

STUDIES I and **II** provided evidence of similar historical continuities in industrial modernity across economically, politically, and culturally diverse societies – Australia, Germany, India, the United States, and USSR/Russia (see Section 3.3.5 for a diversity assessment). **STUDIES I** and **II** found qualified quantitative support for the claim expressed by Kanger and Schot (2019) that the first signs of the possibly emerging Second Deep Transition can be traced back to the 1960s. However, the two studies significantly added to this claim. **STUDY I** indicated ruptures beginning in the 1960s in the ideational dimension, followed by institutional shifts (from the 1980s), and finally, some nascent changes in the practices dimension (Germany, from the 2000s). **STUDY II** further elaborated on these preliminary findings and quantitatively identified seven substantive changepoints: three in the ideational dimension, two in the institutional dimension, and three in the practice-related dimension. When assessing the changes from the perspective of the two central themes of industrial modernity (i.e., nature as a blind spot and overconfidence in technoscience), the changes could only be described as partial. More precisely, **STUDY I** characterised the changes in the

domain of technology and innovation as a minor deviation and not a transformative change. In contrast, changes in the environmental domain were more significant. Similarly, **STUDY II** found more profound changes in the environmental domain and mostly only emerging trends in the domains of science and technology/innovation.

Next, I will detail the generalisable continuities and ruptures based on **STUDIES I–II** discovered in the three dimensions: ideas, institutions, and practices.

4.1.1 Ideas

Figure 3 presents the continuities and possible ruptures in the ideational dimension. First, in the environmental domain, environmental discourse only started to accelerate in the 1960s. Furthermore, the sentiment of that discourse turned negative around the same period (Figure 3). Therefore, during the first half of the 20th century, the continuity regarding industrial modernity can be observed – the environment was not a part of the public discourse. This continuity was also confirmed by testing for structural breaks in the time series, identifying change points during 1955–1969 for all the countries' analyses. These trends are consistent with historical evidence, highlighting the growth of the increasingly transnational environmental movement during the same period (McNeill & Maudlin, 2012; Warde et al., 2018: 123–150). The acceleration and the change in the sentiment, however, can illustrate a significant rupture: the environment that had been something to be controlled and dominated by humans was now seen as valuable and worth protecting.

Second, in the domain of technoscience, discourse on science and technology remained highly prevalent throughout the observation period (Figure 3). This finding can be interpreted as another continuity of industrial modernity. The sentiment of the discourse, however, changed in two notable ways since the 1960s: 1) the sentiment towards technology surpassed sentiment towards science in all countries between the 1960s and the 1980s, and 2) optimism towards technology resurged in the context of the natural environment during the 2000s after a decline starting in the 1970s-1980s. As the first finding supports historical analysis that argues a turning point in the 1980s resulting in technology assuming cultural supremacy over science (Forman, 2007), it was not interpreted as a rupture but rather an intrinsic transformation. The second finding corroborates the literature that highlights the current dominance of the ecological modernisation or green growth narrative, which emphasises resource efficiency through technological progress and contestably argues for the compatibility between economic growth and planetary boundaries (Hickel & Kallis, 2020; Wiedmann et al., 2020; Cohen, 2021). In other words, while environmental degradation is now seen as a problem, science and technology are dominantly seen as the ultimate solution. Thus, in the domain of technoscience, the data shows no permanent ideational ruptures.

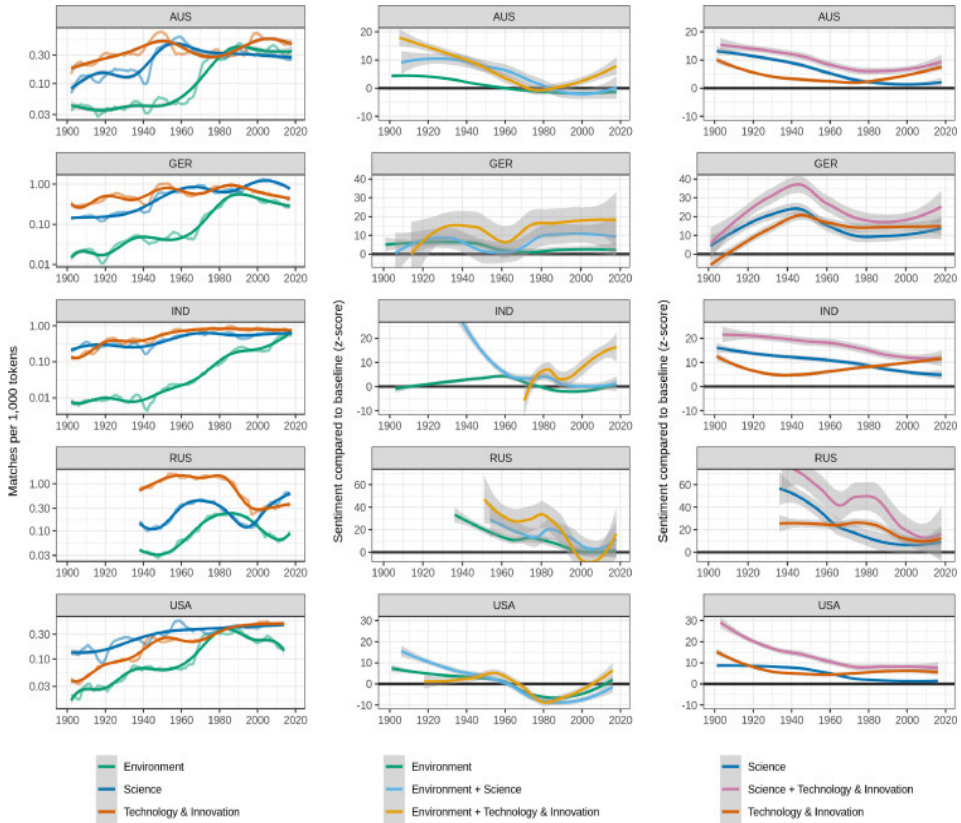

Figure 3. Continuities and ruptures in the ideational dimension of industrial modernity (**STUDY II**: 7)

Note. A: Relative frequency of keywords signifying technology and environment by country, 1900–2015 (logarithmic scale). Data for USSR/Russia starts from 1935 (see Appendix B2 in **STUDY II**). The lighter line shows the rolling 5-year average for each topic, and the darker line shows a generalised additive model fit on the data (y ~ s(year, adaptive smooth, k = 10, m = 5)). Data source: Aggregated digitised newspaper collections (see Table 2). **B, C:** Sentiment levels compared to the baseline for each discussion genre based on the main sentiment lexicon by country, 1900–2020. Z-score is defined against the standard deviation of 10 similar-sized baseline samples. The plot starts at 100 cumulated observations. Data for USSR/Russia starts in 1935. The line shows a LOESS fit to the data with a span of 0.7. On all figures, the grey area behind the smoothed line represents the 95% confidence interval of the model. Data source: Aggregated digitised newspaper collections (see Table 2). Note that the y-axes are variable for A-C, allowing for a better visual representation of the dynamics of each country.

4.1.2 Institutions

Figure 4 illustrates the continuities and possible ruptures in the institutional dimension. In the environmental domain, the analysis demonstrated that intellectual property rights have a long history, with four out of six major treaties included in **STUDY II** being introduced by the 1970s. In contrast, over 80% of environmental treaties originated after the 1970s. The adoption of these followed the same trend. The first half of the observation period showed evidence of continuity in industrial modernity, as indicated by technological regulation, but a relative institutional neglect of environmental issues. However, there was a sharp rise in the adoption of international environmental treaties from the late 1980s, mirrored by exponential growth in national environmental legislation that could be interpreted as a possible rupture. We confirmed the rupture using the densities of environmental treaties and intellectual property rights. The period in which the former exceeded the latter for at least five years fell between the 1970s and 1980s in all five countries.

In the domains of science and technology/innovation, similarly to the ideational dimension, there has been less change (Figure 4). Technocracy measures exhibited few generalisable trends other than the prevalence of technocratic discourse throughout the observation period, and perhaps that the discourse has become relatively stable since the 2000s. Germany is the only exception to this observation. The gap between technocratic and participatory discourse in Germany has widened somewhat in the post-WWII era, primarily due to the country's increase in the participatory democracy index score. Furthermore, **STUDY II** did not support the distinction between the "Age of Technocracy" (1945–1970) and the "Age of Participation" (1970–2015) suggested by van der Vleuten et al. (2017). Instead, the findings were more consistent with the thesis of Esmark (2020), who argues that technocracy has undergone an internal transformation since the 1980s but continues to be a dominant approach in policy-making. Thus, the science domain displayed an internal transformation but no ruptures. However, since newspaper data mining was used to measure technocratic reasoning in policy circles, caution should be applied to these interpretations (see Section 3.5 for a discussion on this issue).

The analysis of technoscientific institutions showed that reactive and conservation-oriented environmental laws were more prevalent than proactive laws in all countries throughout the observation period (Figure 4). This trend can be interpreted as evidence of continuity in industrial modernity, reflecting a tendency to focus regulatory efforts on addressing the consequences of using various technologies (either by alleviating known impacts or preventing these impacts from spreading to new locations). Germany was an exception to this trend, as it had a more balanced mix of reactive, conservation-oriented, and proactive regulations than other countries. Still, the 1980s and 1990s marked a turning point, as this was when the proportion of proactive laws began to grow steadily in each country. When we used the 16.7% threshold from the diffusion of innovation literature (Rogers, 2003) as a benchmark, all five countries reached it by the early

2000s (Figure 4). This finding suggests the domain of technology has experienced an institutional rupture.

Figure 4. Continuities and ruptures in the institutional dimension of industrial modernity (**STUDY II**: 9)

Note. A: Joining of major international treaties on intellectual property rights (n = 6) and the environment (n = 21) by country, 1884–2020. The bold line shows the cumulative proportion of treaties joined by each country. The black points show the date of origin for particular treaties connected by a lighter line to when the treaty was put into force in a country. The grey columns on the background show the number of legislative and regulative environmental documents adopted by year by country. Data sources: ECOLEX, WIPO Lex. **B:** The presence of technocratic keywords in texts about government activities by country and the country's score on the participatory democracy index. Data source: Aggregated digitised newspaper collections (see Table 2), V-Dem. **C:** The estimated probability of a legislative or regulative document belonging to a reactive, conservation-oriented or proactive category by adoption year by type by country, 1900-2020. The lines show the generalised additive model for each type following a binomial distribution (success/fail ~ s(year, adaptive smooth, k = 10, m = 5)). The model starts at the 10th data point and gives earlier data points the same date. For this reason, the time series for Australia begins in 1902, Germany in 1932, and USSR/Russia in 1959. The grey columns on the background show the number of legislative and regulative environmental documents adopted by year by country that were the basis of the models. The coloured area behind the smoothed line represents the 95% confidence interval of the model. Data source: ECOLEX.

4.1.3 Practices

Figure 5 shows the continuities in the dimension of practices. In the environmental domain, energy production data revealed significant continuities: the energy mixes in all countries analysed were dominated by fossil fuels (i.e., coal, oil, and natural gas), and energy production continued to grow throughout the observation period. A rupture, defined as the point in time at which the share of renewables in the energy mix crossed the 16.7% threshold (cf. Yang et al., 2020), was only detectable in German energy production data (Figure 5). However, as **STUDY II** notes, a large share of Germany's energy needs are met by imported fossil fuels (US EIA, n.d.), which are not included in production data. Thus, in reality, no rupture was detected in the environmental domain.

In the science domain, except for the USSR, the proportion of publications on environmental engineering has remained relatively constant in all countries throughout the observation period (Figure 5). The one exception likely reflects the importance of engineering for remaking nature, as exemplified by Joseph Stalin's "Great Plan for the Transformation of Nature" (1948), which instigated a series of dam and irrigation projects that ultimately led to the desiccation of the Aral Sea (Warde et al., 2018). Therefore, the generalisable trend can be interpreted as a continuity in industrial modernity. For ruptures, only emergent trends are observable (Figure 5). Sustainability-related publications in engineering first appeared in each country from the late 1980s to the early 2010s, and this research has steadily grown since then.

In the technology domain, an absolute increase in the number of patents can be observed (Figure 5). This trend can be associated with continuity in industrial modernity. Visualising the Climate Change Mitigation Technologies (CCMT) patents per 100,000 people reveals striking country-level differences, with rapid growth in the USA and Germany, considerably milder growth in Australia and Russia, and virtually none in India. While structural breaks can be observed in all time series, only two can be considered substantial based on historical accounts (Probst et al., 2021): the late 1980s in German data and the 2000s in the USA. These findings indicate a partial rupture in practices related to technology.

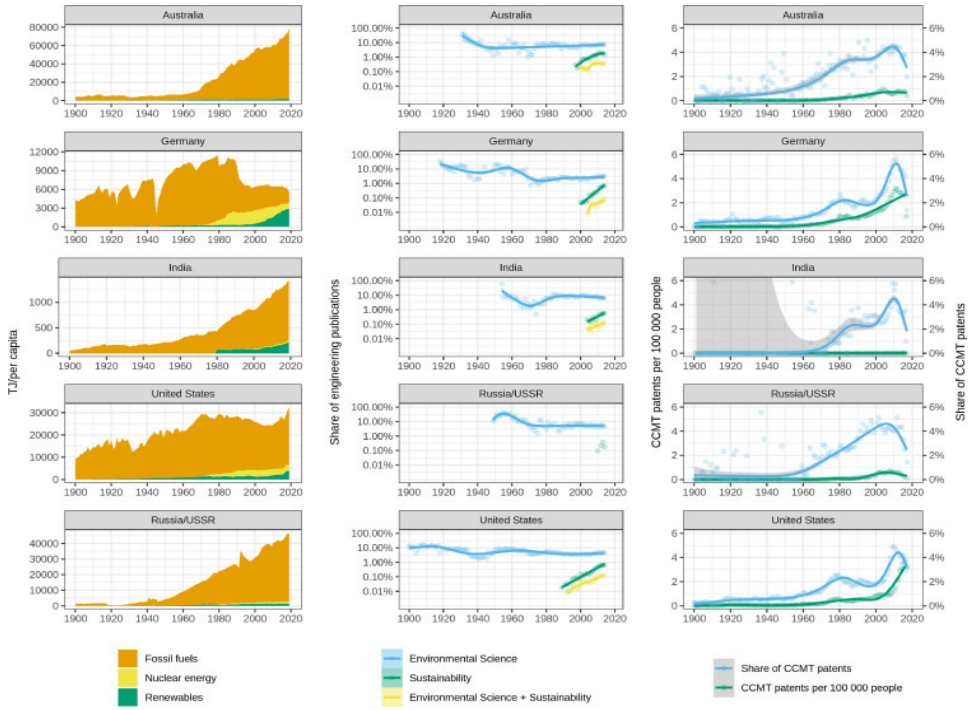

Figure 5. Continuities and ruptures in the practice-related dimension of industrial modernity (**STUDY II**: 10)

Note. A: The yearly primary energy production in terajoules (TJ) per capita by country, 1900–2019, including the shares of fossil fuels, nuclear energy, and renewables from the energy mix. Note that the y-axes are variable, allowing for a better visual representation of the dynamics of each country. Data source: Etemad and Luciani, (1991), U.S. Energy Information Administration, via: theshiftdataportal.org; Maddison (2020), and Gapminder. **B:** The share of engineering publications tagged with environmental science, sustainability, or both, 1900–2019. The line shows a generalised additive model fit on the data (y ~ s(year, adaptive smooth, k = 10, m = 5)). Data sources: MS Academic. **C:** Country's patents related to Climate Change Mitigation Technologies (CCMT) as a share of total and CCMT patents per 100,000 people, 1900–2017. The former line shows a LOESS fit with a span of 0.2. The latter line shows the generalised additive model fits on the data with a binomial distribution (success/fail ~ s(year, adaptive smooth, k = 10, m = 5)). The grey area behind the smoothed line represents the 95% confidence interval of the model. Data sources: PATSTAT, EPO and USPTO, Maddison Project (2020), and Gapminder.

4.2 The current state

STUDY III identified a wide geographical variation in the distribution of industrial modernity (Figure 6). This finding was made apparent by the top of the Industrial Modernity Index (IMI) ranking, populated by countries from Europe, Asia, Africa, and South America, with Sweden being the absolute best performer (Table 10). In addition to Sweden, five countries (Spain, Brazil, Slovenia, Peru, and Nicaragua) scored below the mean value in all dimensions (i.e., ideas, institutions, and practices). In other words, these are the countries where the layer of industrial modernity is comparatively the thinnest and may constitute the core experimental and learning space for the possible emergence of a Second Deep Transition. In contrast, former Soviet countries (i.e., Kazakhstan, Belarus, Russia, Uzbekistan, and Kyrgyzstan) and major oil-producing countries (i.e., Kuwait, Russia, Qatar, China, and Iraq) populated the bottom of the ranking. Therefore, these countries displayed the highest structural restrictions to enact transformative change. Furthermore, as Table 10 shows, a notable number of countries struggled not with a singular dimension but with overall performance. This finding indicates that the traits of industrial modernity and the related unsustainabilities continue to be pervasive globally.

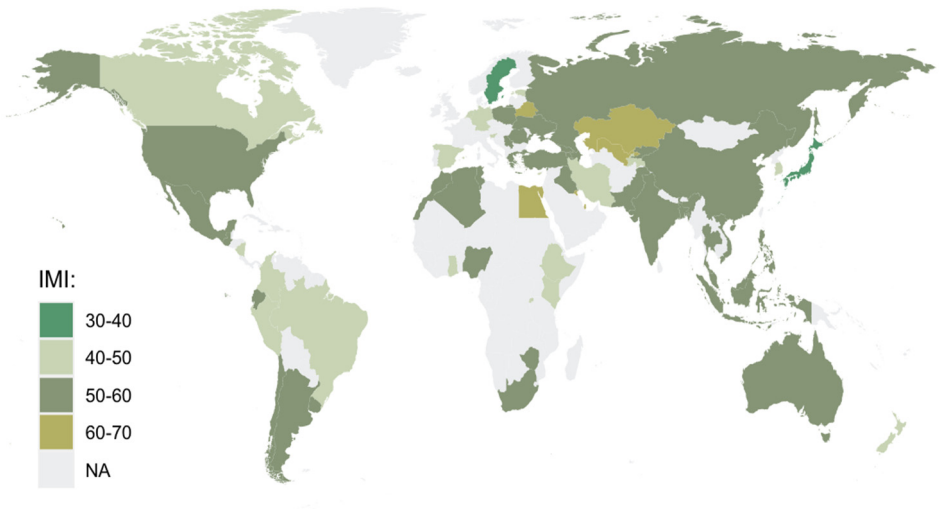

Figure 6. The IMI scores by country (**STUDY III**: 11)

Table 10. The IMI, dimension, and domain scores by country (**STUDY** III: 12)

Rank	Country	IMI	Dimensions			Domains		Main limiting dimension(s)
			Ideas	Institutions	Practices	ENV	STI	
1	**Sweden****	32.83	24.85	31.16	42.48	25.9	39.76	Practices
2	**Japan**	36.21	26.4	19.24	63	41.28	31.15	Practices
3	**Spain***	41.99	27.45	42.98	55.53	42.79	41.18	Practices
4	**South Korea**	43.36	26.45	41.88	61.74	52.17	34.55	Practices
5	**Germany**	43.73	27.4	45.04	58.75	40.18	47.29	Practices
6	**Ethiopia**	44.47	56.35	46.17	30.9	41.28	47.67	Ideas & Institutions
7	**Rwanda**	45.11	54.4	58.47	22.46	35.75	54.46	Ideas & Institutions
8	**Estonia**	45.2	32.95	43.42	59.24	42.81	47.6	Practices
9	**Brazil***	45.5	35.6	45.19	55.72	44.95	46.06	Practices
10	**Singapore**	45.69	32.05	38.83	66.18	54.47	36.9	Practices
11	**Ghana**	46.21	43.2	47.88	47.55	52.94	39.48	Practices
12	**Slovenia***	46.48	31.9	54.63	52.92	38.03	54.94	Practices
13	**Kenya**	47.11	50.05	57.8	33.48	42.6	51.61	Ideas & Institutions
14	**Netherlands**	47.14	27.25	51.09	63.09	45.77	48.52	Practices
15	**New Zealand**	47.15	23.2	62.26	55.98	40.16	54.14	Institutions & Practices
16	**Cyprus**	47.55	36.85	44.17	61.62	49.1	46	Practices
17	**Iran**	47.62	41.3	33.93	67.64	56.25	39	Practices
18	**Tajikistan**	47.62	52.8	48.09	41.98	48.84	46.41	Ideas & Institutions
19	**Peru**	47.66	34.7	48.27	60	51.48	43.83	Practices
20	**Colombia***	47.69	42.85	42.81	57.42	46.32	49.07	Practices
21	**Nicaragua***	48.66	40.7	51.11	54.18	42.39	54.93	Practices
22	**Canada**	49.73	34.3	51.12	63.78	52.27	47.19	Practices

Rank	Country	IMI	Dimensions			Domains		Main limiting dimension(s)
			Ideas	Institutions	Practices	ENV	STI	
23	**Guatemala**	50.06	33	68.31	48.88	42.37	57.76	Institutions & Practices
24	**Australia**	50.07	33.35	45.88	70.97	53.52	46.61	Practices
25	**Greece**	50.53	35.55	57.26	58.77	48.47	52.58	Institutions & Practices
26	**Vietnam**	50.62	36.25	53.27	62.35	54.49	46.76	Practices
27	**Romania**	51.03	49.45	49.47	54.17	49.7	52.36	Practices
28	**United States**	51.09	37.1	52.19	63.97	49.92	52.25	Practices
29	**Uruguay**	51.96	30.2	73.43	52.24	46.08	57.83	Institutions & Practices
30	**Georgia**	52.08	33.2	64.32	58.72	44.76	59.39	Institutions & Practices
31	**Philippines**	52.09	35.95	71.53	48.79	46.21	57.97	Institutions & Practices
32	**Ukraine**	52.6	44.85	52.34	60.6	50.99	54.2	Overall Performance
33	**Ecuador**	52.84	41.1	60.31	57.1	51.72	53.96	Institutions & Practices
34	**Indonesia**	53.26	37.45	65.9	56.43	46.83	59.69	Institutions & Practices
35	**Mexico**	53.48	43.9	53.45	63.08	53.3	53.65	Overall Performance
36	**Zimbabwe**	53.48	58.6	64.78	37.06	39.88	67.08	Ideas & Institutions
37	**Nigeria**	54	57.25	65.64	39.11	47.86	60.14	Ideas & Institutions
38	**Morocco**	54.64	32.55	70.73	60.65	49.34	59.95	Institutions & Practices
39	**India**	55.22	30.9	80.41	54.34	48.35	62.08	Institutions & Practices
40	**Armenia**	55.5	63.4	41.08	62.03	52.43	58.57	Overall Performance
41	**Serbia**	55.78	43.85	63.38	60.12	54.49	57.08	Overall Performance
42	**Kyrgyzstan**	56.36	50	62.04	57.05	47.64	65.08	Overall Performance
43	**Thailand**	56.46	40.45	66.9	62.04	54.53	58.39	Institutions & Practices
44	**Malaysia**	56.79	33.9	72.25	64.22	56.25	57.33	Institutions & Practices
45	**Pakistan**	56.85	57.8	64.43	48.31	53.55	60.14	Ideas & Institutions
46	**Azerbaijan**	57.89	49.4	54.44	69.82	55.28	60.49	Overall Performance

Rank	Country	IMI	Dimensions			Domains		Main limiting dimension(s)
			Ideas	Institutions	Practices	ENV	STI	
47	**Iraq**	58.03	55.95	51.76	66.39	63.24	52.82	Overall Performance
48	**Poland**	58.44	49.25	61.78	64.29	55.36	61.52	Overall Performance
49	**Argentina**	58.58	41.5	68.44	65.8	56.48	60.68	Overall Performance
50	**Chile**	58.6	36.6	74.39	64.82	52.85	64.36	Institutions & Practices
51	**China**	58.61	44.55	64.1	67.18	54.33	62.89	Overall Performance
52	**South Africa**	58.82	45.35	69.69	61.43	62.89	54.76	Overall Performance
53	**Algeria**	59	46.8	62.93	67.26	59.38	58.61	Overall Performance
54	**Turkey**	59.04	39.55	73.78	63.79	58.92	59.16	Institutions & Practices
55	**Tunisia**	59.63	53.15	65.16	60.59	58.79	60.48	Overall Performance
56	**Bangladesh**	59.72	57.9	70.57	50.69	54.26	65.18	Overall Performance
57	**Russia**	59.81	44.75	67.67	67	57.28	62.33	Overall Performance
58	**Uzbekistan**	60.6	49.55	62.53	69.73	50.83	70.38	Overall Performance
59	**Kazakhstan**	60.64	45	63.58	73.33	60.21	61.06	Overall Performance
60	**Belarus**	61.34	48.7	63.53	71.79	58.08	64.6	Overall Performance
61	**Egypt**	62.78	49.75	76.8	61.8	59.28	66.28	Overall Performance
62	**Qatar**	65.32	54.45	63.06	78.44	64.76	65.87	Overall Performance
63	**Kuwait**	69.67	59.85	72.66	76.5	67.51	71.82	Overall Performance

Note. The k-means cluster means used for finding the restrictive dimensions are available in Appendix B of **STUDY III.**

* Countries scoring below the mean in all the aggregate scores.

** Countries scoring one standard deviation or more below the mean in all the aggregate scores.

Figure 7 provides a helpful illustration of the nuances introduced by the IMI scores through the lens of two countries: South Korea and Ethiopia. Both scored relatively well and placed in the top 10 of the general ranking, 4th and 6th, respectively. However, as Figure 7 shows, these placements were achieved with somewhat contrasting dimension scores. South Korea scored the lowest in the ideational dimension, while Ethiopia scored the lowest in the dimension of practices. While South Korea and Ethiopia have comparatively fewer barriers to achieving a deep sustainability transition than many others, the specific challenges these countries face will likely differ. South Korea's high aggregate practices-related score indicates a need to transform its energy- and material consumption, while Ethiopia faces the challenge of balancing economic growth aspirations with sustainable development.

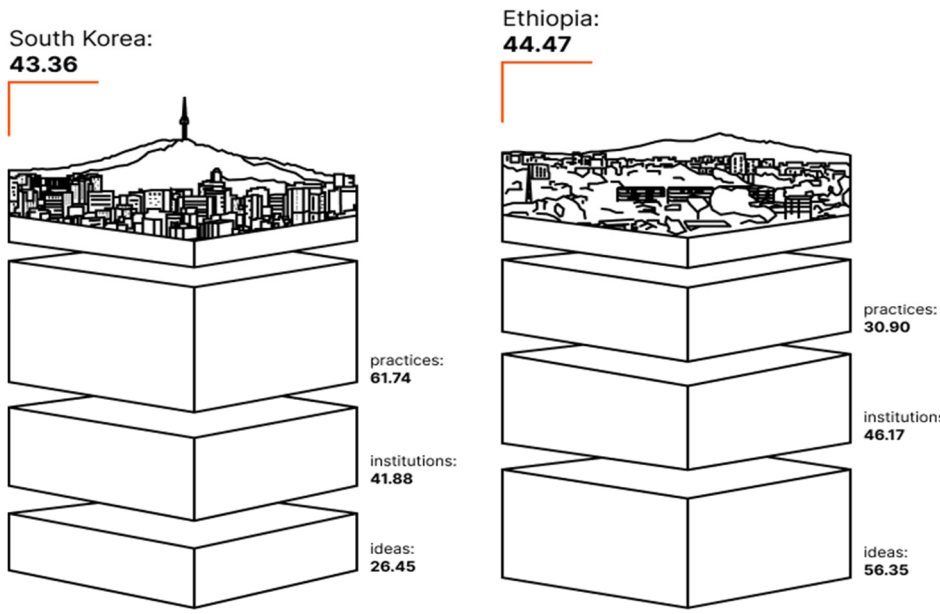

Figure 7. The layer of industrial modernity in South Korea and Ethiopia (**STUDY III**: 13)

Overall, **STUDY III** found the layer of industrial modernity to be thinnest in the ideational dimension, as this dimension displayed the lowest mean score ($\bar{x}$ = 41.83; for more detail, see Table 5 in **STUDY III**). Next was the mean score in the institutional dimension ($\bar{x}$ = 57.33), followed by practices ($\bar{x}$ = 58.37). These results are consistent with the findings of **STUDIES I** and **II**, as the ideational dimension showed the earliest and more significant ruptures, followed by the institutional dimension, and only modest changes in practices (see Section 4.1).

Each dimension tended to have its own distinct best and worst performers. High- and upper-middle-income countries (e.g., Japan, Sweden, and Germany) drove the low scores in the ideational dimension, while low- and lower-middle-income countries (e.g., Rwanda, Egypt, and Pakistan) tended to score more poorly (see Figure 8). This finding can be attributed to support for environmental protection being sensitive to socioeconomic conditions, particularly unemployment (Drews & van der Bergh, 2016; Kenny, 2020). In the institutional dimension, some European, Asian, and equatorial South American countries performed well, while most African, Central, South, and Southeast Asian countries performed poorly (Figure 9). The best and worst performers in the institutional dimension are explained by the overall development level and institutional maturity of these countries, as effective institutions encourage the adoption of renewable energy and green technology while reducing the need for foreign direct investment reliant on polluting methods and technologies (Tang et al., 2021; Xing & Kolstad, 2002). In contrast to the ideational dimension, the practices dimension was where low- and lower-middle-income countries (e.g., Rwanda, Zimbabwe, and Tajikistan) performed well (Figure 10). Most other countries, however, demonstrated relatively higher scores in this dimension, as indicated by the mean scores. It is not surprising that the resource-intensive developed countries displayed high material footprints, as this has been well-established by previous research (Hickel et al., 2022a). However, no high-income country other than Sweden offset its relatively higher score in the environmental domain with a low score in the STI domain. This suggests that the directionality of innovative activities in most countries analysed was not primarily aimed at addressing environmental concerns.

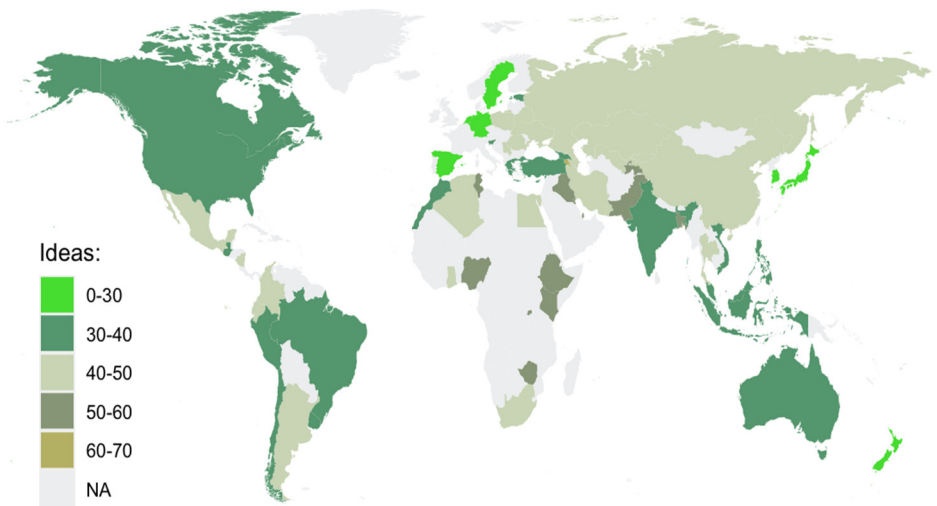

Figure 8. Scores for the dimension of ideas by country (**STUDY III**: 13)

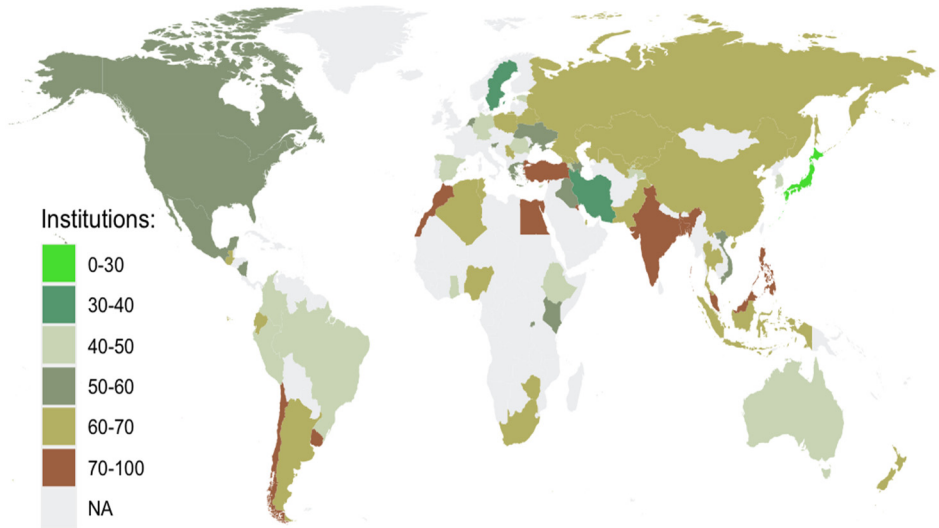

Figure 9. Scores for the dimension of institutions by country (**STUDY III**: 14)

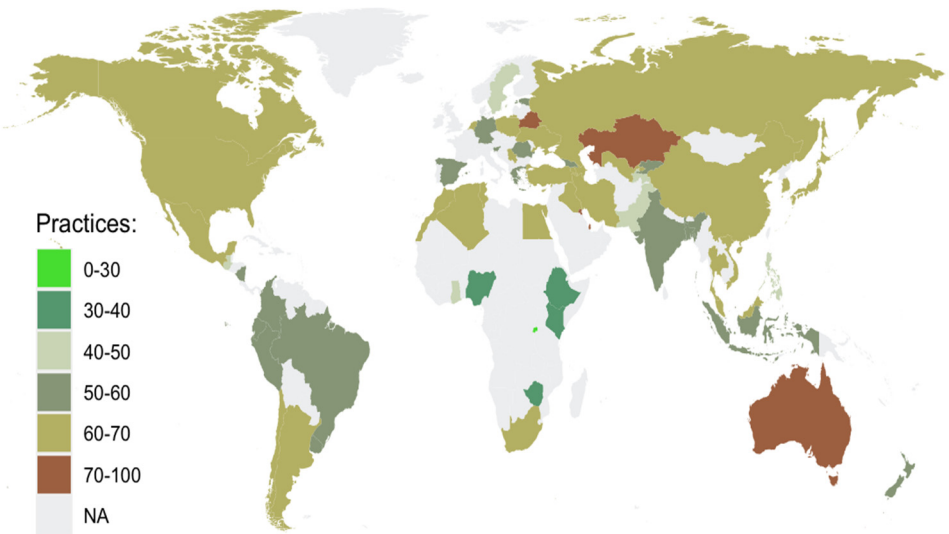

Figure 10. Scores for the dimension of practices by country (**STUDY III: 14**)

Moreover, when analysing the thickness of industrial modernity from the perspective of the two domains, overconfidence in science and technology stood out, with a relatively higher mean score ($\bar{x}$ = 54.54, compared to $\bar{x}$ = 50.48, the mean score of the environmental domain). This difference is also consistent with the ruptures identified in **STUDIES I** and **II**, as there were more ruptures in the

environmental domain than in the domains of science and technology (see Section 4.1). Figure 11 shows that countries in equatorial Latin America (e.g., Brazil and Colombia) perform well in the environmental domain. In contrast, Figure 12 shows some Asian countries (e.g., Japan and South Korea) tend to excel in the STI domain. Former Soviet nations tended to display higher-than-average scores in both domains. The reasons for these findings are unclear and merit further investigation.

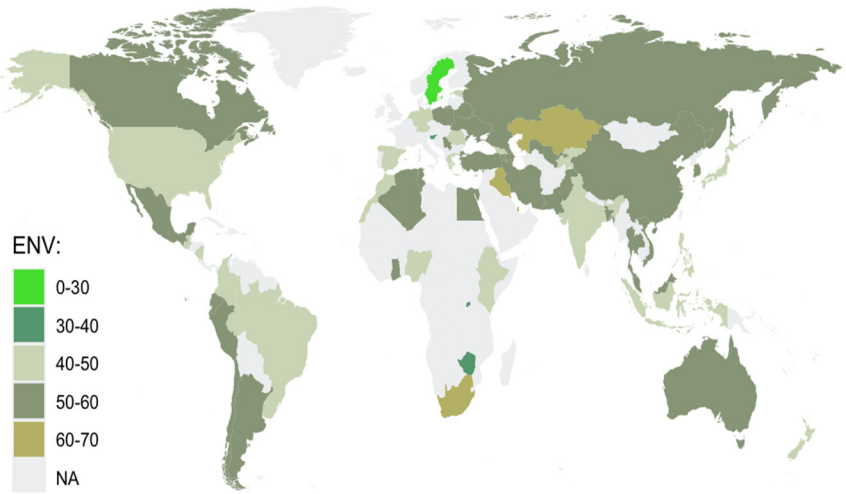

Figure 11. Scores for the environmental domain by country (**STUDY III: 15**)

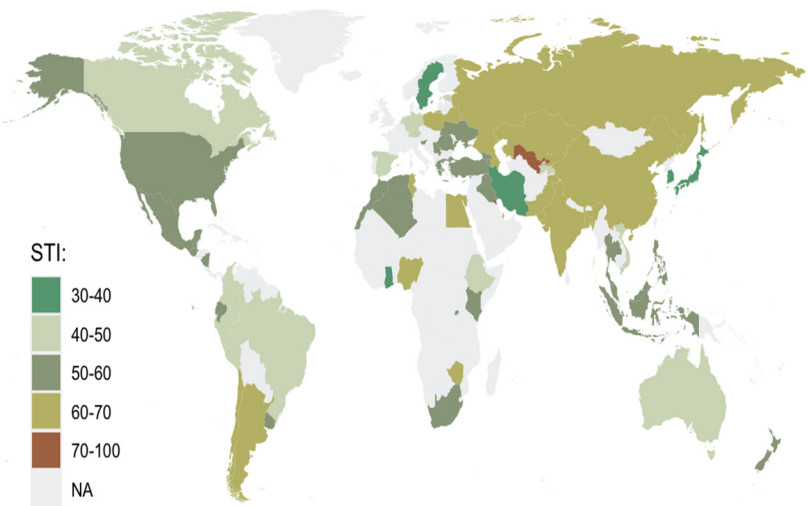

Figure 12. Scores for the domain of STI by country (**STUDY III**: 15)

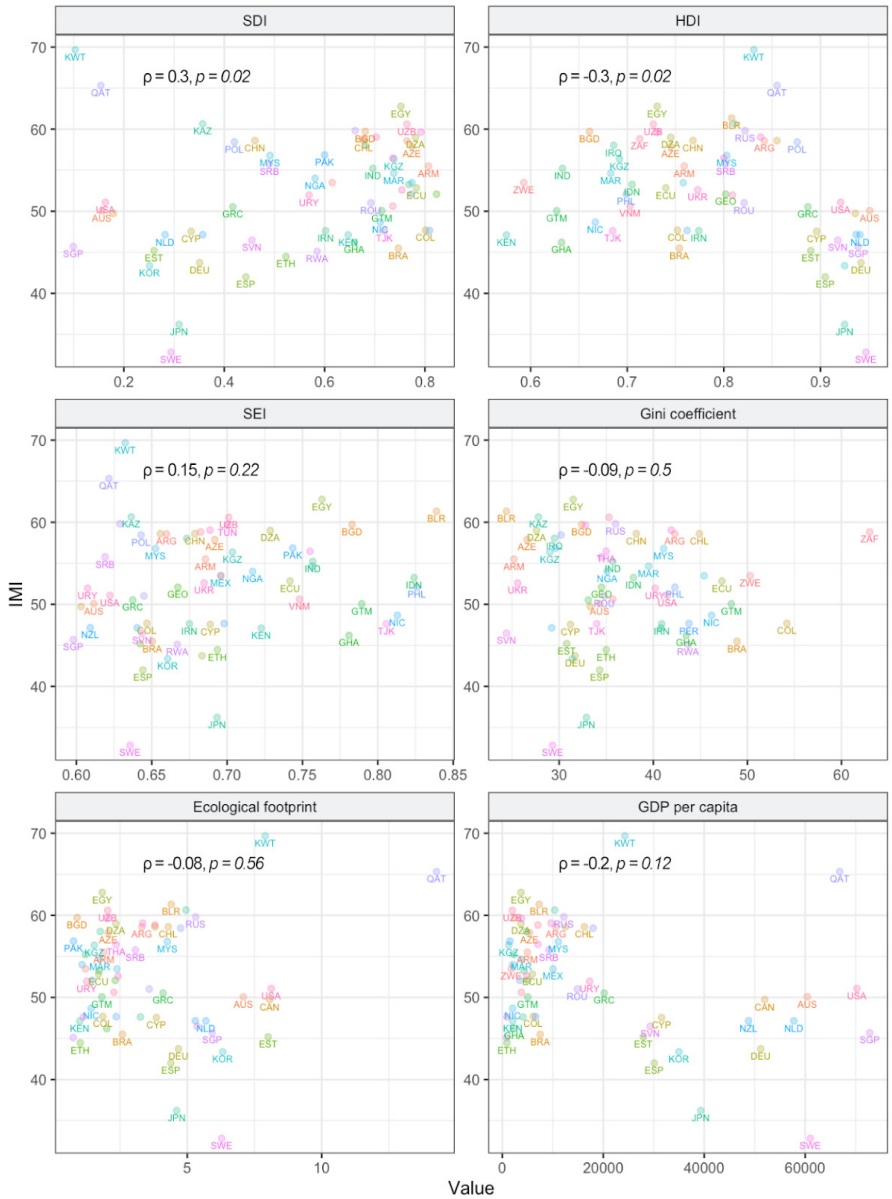

Figure 13. The Spearman's rank correlation coefficients, the IMI and other indicators (**STUDY III:** 17)

Note. For the Gini coefficient, we use the last available data between 2003-2021, for HDI 2021-2022, and for GDP per capita 2020-2021. For SEI, we use data from 2015, 2018 for Ecological footprint, and 2019 for SDI. Data sources: World Bank (Gini index, GDP per capita), www.sustainabledevelopmentindex.org (SDI), United Nations (HDI), https:// www.footprintnetwork.org (Ecological footprint), https://doi.org/10.5061/-dryad. 866t1g1rq (SEI).

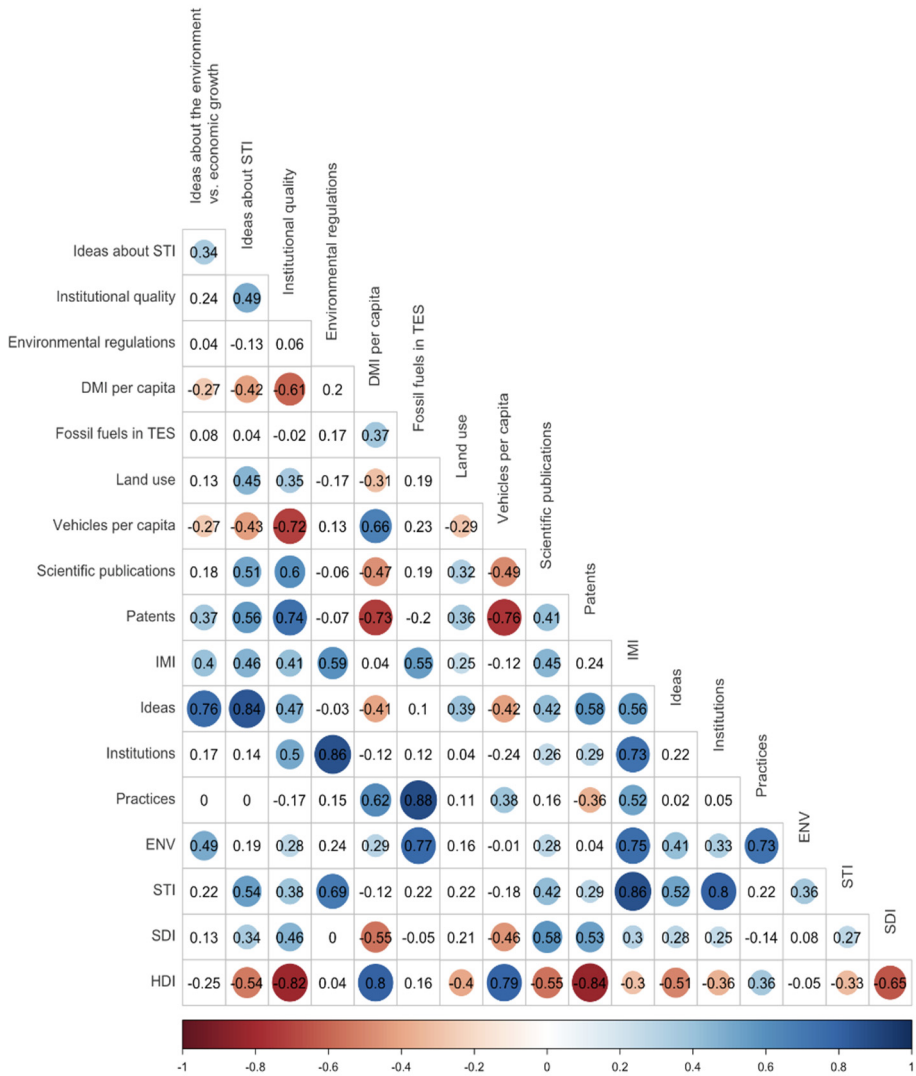

Figure 14. The Spearman's rank correlation coefficients of the IMI indicators, SDI, and HDI (**STUDY III,** Appendix F)
Note. HDI data used for the analysis is from 2021-2022 and for the SDI from 2019. Data sources: United Nations (HDI), www.sustainabledevelopmentindex.org (SDI).

Comparing IMI scores with other progress indicators highlights a key strength of this novel composite indicator. As illustrated by Figure 13, the IMI shows no significant correlation with the Gini index, Social-environmental index, Ecological footprint, or per capita GDP. However, it does exhibit weak yet significant associations with the Sustainable Development Index (SDI) ($\rho = 0.3$, $p < 0.05$) and the Human Development Index (HDI) ($\rho = -0.3$, $p < 0.05$). Figure 14 offers

a deeper look into these relationships, detailing the Spearman's rank correlation coefficients between individual IMI indicators, SDI, and HDI. To understand these correlations, the two indicators should be analysed in the context of the IMI's underlying dimensions. SDI, essentially HDI adjusted for environmental impact, tends to underestimate the importance of institutional quality and innovative activities (Hickel, 2020). This means that countries with low material input, but also weak institutions and environmentally insensitive innovation, might perform well on the SDI yet be penalised by the IMI. Conversely, HDI considers institutional quality and innovation but overlooks ecological footprints (*ibid*.). Consequently, wealthier countries with higher material footprints often score well on the HDI but are penalised by the IMI. Thus, these relationships highlight the IMI's distinct approach to measuring societal progress as it considers both aspects.

It follows that including data on ideation, institutional approaches, and practice-related to the environment and technoscience provides a more nuanced picture of the sustainability challenge than that typically depicted by conventional metrics. Some developed nations characterised by high per capita GDP, HDI scores, and Gini coefficients, such as the United States and Australia, demonstrate only moderate potential, as these countries relatively lack ideational and institutional support and exhibit (excessive) optimism in technoscience. Similarly, some developing countries displaying relatively low ecological footprints and SDI scores can also be lacking in these areas, as illustrated by Algeria, Tunisia, and Egypt. These results indicate that the constraints to enacting transformative change are not defined by wealth or environmental impact.

5. DISCUSSION

My thesis aimed to measure industrial modernity's evolution and current manifestation. To accomplish this, I used a novel multi-dimensional and multi-domain approach that integrates insights from various sustainability-related research fields to provide a more comprehensive understanding of industrial societies' approach to environment and technoscience. This approach represents an important contribution to the field of sustainability transitions research, as it operationalises the concept of industrial modernity and provides a systematic assessment of landscape processes. It also offers sustainability science a concrete and theory-driven understanding of how the historical legacy of industrial societies contributes to the climate crisis. Moreover, by connecting fragmented observations about environmental and technoscientific ideas, institutions, and practices within and beyond sustainability science, my thesis offers a holistic view of industrialism that was missing from the previous literature. This chapter is structured as follows. In Section 5.1, I will discuss the implications of my results for sustainability transitions research and (sustainability) science, as well as propose possible future research directions. In Section 5.2, I will overview the implications of my thesis for policymaking.

5.1 Implications for research

5.1.1 Implications for sustainability transitions research

My thesis significantly contributes to the DT framework by offering a novel conceptualisation of industrial modernity and empirically testing the associated theoretical claims. In **STUDY I**, my co-authors and I proposed a multi-domain and multi-dimensional conceptualisation of industrial modernity that allowed us to differentiate between industrial societies' ideas, institutions, and practices regarding environment and technoscience. This conceptualisation proved useful for operationalisation and can be further utilised to understand the developments in the various traits of industrial modernity. Consistent with what has been theorised in the DT framework, **STUDIES I** and **II** indicated that the onset of the Second Deep Transition can be traced back to the 1960s. However, as a novel contribution, in this period, the two studies indicated a change only in the ideational dimension. An institutional transformation followed ideational ruptures in the 1980s and emergent changes in the practices during the 1990s and 2000s. Furthermore, there are more significant ruptures in the environmental domain than in the domains of science and technology/innovation. These preliminary findings add a more nuanced understanding of industrial modernity's evolution and open new avenues for DT research to focus on additional mechanisms, such as furthering the knowledge of the synergies between ideas, institutions, and practices and researching the relationship between the environmental and technoscience domains.

STUDY III also contributes to the DT literature by empirically showing that the landscape of industrial modernity is unevenly distributed, with Sweden having the best conditions for the onset of the Second Deep Transition. Furthermore, the results confirmed the findings of **STUDIES I** and **II** by suggesting that the pathway to deep sustainability transition is characterised by a change in ideation first, followed by an institutional transformation, and finally, a change in practices. The novel composite indicator introduced in **STUDY III** identified country-level restrictions for enacting the deep sustainability transformation and the possible development directionalities for the countries analysed. While it is true that the Global North and South have different expectations for contributing to sustainability (Hickel et al., 2022b), the varying levels of industrial modernity across countries indicate that there are many opportunities for countries to experiment with different approaches. The latter is especially true because **STUDY III** found that countries on both sides of the divide have the potential to transform industrial modernity. However, further research is needed to fully understand the specific challenges and opportunities countries face to leverage the findings of **STUDY III**. Detailed country-level case studies could provide valuable insights into the challenges and opportunities.

Future research could expand the DT framework by examining industrial modernity's interplay with other facets of modern society. While my research highlights how industrial societies' approach to technoscience can hinder the practical implementation of ideational and institutional shifts (**STUDIES I–III**), other societal trends likely also play a significant role. For instance, Kemp et al. (2022) and Geels (2024) note the DT framework's limitation in not engaging with socio-economic trends like marketisation and financialisation. Similarly, promising research has conceptualised scenarios for deep cultural change (Hughes et al., 2024) and the impact of wars on deep transitions (Johnstone & McLeish, 2020; 2022). Investigating the interplay between industrialism and other pillars of modernity, such as cultural, economic, and military forces could be instrumental in understanding the barriers to the deep sustainability turn.

Beyond DT research, my thesis also made a significant contribution to the field of sustainability transitions by introducing a theory-driven understanding of landscape developments and their current state (**STUDIES I–III**). In turn, this understanding points to a need to steer landscape processes to break down industrial modernity and create conditions to accelerate transitions in multiple, if not all, socio-technical systems. The DT framework and my research open the concept of landscape in transitions studies to be more than just pressure on the regimes with varying speed and intensity. Instead, through the work on industrial modernity, the landscape can now be understood as a key element in steering transitions. There are multiple avenues for this.

Much necessary work has been done on various niches (Köhler et al., 2019) and even niche clusters (Penna et al., 2023b) in single and multiple systems. Similarly, transitions research has recently recognised the need to "tilt" the landscape to make it more favourable towards transitions in multiple socio-technical systems through global institution-building as well as international and

regional agreements (Kanger et al., 2020; Lazarevic et al., 2022). However, given the uneven progress in breaking down industrial modernity (**STUDIES I–II**) and the pervasive unsustainabilities highlighted in **STUDY III**, more intentional approaches to breaking down landscape-level barriers are needed. Landscape-making niches present a promising research direction that could be incorporated into the transitions research agenda for that purpose (**STUDY IV**). These niches aim to change the underlying structures of industrial societies, for example, degrowth (Hickel et al., 2022a) and rights of nature (Pecharroman, 2018) for the environmental domain and the Responsible Research and Innovation (RRI) framework (Owen et al. (2013), frugal innovation (Numminen & Lund, 2017), and inclusive innovation (Onsongo & Knorringa, 2020) for the domains of technoscience. Because there have been fewer ruptures in the technoscience domain (**STUDIES I–II**), I propose focusing more on landscape-making niches that provide alternatives to the traits in these domains (see Section 5. for further discussion on the RRI).

Furthermore, when one considers the resurgent optimism about the potential of technology to address environmental concerns (**STUDIES I–II**) during the gradual development of landscape-making niches, it becomes clear that more than alternatives to the dominant traits of industrial modernity are required. In line with transitions research suggesting that sustainability transformations require not only new developments but also a focus on addressing unsustainabilities (Kivimaa & Kern, 2016; Markard et al., 2023), I propose the need to develop methods to directly challenge the current status quo to transform industrial modernity and move towards the Second Deep Transition. The current approaches to accelerating transitions in single systems could be expanded to accelerate transitions in multiple systems. For example, Kanger et al. (2020) propose a framework of six intervention points that include accelerating various niche innovations, connecting niche innovations, destabilising the current regime, addressing the repercussions of doing so, coordinating multi-regime interactions, and tilting the landscape. My research directs to a need to apply these on a broader scale precisely to *tilt the landscape*. In other words, future research in this area could focus not only on accelerating landscape-making niches but also on destabilisation strategies to disrupt the current traits of industrial modernity, addressing the repercussions of doing so, and on how to coordinate multi-system transitions and how the dependencies between systems could be either leveraged or redesigned in this context. Examples of destabilisation strategies can include directly protesting further investments in dangerous technological advances (see Biermann et al. (2022) for an example regarding solar geoengineering) or making groundwork for legal frameworks for granting legal rights to the natural environment so that those who are harming them can be held directly accountable (Boyd, 2017).

Finally, **STUDY III** emphasises the need to connect favourable landscape conditions with the capabilities required to initiate and direct these transformations. Thus, it is important to remember that enacting a deep sustainability transition necessitates not only the absence of constraints but also the presence of

landscape-making actors (**STUDY IV**). Furthermore, while my work did not empirically deal with the question of justice, it is undoubtedly a crucial research direction for making way for the Second Deep Transition (**STUDY IV**).

5.1.2 Implications for (sustainability) science

STUDIES I–III additionally make a significant contribution by offering a holistic perspective on the development and current state of industrial societies, which has been missing in sustainability science. The introduction of my thesis explores various factors that could be driving environmental degradation, including human population overshoot (Vollset et al., 2020), affluence (Wiedmann et al., 2020), growth orientation (Hickel et al., 2022a), increasing resource consumption (Schaffartzik et al., 2014; Haberl et al., 2019), and toxic institutions (Hughes et al., 2021). **STUDIES I–III** indicate that these issues could all be symptoms of a deeper problem rooted in industrial societies' shared values, institutional structures, and practices. Based on the findings of **STUDIES I** and **II**, it can be inferred that industrial modernity evolved similarly across countries with varying economic conditions, social structures, populations, energy consumption, and industrialisation timelines. These include Australia, India, Germany, the United States, and the USSR/Russia. Although these findings are preliminary and require further research to establish a causal relationship between industrial modernity and the various developments identified, they suggest that industrialism is a complex phenomenon with its own internal mechanisms that are not solely attributable to economic or social structures. Furthermore, the ruptures detected in the environmental domain (**STUDIES I–II**) suggest that, indeed, there is very little change in the workings of industrial societies if one only focuses on practices. However, seeds of change could be observed in ideational and institutional dimensions.

This holistic view allows to articulate that industrial societies' approach to technoscience could be a major landscape-level barrier to enacting a deep sustainability turn (**STUDIES I–III**). **STUDIES I** and **II** suggest a dominance of an ecological modernisation mindset (Hubler, 1982; Jänicke, 1984; Spaargaren & Mol, 1992). The dominance of the view is supported by the increasing ideational and institutional environmental awareness, the techno-optimist public discourse that has re-emerged in recent decades, and the continuous technocratic emphasis throughout the observation period (**STUDIES I–II**). The ecological modernisation approach aligns highly with dominant interests, power structures, and the green growth narrative (Wiedmann et al., 2020), as demonstrated by its broad acceptance at the core of policymaking in the European Union[7] (Machin, 2020) and the United Nations' Sustainable Development Goals (Weber & Weber,

[7] Kallis et al. (2023) demonstrate that alternative perspectives on growth that would go beyond the ecological modernisation approach, such as degrowth and ecosocialism, are present among the EU's political elites, but they have yet to be translated into concrete policy.

2020). It is often framed as the only solution to environmental degradation (Leipold, 2021), leaving out other possible narratives such as the local government-led low-carbon transformation, autonomous ecological living, or degrowth initiatives (Luederitz et al., 2017).

Although the shift toward ecological modernisation represents a major internal transformation of industrial modernity, it is likely still not enough to address the deep-seated problems of industrial societies (**STUDIES I–II**). There are several reasons for this. First, the tunnel vision on ecological modernisation in itself is problematic. Focusing on ecological modernisation stifles the cross-pollination of ideas between different sustainability narratives and forecloses the possibility of exploring a broader range of possibilities to transform the current way of doing things (Demaria & Kothari, 2020; Escobar, 2018). Moreover, it reduces the complexity of sustainability issues in a way that is not only arbitrary but also ill-equipped to deal with deep uncertainty inherent to transformations such as the Second Deep Transition (Stirling, 2010). Finally, and perhaps most importantly, empirical evidence does not support ecological modernisation's central tenet of absolute decoupling from resource use and carbon emissions (Hickel & Kallis, 2020).

Second, according to the DT approach, transformation in industrial modernity is needed that would cover both of its major themes, nature as a blindspot *and* overconfidence in technoscience (**STUDIES I–II**). Therefore, addressing the technoscientific legacy of industrial modernity could be essential to make the landscape conditions more favourable for the fundamental socio-technical change needed for the Second Deep Transition. This rethinking could enable the translation of the ruptures in environmental ideas and institutions into tangible gains in practices and make the landscape more favourable toward a deep transformation (**STUDIES I–III**). Further emphasis on technoscience, however, could be counterproductive, as research shows that technological promises, rather than leading to accelerated climate action and changes in practices, actually tend to result in policy inaction (McLaren & Markusson, 2020).

Somewhat ironically, the sciences, which are responsible for the current issues with technoscience, are also the only ones that can rethink these traits of industrial modernity and provide a solution. As Beck (1992) puts it, "not only does the industrial utilisation of scientific results create problems; science also provides the means – the categories and the cognitive equipment to recognise and present the problems as problems at all, or just not to do so. Finally, science also provides the prerequisites for overcoming the threats for which it is responsible itself" (Beck, 1992: 163). Fortunately, efforts are underway to address these issues in all three domains. Examples of these include the circular economy (Geissdoerfer et al., 2017), the slow science movement (Stengers, 2016), and value-based engineering (Boehm, 2003). Given that institutional capacity has been deemed one of the most crucial components of transformative potential (Andrijevic et al., 2020; Barnes et al., 2020) and **STUDY III** found restrictions in the institutional dimension almost as high as those in the practice-related dimension, I will discuss

two examples of institutional change in more detail: the precautionary principle (PP) and the Responsible Research and Innovation (RRI) framework.

Because **STUDIES I** and **II** found more significant ruptures in the environmental domain, it is unsurprising that the first example, the PP, originated in the environmental domain. First introduced in German environmental law in 1972, the PP calls for adopting precautionary measures to address potential risks in environmental policy (Currie, 1981). This principle opposes the view that societal interests should be prioritised over environmental concerns, an ideational trait of industrial modernity. Since its inception, the PP has been adopted in various international environmental agreements (e.g., the Rio Declaration on Environment and Development, 1992; the Stockholm Convention on Persistent Organic Pollutants, 2001; and the Cartagena Protocol on Biosafety, 2000). There have been calls to extend the PP to technoscientific governance, as exemplified by the RRI framework proposed by Owen et al. (2013). Opposing the uncritical view of technoscience, this framework argues that to address technoscientific risks, there is a need to foster "reflexive capital", which entails evaluating the purposes, processes, and products of science and innovation in an iterative, inclusive, and deliberative manner (*ibid.*). There is growing support for RRI beyond academia[8]. For example, Peters et al. (2020) propose guidelines for the ethical design of autonomous and intelligent systems for engineers working in industry, indicating that a shift in a more responsible direction is also already underway in professional technology organisations.

Implementing substantial changes like the PP and the RRI framework is no easy feat. It is a process that takes time, as evidenced by the slow progress of the PP from national law to international agreements and the current uneven institutionalisation of the RRI (Owen et al., 2021). Moreover, these ideas are ambitious and controversial, which makes them unpopular and difficult to implement. For one, the RRI necessitates changes to existing values, science cultures, and even the economic objectives of R&D (Tabarés et al., 2022). The PP, on the other hand, has been called "anti-science" because it questions the inherent goodness of technoscientific advances (Stirling, 2023). Despite these challenges, I believe it is crucial to continue researching the synergies between the domains of environment, science, and technology/innovation and to find ways to accelerate the adoption of approaches like the RRI. It is also important to remember that these precautionary approaches are often seen as anti-science precisely because they challenge the underlying optimism about technoscience characteristic of industrial modernity. However, based on the findings of **STUDIES I–III**, I believe that directing our intellectual and financial resources toward remaking our approach to research to find a better balance between pushing the frontier and ensuring that we are not doing more harm than good in the long run is the best path forward. For example, as Ord (2020: 29) points out, the entire spending on reducing existential risks from advanced artificial intelligence is in the tens of millions of

[8] The RRI was one of the main focus areas for the European Commission's research program Horizon 2020.

dollars, while the global budget for improving artificial intelligence capabilities is in the billions of dollars. This difference indicates that we are currently very far from an even balance.

5.2 Implications for policymaking

The proposition to transform the traits of industrial modernity calls not only a fundamental change in research but also for policy action. However, here too, there might be some apprehension, especially regarding industrial societies' approach to technoscience. The IPCC (2023) reports that it is now likely that global warming will exceed 1.5°C during the 21st century. If the aim is to avoid the most adverse impacts, technological mitigation and adaptation options remain a part of the solution[9]. Paradoxically, the crisis demands fast action, while the precautionary approaches discussed in the section above call to slow down, include the opinion of all affected stakeholders, and reconsider when necessary (Owen et al., 2013). However, the question is if action following the current techno-optimist traits of industrial modernity indeed provides a fast solution to the problems at hand. For example, Jacobson et al. (2019) claim that a complete transition to renewable energy will result in a 57.1% reduction in global energy demand. While intuitively a step in the right direction, just a techno-fix change such as this will likely further emphasise the continued legacy of industrial modernity. This is precisely because the approach overlooks pervasive rebound effects that have repeatedly offset most gains in energy efficiency (Brockway et al., 2021). Instead, if an accelerated speed of change is desired, my research points me to suggest technology to be viewed as a tool that complements approaches that address the root causes of the problem, such as deep transformative social and institutional innovation (Hughes et al., 2021; Pel et al., 2020). As Rogge et al. (2023) propose, these innovations should be given equal importance and endorsement in policy discussions on climate change as technological

[9] First, I will note that I am not referring to continuously pushing the technological frontier as it is important to keep in mind that many argue (e.g., Jacobson et al., 2019; Larson et al., 2021) that we already have the necessary technologies for the transition and the barrier is mainly institutional (Gazmararian & Tingley, 2023; Meckling & Karplus 2023). Second, while climate adaptation proves increasingly critical, I will deliberately focus on the role of policymakers in driving the transformation of industrial modernity to foster climate mitigation. As previously emphasised, current developments align with the ecological modernisation mindset. Similarly, climate adaptation actions appear to concede defeat and perpetuate the status quo. This intuition is confirmed by the prevailing understanding that climate adaptation has primarily been and will be incremental and reactive, contingent upon the climate events of the time (Massetti & Mendelsohn, 2018). The inclination towards reactive responses to environmental consequences, in turn, aligns closely with the prevailing traits of industrial modernity. Therefore, while climate adaptation activities do demand policy attention as they are crucial in alleviating human suffering, they do not necessarily challenge the traits of industrial modernity.

innovation. For if the root cause is not addressed in policymaking, the continuities in industrial modernity found in **STUDIES I** and **II** give very little reason to believe that relying on just technological options is enough to transform the current practices.

When analysing the current practices, reducing material footprints and energy consumption will indeed be a challenging policy goal for many rich nations (**STUDY III**). However, it is only one piece of the puzzle. Although research on post-growth suggests that poor nations are less of a sustainability concern (Hickel, 2020), **STUDY III** indicates that ideas and institutions play a significant role in limiting the capacity to enact the Second Deep Transition. It is just as crucial for developed countries to address the environmental damage they have already caused as it is for developing countries with current low practice-related scores to anticipate the worst effects of technology-centric and growth-oriented practices. The groundwork for this can be done, for example, through the strategic reframing of public discourse and the mobilisation of transformative innovation policy (Haddad & Bergek, 2023; Schot & Steinmueller, 2018). Taking steps in a new direction is critical because these nations' scores indicate that conventional attitudes and institutions regarding the natural environment and technoscience are still prevalent (**STUDY III**). If rich countries continue to be simply imitated, these trends will likely contribute to future environmental degradation. Thus, in different ways, the policy challenge of utmost importance on both sides of the Global North/South divide seems to be making frugality aspirational.

In addition to taking various approaches to reach the same goal, there is also the question of competition vs. collaboration. The search for "solutions" to the sustainability crisis is a competitive endeavour, with economic objectives to win the race[10] and harness the most advantages from being the first to find a solution that "sticks". This can mean that, for countries in the race, there is something to be gained from not discussing their plans in detail. However, the proponents of experimentalist governance (Sabel & Victor, 2022) argue that the strictly results-oriented approach, which only compares the outcomes and not the notes on the different attempts and the mistakes made in reaching them, can be counterproductive as it inhibits pooled learning. At the organisation level, open innovation approaches (Chesbrough, 2003; Dahlander & Gann, 2010) that involve collaboration between different actors and participation in a co-creative process have proved to be increasingly relevant in the field of sustainability (Payán-Sánchez et al., 2021). Both of these, on different levels, underline the need for cooperation. Thus, to build and increase institutional capacity, cooperative approaches such as open innovation and experimentalist governance prove increasingly crucial for different regions to make piecemeal contributions to the major transformative change and enable deep mutual learning in an international arena (Kanger &

[10] There is also incentive not to enter the race; see, for example, Newell (2021: 75–77) for a discussion on how incumbent actors tend to find ways to legitimise the need to expand the current ways of doing things in the context of energy transitions.

Schot, 2019; Schot & Steinmueller, 2018). The best example the success of co-operative approaches is the execution of the Montreal Protocol (1984) resulting in phasing out the production and consumption of ozone-depleting substances. Sabel and Victor (2022: 18-47) highlight it precisely for its experimentalist and cooperative nature.

The latter brings me to highlight further that joint efforts can be made to find solutions that work best for each country or region. According to **STUDY III**, the onset of the Second Deep Transition is possible in a diverse range of countries with varying socioeconomic conditions. Research also indicates that policy-makers respond differently to similar challenges based on their unique circum-stances (Meckling et al., 2022). Similarly, the emergence of different landscape-making niche innovations (e.g., degrowth, rights of nature, frugal innovation) tends to be geographically varied. Thus, indeed, there is an international arena to find solutions for the challenges identified in **STUDIES I–III**, including the narrow focus of ecological modernisation, the overreliance on technological solutions, and, ultimately, the search for alternatives to the traits of industrial modernity. Policymakers must collaborate and share information and experiences with various policies and programs to succeed.

I understand that the reader may perceive a discussion on cooperation and joint efforts as naive, especially considering the prevalence of competition and protec-tionism in today's world. For instance, despite the potential for many European countries to spearhead the Second Deep Transition (**STUDY III**), the prevailing narratives and development plans for the EU are still centred around green growth and ecological modernisation (Kallis et al., 2024). Moreover, crises such as Russia's attack on Ukraine and economic competition between global powers like the United States and China can drive countries towards trade protectionism, which can subsequently lead to increased carbon emissions (Wang et al., 2023). Nevertheless, I believe researchers must persistently remind policymakers that we already possess numerous solutions capable of altering our current trajectory. In alignment with the IPCC (2023), I maintain that it is not too late to surmount the frequently discussed political barriers hindering climate change mitigation. It is important to acknowledge that no country can evade the adverse impacts of the climate crisis and continue to thrive without a hindrance while global warming devastates the livelihoods of those in more vulnerable nations. However, a country could emerge as the catalyst for the Second Deep Transition.

Having highlighted the possibility of a country leading the Second Deep Tran-sition, it is crucial to assess the state's capacity to spearhead such a shift. Scholars debate whether the state's capacity to accelerate sustainability is declining (Mol, 2016) or experiencing a resurgence (Geels, 2024: 97), revealing there are both obstacles and opportunities.

Johnstone and Newell (2018) discuss the state's dual role as both the "enabler and barrier" to sustainability transformations. For instance, while the concept of a green state envisions the state as a regulatory mechanism guiding markets and society towards sustainability, the state often has significant investments in carbon-intensive industries (Babić & Dixon, 2023). Drawing on neo-Marxist and

neo-Weberian perspectives, Eckersley (2022) contends that the state is inherently limited in its ability to drive a deep sustainability transition due to conflicts with its core functions, such as capital accumulation and legitimation. This limitation, known as the "glass ceiling" of environmental transformation (Hausknost 2017; 2020), poses a structural barrier that hinders the state from advancing sustainability beyond a certain threshold, as further progress would compromise its other essential roles. However, Eckersley (2022) also identifies state-society complexes where transitions are already underway, suggesting that efforts should focus on amplifying these existing potentials. Additionally, Geels (2024: 96) contends that while accelerating sustainability has historically clashed with other state functions, recent events (e.g., war in Ukraine, energy crisis, net-zero pledges) have created a window of opportunity, framing sustainability as a crucial goal in fulfilling these functions. For example, Putin's war has prompted a discursive shift and increased support for renewable energy funding and implementation, linking it to state security and sovereignty (Wiertz et al., 2023).

These insights lead me to propose strategies that bridge the gap between current practices and potential alternatives within the current epoch, as well as approaches to expand existing limits. First, meta-governance principles (Bornemann et al., 2024) could be applied to shape governance arrangements and functions to be better aligned with transforming industrial modernity. For instance, RRI principles could widely be included in innovation policy and strategy. Second, policymakers could weaken the status quo by pushing the state closer to the glass ceiling. For example, Babić and Dixon (2023) suggest retaining state investments in certain industries but shifting their focus towards greener practices. While this aligns with ecological modernisation theory, which I have critiqued, such incremental changes could pave the way for transformative investments (Penna et al., 2023) that target systemic change. Still, if the aim is to transform industrial modernity, it is important that deliberate policy actions are made to stimulate and accelerate landscape-making niches.

The latter brings me to my last suggestion, identifying and supporting smaller initiatives that foster landscape-making niches. Greater attention should be given to windows of opportunity where change is already possible by experimenting with more deliberative and direct-democratic decision-making (Hausknost & Hammond, 2020). For instance, while enacting a national law granting rights to all non-human entities might be overly ambitious, local governments can leverage public pressure through direct decision-making platforms like public assemblies to address local environmental harms. Citizens' climate assemblies (cf. Devaney et al., 2020) are a good example of this approach. Similarly, in the domain of technoscience, new meanings, actor alliances, and communities could be created through supporting transdisciplinarity (Lang et al., 2012). This could involve actively funding and creating space for research formats that integrate knowledge from diverse research fields and stakeholders to develop a more comprehensive understanding of the potential limitations of technoscience in driving the deep sustainability turn.

To conclude this section, I will emphasise another key element of states' capacity for a deep sustainability turn, democratic governance. Political science literature has discussed how theories and practices of democracy will fare in the context of the current climate crisis (e.g., Fischer, 2017; Fritsch, 2023; Machin, 2022). The dominant neoliberal worldview supports the above-discussed and problematic ecological modernisation, which, as Fischer (2017) argues, either intentionally or unintentionally, sidesteps the questions of environmental justice and democracy by pushing yet another technology as *the* solution. Since neoliberalism has led to the perception that the private sector is more effective and efficient than the government, it has also led to governments outsourcing their capacity to address the climate crisis, further undermining democratic processes (Mazzucato & Collington, 2023). The unfitness of the very same worldview for the current time is also made apparent by policy failures such as Elon Musk (Heer, 2023), who now, without a democratic mandate, has the power to make unilateral decisions affecting whole nations (see, for example, Robinson's (2023) discussion on Musk's involvement in the war in Ukraine). At the same time, it is becoming evident that countries with strong democracies and redistributive institutions have the capacity to be frontrunners in sustainability efforts (Meckling et al., 2022)[11]. Thus, in addition to shaping practices fit for the future (Fischer, 2017; Keller et al., 2022), the role of citizens in our response to the climate crisis ought to be to elect representatives that support democratic decision-making and leave room for experimentation. In the case where there are no such representatives, to become one. For if the democratic discussion about our future is neglected in democratic countries, there is very little room for hope. Especially since most of the world's population does not live under democracy and, in many countries, there is currently very little evidence of the coming of the Second Deep Transition (**STUDY III)**.

[11] It should be noted that Victor et al. (2022) found, after controlling for institutional quality and climate ambitions, some less-democratic countries to be making more credible commitments in international climate policy.

CONCLUSIONS

The Deep Transitions framework guiding my thesis theorises the need to transform industrial modernity to accelerate the onset of the Second Deep Transition, a fundamental change in the workings of industrial societies that promises to alleviate current challenges related to climate change and ecological degradation. My thesis sought to contribute to sustainability transitions studies and sustainability science by operationalising the theoretical notion of industrial modernity, an umbrella term for various industrialisation-related continuities. More precisely, guided by the research agenda proposed in **STUDY IV** and the two specific research questions, I measured the continuities, ruptures, and the current state of industrial modernity. I will give concrete answers to the research questions in this chapter.

I. To what extent is it possible to observe continuities and ruptures in industrial modernity in different countries between 1900 and 2020?

- The evolution of industrial modernity between 1900–2020 was generally uniform in countries with diverse income levels, social structures, populations, energy consumption, and timing of industrialisation (**STUDIES I–II**). In other words, several continuities were observed in all five countries analysed: Australia, Germany, India, the United States, and the USSR/ Russia.
- Several traits describing the ideas, institutions, and practices characteristic of industrial modernity displayed ruptures. However, this was not true of all traits measured, particularly those related to technoscience (**STUDY II**). Furthermore, most ruptures in the practice-related dimension were just emergent. Measuring the current state of industrial modernity further confirmed these findings (**STUDY III**). Out of the countries analysed, Germany exhibited the most signs of rupture (**STUDIES I–II**).

II. Where is the onset of the Second Deep Transition the most likely?

- There were substantial differences in the manifestation of the traits of industrial modernity and, thus, the capacity to enact transformative change, regardless of development level (**STUDY III**). Sweden was the absolute best performer out of the 63 countries analysed. In the general ranking, the top five countries were Sweden, Japan, Spain, South Korea, and Germany. Belarus, Egypt, Qatar, and Kuwait occupied the bottom of the ranking.
- The dimension of practices posed the highest structural restrictions to transformative change necessary for the Second Deep Transition, although the institutional dimension also proved problematic (**STUDY III**). It follows that the onset of the Second Deep Transition is likelier in countries that can surmount the restrictions posed by these dimensions.

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SUMMARY IN ESTONIAN

Tööstusliku modernsuse mõõtmine 1900–2020, võrdlev perspektiiv

Kestliku arengu kontseptsioon sõnastati esmakordselt Bruntlandi aruandes juba 1987. aastal. Mõjuka aruande definitsiooni järgi peaks kestlik areng tagama tänase põlvkonna vajaduste rahuldamise, ilma et kahjustataks tulevaste põlvede võimalusi rahuldada omi vajadusi (ÜRO, 1987). Sellisel kujul seisis kestlik areng selgelt vastuolus valitsenud arusaamaga, kus tööstusühiskondade majandus saab piirideta kasvada (Meadows et al., 1972). Hoolimata pingutustest kliimamuutusega võitluses ning ressursside ammendumise ja bioloogilise mitmekesisuse vähenemise pidurdamises, on tööstusühiskonnad jätkuvalt jätkusuutmatul arengurajal (IPBES, 2019; IPCC, 2023). Veelgi enam, tallatud rada on viimastel kümnenditel süvenenud (McNeill & Engelke, 2016; Steffen et al., 2015). Märgilise tähtsusega on pidevalt kasvav energia- ja materjalikasutus (Haas et al., 2020; Haberl et al., 2019) ning kestev planeedi piiride ületamine ühiskondlike vajaduste rahuldamiseks (Fanning et al., 2022; O'Neill et al., 2018; Richardson et al., 2023). Samas viitavad teadustööd erinevatest kestlikkusega seotud valdkondadest ka sellele, et tööstusühiskondade aregus võib täheldada suunamuutust. Positiivset suunda näitlikustavad keskkonnaväärtuste, -institutsioonide ja -liikumiste lai levik (Dietz et al., 2005; Giugni & Grasso, 2015). Ka keskkonnapoliitika on rangem kui kunagi varem (Galeotti et al., 2020) ning muutuseid on märgata ka tehnoloogiliste uuenduste trajektoorides, näiteks rohepatendid näitavad kasvutrendi (Probst et al., 2021).

Siiski, olenemata käputäiest toodud näidetest ühe või teise poole toetuseks, ei ole täpselt selge millised tööstusühiskonade osad süvendavad jätkusuutmatut arengurada ning millised osad on juba muutunud, sest tööstusühiskondade arengust puudub terviklik ülevaade. Viimast eelkõige seepärast, et teadustöö, mis kestlikkusega tegeleb, kipub jääma valdkondlikesse piirdidesse (Clark ja Harley, 2020).

Oma doktoritöös soovisin erinevate valdkondade teadmised kokku tuua ja luua tervikliku pildi tööstusühiskondade lähenemisest keskkonnale, teadusele ja tehnoloogiale. Probleemile lähenemiseks kasutasin Suurte Siirete raamistikus (Kanger ja Schot, 2019; Schot ja Kanger, 2018; Kanger, 2022) defineeritud tööstuslikku modernsust, mis kirjeldab tööstusühiskondade suundumusi alates Tööstusrevolutsioonist. Laias laastus iseloomustavad tööstuslikku modernsust kaks suurt teemat: usk progressi läbi teaduse ja tehnoloogia ning ühiskondlike vajaduste eelistamine keskkonnamurede ees. Püstitasin tööstusliku modernsuse mõõtmiseks läbi aja ja ruumi kaks uurimisküsimust:

1. Mil määral on võimalik vaadelda tööstuslikus modernsuses jätkuvusi ja katkestusi erinevates riikides ajavahemikus 1900–2020? (**UURIMUS I** ja **UURIMUS II**)

2. Millises riigis on tööstuslikku modernsust praegu kõige vähem ehk kust võiks alguse saada radikaalne pööre kestlikkuse suunas? (**UURIMUS III**)

Uurimisküsimustele vastamiseks kasutasime kvantitatiivseid meetodeid, rakendades aegridade analüüsi ning ajalehtede ja teiste meediaväljaannete tekstikaevet, et analüüsida muutusi keskkonda, teadust ja tehnoloogiat puudutavates ideedes, institutsioonides ja praktikates (**UURIMUS I** ja **UURIMUS II**). Samuti töötasin välja koondnäitaja Tööstusliku Modernsuse Indeks (ingl *Industrial Modernity Index)*, et hinnata tööstusliku modernsuse geograafilist jaotumist 63 riigis üle maailma **(UURIMUS III**). Järgmiseks esitan tulemused vastavalt uurimisküsimustele.

I. Mil määral on võimalik vaadelda tööstuslikus modernsuses jätkuvusi ja katkestusi erinevates riikides ajavahemikus 1900–2020?

- Tööstusliku modernsuse levik oli võrdlemisi ühetaoline erineva sissetulekutaseme, sostsiaalse ülesehituse, rahvaarvu, energiatarbimise ja industrialiseerimise ajastusega riikides. Teisisõnu, kõigis viies analüüsitud riigis – Austraalias, Saksamaal, Indias, Ameerika Ühendriikides ja NSVLs/Venemaal – võis täheldada sarnaseid jätkuvusi (**UURIMUS I** ja **UURIMUS II**).
- Mitmed tunnused, mis kirjeldavad tööstuslikule modernsusele iseloomulikke ideid, institutsioone ja praktikaid katkesid mõõteperioodi vältel. Kuid see ei kehtinud kõigi mõõdetud tunnuste kohta, eriti nende kohta, mis on seotud tehnoteadusega **(UURIMUS II**). Ka tööstusliku modernsuse praeguse leviku mõõtmine viitas sarnastele suundumustele (**UURING III**). Lisaks olid enamik praktikates tuvastatud katkestused pelgalt esile kerkimas (**UURIMUS II**). Analüüsitud riikidest võis Saksamaa andmetes täheldada kõige rohkem märke katkestustest (**UURIMUS I** ja **UURIMUS II**).

II. Millises riigis on tööstuslikku modernsust praegu kõige vähem ehk kust võiks alguse saada radikaalne pööre kestlikkuse suunas?

- Tööstusliku modernsuse tunnuste avaldumises ja seega ka võimes ellu viia radikaalseid muutusi kestlikkuse suunas olid märkimisväärsed erinevused, sõltumata arengutasemest (**UURIMUS III).** Rootsi oli 63st analüüsitud riigist absoluutne parim. Üldises järjestuses olid esiviisikus Rootsi järel Jaapan, Hispaania, Lõuna-Korea ja Saksamaa. Edetabeli allosas asusid Valgevene, Egiptus, Katar ja Kuveit.
- Kõige suuremaks tulevikuväljakutseks võis pidada praktikate dimensiooni, ehkki ka institutsioonide dimensioon osutus probleemseks (**UURIMUS III**). Sellest järeldub, et radikaalne muutus kestlikkuse suunas on tõenäolisem riikides, mis suudavad ületada nende dimensioonide poolt seatud piirangud.

Minu doktoritöö panustab siirdeuuringute valdkonda, kuna operatsionaliseerin tööstusliku modernsuse mõiste. Samuti annan kestlikkust uurivatele teadustele konkreetse ja teooriapõhise arusaama sellest, kuidas tööstusühiskondade ajalooline pärand panustab kliimakriisi. Lisaks, ühendades killustatud tähelepanekud keskkonna- ja tehnoteaduslike ideede, institutsioonide ja praktikate kohta, pakun enda doktoritööga tervikliku vaate tööstusühiskondade arengust, mis oli varem teaduskirjandusest puudu.

PUBLICATIONS

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Publications:

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