Unravelling

UNRAVELLING: THE DYNAMICS OF TECHNOLOGICAL DECLINE

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UNRAVELLING: THE DYNAMICS OF TECHNOLOGICAL DECLINE

Dissertation

to obtain the degree of Doctor at Maastricht University,

on the authority of the Rector Magnificus,

Prof. Dr. Pamela Habibović

in accordance with the decision of the Board of Deans,

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by

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For my family

Contents

Summary (English)

This PhD dissertation by Zahar Coreţchii, better known by his academic pen name Zahar Koretsky, is a study of three historical cases of decline of technologies. The dissertation belongs to the fields of Science, Technology and Society studies and Sustainability Transitions studies. Zahar explores the processes of decline of cloud seeding in the US, the incandescent light bulb in the EU, and the *Ural* computer in Russia, and presents an approach to trace, make sense and, possibly, act on technological decline.

In the dissertation decline is conceptualised as "unravelling" of entangled socio-material elements that constitute a technology: materials, meanings and forms of competences. They "unravel" as competences become less used, materials are harder to come by, and the meanings turn outdated. Six ideal-type pathways for the outcome of unravelling are formulated, some of which result in decline, while others in its reversal and a return of a technology.

There is a growing recognition in the academic, policy and activist worlds of an urgency to navigate the current climate crisis by refusing to support production and use of certain technologies and infrastructures that are not environmentally sustainable (anymore). *Unravelling: The Dynamics of Technological Decline* may be of relevance to scholars, policy-makers and anyone else curious of reading about why some technologies remain abandoned and do not return (such as an old computer line from the 1960s), while others do (such as cloud seeding for geoengineering or the vinyl record). The book may also be of interest for those curious about preventing or slowing down the decline of desirable technologies – desirable for ethical, environmental or other reasons, e.g. traditional crafts, traditional farming, or cycling.

Samenvatting (Nederlands)

Deze dissertatie van Zahar Coreţchii, beter bekend onder zijn academische pseudoniem Zahar Koretsky, gaat over de afname van de productie en het gebruik van drie historische technologieën. De dissertatie valt onder de vakgebieden Science, Technology and Society studies (wetenschap- en techniekstudies) en Sustainability Transitions studies. Zahar onderzoekt de afname van de productie van regen in de VS, de gloeilamp in de EU, en de *Ural*-computer in Rusland, en presenteert een benadering om technologische afname te traceren, te begrijpen en er mogelijk naar te

handelen.

In het proefschrift wordt verval geconceptualiseerd als het "ontrafelen" van verstrengelde sociaal-materiële elementen die een technologie vormen: materialen, betekenissen en vormen van competenties. Ze "ontrafelen" naarmate competenties minder worden gebruikt, materialen moeilijker te verkrijgen zijn, en betekenissen verouderd raken. Er worden zes ideaaltypische paden voor de uitkomst van ontrafeling geformuleerd, waarvan sommige resulteren in afname, en andere in een tegenovergesteld proces en de terugkeer van een technologie.

In academische, beleids- en activistische werelden wordt steeds meer erkend dat het dringend noodzakelijk is om de huidige klimaatcrisis het hoofd te bieden door te stoppen met het ondersteunen van bepaalde technologieën en infrastructuren die niet (meer) duurzaam zijn. *Unravelling: The Dynamics of Technological Decline* ("Ontrafeling: De Dynamiek van Technologische Afname") kan van belang zijn voor wetenschappers, beleidsmakers en iedereen die wil lezen over waarom sommige technologieën afgedankt worden en niet terugkeren (zoals een oude computerlijn uit de jaren 1960s), terwijl andere dat wel doen (zoals productie van regen voor geo-engineering of de vinylplaat). Het boek kan ook interessant zijn voor iedereen die nieuwsgierig is naar het voorkomen of vertragen van de afname van wenselijke technologieën – die wenselijk zijn om ethische, milieu- of andere redenen, bijvoorbeeld traditionele ambachten, traditionele landbouw, of fietsen.

Резюме (Русский)

Докторская диссертация «Распутывание и динамика технологического сокращения» за авторством Захара Ивановича Корецкого является работой в междисциплинарных сферах исследований науки, технологий и общества (Science, Technology and Society) и переходов к устойчивости (Sustainability Transitions). В ней изучены три исторических кейса сокращения (decline) технологий – «засев облаков» в США, лампа накаливания в Европе и советский компьютер «Урал» – на основе которых предлагается подход для отслеживания, понимания и, возможно, принятия мер по технологическому сокращению.

В диссертации сокращение исследовано как «распутывание» спутанных социо-материальных аспектов, из которых соткана та или иная технология: материя, смыслы и формы навыков (компетенций). Они «распутываются» друг от друга когда компетенции используются меньше, материальные элементы сложнее добыть, а смыслы теряют актуальность. В книге сформулированы шесть идеальных типов путей, по которым проходит распутывание. Некоторые из

этих путей заканчиваются сокращением, а некоторые – его обращением вспять.

Всё больше активистов, академиков и руководителей (policy makers) признает, что необходимо срочно справиться с текущим климатическим кризисом путем отказа от поддержки производства и использования определенных технологий и инфраструктуры, которые (больше) не устойчивы с точки зрения окружающей среды. «Распутывание и динамика технологического сокращения» может быть полезна ученым, руководителям и всем прочим, кого интересует почему некоторые технологии остаются заброшенными (как, например, старая линейка компьютеров из 1960-х), а другие возвращаются (как, например, засев облаков для геоинженерии или виниловые пластинки). Эта книга также может быть интересна всем, кому любопытно как предотвратить или замедлить упадок желательных технологий – желательных с этической, экологической или других точек зрения, как, например, традиционные ремесла, традиционное сельское хозяйство или езда на велосипеде.

Propositions

1. To study the socio-technical processes of *technological decline*, a metaphor of "unravelling" is useful to conceptualise the loosening and unknotting of the seamless web of meanings, competences and material entities constitutive of a given technology.
2. To counteract the prevalence of studies on new and emergent technologies, scholars in science, technology and society (STS) and in transitions studies should also focus more on technologies' *'end of life'*.
3. After declining, some technologies *return*, such as cloud seeding for geo-engineering or the vinyl record.
4. STS scholars should not shy away from *middle range theorisation* in favour of exclusively exploring the messiness of case studies.
5. The proposed unravelling *approach* may help study future cases of decline.
6. For technologies, in broad sense, such as a coal-fired power plant, internal combustion engine, or mass-scale digital 'snooping' and autonomous killer robots, it is already too late to try to steer their *development*, as is traditionally the task of Technology Assessment and Responsible Research and Innovation. Transitions away from these technologies need to be *accelerated* with the help of more active governments.
7. Because transforming, nudging and offering alternative technologies via the market is insufficient to address the climate crisis, governments should acquire *capabilities* to phase out those technologies that are decided to be undesirable.
8. For deliberate decline of an established technology, governance actors may need to *support* the unravelling processes by way of, for instance, awareness raising, resource management, regulation and monitoring, leaving room for those with interest to continue working in a niche (in which case technology impacts could be better controlled), as well as trade instruments and international agreements for leveraging other countries' decline of the given technology.

Chapter 1. **Introduction**

1.1. Problematisation

> "…nor were all bicycles thrown in the ditch and all horses shot when the first Model T rolled off the assembly line."
>
> (Lindqvist, 1994)

This thesis will focus on the study of processes involved in technological decline. As the quote above hints, it is not a straightforward or automatic process of substitution—otherwise this would have been one short book! Technology, if understood broadly as a "configuration that works" (Rip & Kemp, 1998, p. 330), is in many ways a characteristic feature of humanity (Ellul, 1964). Technologies are "society in the making" (Callon, 1987) and "society made durable" (Latour, 1991). They embody and preserve societal values, reflecting fashion, beliefs and practices of a given time and place. Technologies are delegated the power to enforce rules and value judgments (Foucault, 1977). Like commodities are "crystallized labour" (Marx, 1976, p. 9), so are, if not more, I would argue, technologies. A key research interest in science and technology studies (STS), and the adjacent transition studies, is to understand society better through the study of technology.

A key insight from this literature is that technology becomes painfully obvious when it is not functioning as expected or at all. The problems with technology that does not work are quickly felt and are more impactful the more entwined the technology is with norms, culture and practices. Consider the historical examples of the controversial coal mining curtailment in the UK (Turnheim, 2012; Turnheim & Geels, 2012), the paralysing oil shortages in the West in the 1970s (e.g. Burnett, 1991; Rüdiger, 2014), the disruptive pushing-out of traditional hand weaving in India (Mamipudi, 2016), or discontinuations of popular products (e.g. Tushman & Anderson, 1986; Ehrnberg, 1995; Levain et al., 2015) such as the Polaroid (Minniti, 2016) or the incandescent light bulb (Stegmaier, Visser, et al., 2021). Irrespective of how visibly or quickly technologies disappear, their disappearance contributes to small or large economic, environmental, cultural and individual losses. For example, the losses of blacksmithing, certain traditional crafts or cycling. Technologies can be fused with identities, whether it's hunt weapons of Tanzania tribes (e.g. Kaare, 1994) or cars in the US (e.g. Moyers, 1997; Ellsworth, 2005). A related and reversed problem, or sometimes hazard, is an unexpected comeback of a previously supposedly phased out technology. One example is chemical weapons, banned internationally in

1997 but used in Syria in 2013 (OPCW, 2021); or weather modification, banned in 1978 but now gaining legitimacy as geoengineering (more on this case in Chapter 4). In all such cases, changes related to materiality of technology (i.e. unexpected physical absence or presence) caused changes in symbolic and social order (e.g. in skills and knowledge, relationships and interpretations, laws and policies), and *vice versa*.

Seeing the cultural-material entanglement of technologies, it is no surprise technologies are enabling both solutions and problems at the same time. For example, electricity use is a daily part of life of 90% of the global population (World Bank Global Electrification Database, 2021), and the number one source of global carbon emissions (Ritchie & Roser, 2020). Cars with internal combustion engines are indispensable in parts of the world with poor public transport or cycling options, and a major cause of emissions in the transport sector and a source of demand for fossil fuel extraction and processing industries (UNEP, 2019). Pesticides have been crucial to industry-scale food production, but they also tend to gravely destabilise ecosystems (Carson, 1962; IPCC, 2021). Digital technology has enabled all sorts of phenomena unthinkable ten years prior, like the effective disappearance of distance with the advent of digital communication, as well as ransomware attacks of public infrastructure such as hospitals and universities (Reshmi, 2021). In fact, technology is intricately connected to problems of and solutions for most, if not all, of the current societal challenges (e.g. EC, n.d.).

While in the first half of the 20th century technology was lauded as the embodiment of progress and solutions, and the second half increasingly acknowledged its risks and the need to try to steer its development and impacts, the beginning of the 21st century is seeing wider than ever discussions to abandon certain technology altogether. Unlike the early 19th century luddite[1] activity to limit the spread of new technology, there are increasing calls from the academic and policy (not to mention activism) worlds to seriously discuss and practice phasing out certain established technologies, systems and practices that are systemically, structurally damaging the environment and/or people's wellbeing. Research (e.g. Delina & Diesendorf, 2013; Rogge & Johnstone, 2017; Schlaile et al., 2017; C. Roberts et al., 2018) shows that ongoing transitions from environmentally unsustainable towards more sustainable modes of living are currently lagging and need to be accelerated, likely with help beyond market forces. Bolder claims are being made to prohibit certain old, unsustainable or otherwise undesirable ways of doing things. As an example, cities have been taking it upon themselves to ban cars from city centres. An anti-coal advocacy group

1 Luddite – one of a group of early 19th century English workmen destroying labour-saving machinery as a protest. Perhaps from Ned *Ludd*, 18th century Leicestershire workman who destroyed a knitting frame (Merriam-Webster, 2021).

Powering Past Coal Alliance emerged in 2019[2]. In 2020, the UK government requested public advice about phasing out petrol, diesel and hybrid cars (UK Department of Transport, 2020). Other high level initiatives emerged to regulate or curtail problematic technologies, such as artificial intelligence (Murgia & Shrikanth, 2019) and autonomous weapon systems (Gayle, 2019). Global response to the COVID pandemic in 2020 showed that a fast and widescale shift of modes of living, entangled with various technologies, is a real possibility.

The economic stagnation of the last decades (Streeck, 2014; Albertson, 2020) and instances of dissatisfaction with the way institutionalised decision-makers have been handling economic and environmental issues (Majone, 1998; Follesdal & Hix, 2006; Scharpf, 2009; Oreskes & Conway, 2010a, 2010b; Wille, 2010) may have something to do with the rise of attention to deliberate phase-out of technologies and systems, beyond the physical artefacts. One may notice this shift from a post-war modernist techno-optimism and from a postmodernist ironic scepticism and apathy, to a Greta Thunberg- and Extinction Rebellion-esque protest and determination to dismantle old systems that are perceived to be failing to deliver. As a response to financial and climate crises, geopolitical instability, political extremism, growing income gaps, technological threats of late capitalism, and a global pandemic, postmodern ironic scepticism and apathy is being replaced with a “metamodern” pragmatic idealism which oscillates between “a modern enthusiasm and a postmodern irony” (Vermeulen & van den Akker, 2010). The enthusiasm is now largely fuelled not by the need for post-war reconstruction and defence of a grand narrative (be it the free market or communism), the irony is fuelled not by introspection and desire to mock the surrounding material and ideological stability and comfort, but by the need for change and perceived powerlessness to fulfil this need.

The topic of deliberate technological decline is not limited to questions of environmental and socio-economic sustainability embodied in existing technologies, and continues with issues of morality and ethics of new technologies. Should mass-scale digital ‘snooping’ be tolerated (Kirchgaessner et al., 2021)? Or being sacked by an app (Crispin, 2021)? Or using, let alone being a target of, an autonomous weapon system (Wadhwa & Salkever, 2021)? Technologies such as these are already part of life in certain regions of the world and certain areas of practice, and so it is already getting too late to try to steer their *development*, as is traditionally the task of Technology Assessment and Responsible Research and Innovation policy methodologies.

So, the decline of existing technologies is a topic that is gaining more attention in academia, policy and activist circles. It is thus surprising that academic literature has

2 https://poweringpastcoal.org/ [Accessed on October 13, 2021]

been for a long time preoccupied mostly with studying emerging, new technologies and focused on their impacts (as I show in Chapter 2), forgetting about how and why technologies decline. Besides it being a pressing political topic, declining technologies is an academically interesting phenomenon by itself. Some technologies return, such as the electric car (first invented in the 1880s but afterwards outrun by the internal combustion engine), the vinyl record, the Polaroid, or the banned but still prominently sold incandescent light bulb (as discussed in Chapter 5). Some technologies remain in decline, such as the steam car or the VHS. Often, the remnants of a bygone technology still exert influence on their natural or cultural environment. A classic case is the white-marble ruins of ancient Roman temples and palaces, repurposed for barns and houses in the Middle Ages and during the Renaissance reflected in art. For a long time the presumed whiteness of the ruins was a symbol of ancient purity and grace, whereas at the time of Caesar and Marcus Aurelius those buildings were, in fact, richly decorated. In other cases, the declined technology leaves lasting marks in the form of nuclear waste and decommissioned infrastructure that often needs great effort and money to be erased. Old and gone technologies also generate relics in the language. For example, "to hang up a phone" or "Coca-Cola": today, there is usually nowhere to hang a modern phone, nor does Coca-Cola, one can hope, contain cocaine. Issues of residual effects of abandoned technology are part of the under-conceptualised topic of technological decline.

Technological decline is not trivial, but is often implicitly trivialised by economists by sheer omission. Literature on technology life cycles and disruptive innovation (e.g. Ayres, 1987; Yu & Hang, 2010; Taylor & Taylor, 2012) is illustrative here: models of the life cycle do not have room for decline or phase-out, nor are the processes and implications of disruptions described with any degree of granularity, except those relevant for management of innovation (more on this in Chapter 2). The implications of technological decline discussed thus far warrant a more detailed empirical study and analysis than is currently available. If societies are to deal with the climate crisis, we must learn very quickly about technological decline and how to navigate it without inducing much suffering. Figuring out where we are on this learning curve and what can be done to improve is, in a nutshell, the aim of this book.

By now I have mentioned the term 'technological decline', key for the present book, without making clear what I actually mean by it. I will use this term in the following chapters to mean an umbrella label for complex process of scaling down of production and/or use of a given technology to a niche and/or to complete abandonment. There is more to say about terminology and I return to this in Chapter 2. By putting the spotlight on technological decline, I do not aim to imply that deliberate decline will be the silver bullet for the current climate crisis. But it could be a part of the toolbox, alongside other means proposed in literature: system transitions (Geels, 2020b), climate finance and technological innovation (IPCC, 2018), or change of individual or collective practices and civil resistance (Feola, 2019). Technology phase-out, i.e. a specific regulation to induce decline, is a possible option and one that is already being implemented around the world, but it is also one that we do not have an advanced understanding of (more on this in Chapter 2).

Overall, I see three applied, or political reasons to study technological decline (next to a purely academic one to understand it better): (i) an urgency to navigate the climate crisis in both mitigation (phasing out technologies whose use contributes to the crisis) and adaptation (phasing out or transforming infrastructures that are no longer useful for a globally warmer world and with a higher sea level); (ii) a need to ensure, if at all possible, long-lasting abandonment of phased-out technologies (such as chemical weapons); (iii) a need for care and prevention of decline that is actually unwanted for ethical, environmental or other reasons (e.g. traditional crafts, traditional farming, cycling).

1.2. Research questions

The aim of the thesis is to explore the understudied phenomenon of technological decline. The rationale of questions to be asked in this book is threefold: empirical, theoretical and political. The three are interrelated. Empirically, the task is to explore technological decline with high granularity of analysis, i.e. with a rich case analysis, detailed attention to events and their timing and sequence; and, in order to do so, find and use a suitable heuristic to study decline with high empirical granularity. Then, theoretically, the puzzle is to formulate in a grounded way higher-level abstractions and generic claims about technological decline and its mechanisms. The political challenge is to understand when and how to intervene, in order to limit or even end the use of undesired technologies. Thus, the research questions of the present thesis are:

1) Empirical: how to characterise the processes of technological decline?
2) Theoretical: how to understand the processes of technological decline?
3) Political: how to intervene in the processes of technological decline?

Answering these questions will be possible with so-called middle-range theorising. A middle-range type of theorising implies an analytical focus on a specific phenomenon, and not on the entire social system, as would be the case in a ‘grand theory’

(Merton, 1949). Such narrower focus allows middle range theories to close in on the observed phenomenon, while being abstract enough to explain the observed variations between its instances across cases. Robert Merton[3] (1949) emphasises that middle range theories are not logically derived from a larger theory of social systems (though they may be consistent with them), rather, they start with empirical observation and basic generalisations, which are complexified upon further observation and abstraction of patterns.

The importance of middle range theory has been recognised in STS and transition studies (e.g. Frickel & Moore, 2006; Geels, 2007a; Hamlin, 2007; Wyatt & Balmer, 2007) as part of ongoing self-reflection on own societal value. Sally Wyatt & Brian Balmer (2007) asked whether STS, sceptical of grand theorising, has become too preoccupied with the non-generalisability of case studies and thus has given up on theorising, and Scott Frickel & Kelly Moore (2006) call STS scholarship to stop criticising and start understanding. Since then, middle range theorising has been picked up in studies of healthcare technology implementation (Lyle, 2021), urban transitions (Mora et al., 2021), social innovation (Pel et al., 2020) and sustainability transitions (Geels, 2018), among other. I aim to contribute to this trend and, by the end of this thesis, formulate an approach to summarise my findings and to further analyse technological decline.

In this endeavour towards middle-range theorising I am inspired by Clayton Christensen's (2006) approach of descriptive and predictive theory building. Christensen suggests to start inductively, with a careful description and documentation of the observed phenomena, and to continue with formulating abstractions to rise above the messy empirical detail and to understand key operations of the phenomena. From there, he asserts, it is possible to inductively classify those abstractions into a typology to simplify and organise the studied phenomena. Finally, the task is to identify associations between the category-defining attributes of the phenomena and the observed outcomes. Similarly, Kathleen Esienhardt and Melissa Graebner (2007) argue that the theory-building process occurs via recursive cycling among rich empirical data, emerging theory and extant literature. The hope is that the result will be able to produce theory that is accurate, parsimonious, interesting and testable (Eisenhardt & Graebner, 2007).

The book continues as following. In the next chapter I review and analyse the relevant literature. Based on this review, in Chapter 3 I formulate a heuristic to conduct my research. Chapters 4-6 present the empirical material: three cases of technological decline. Each empirical chapter is followed by a flagpost "Intermission" mini-chap-

[3] I will include the author's first name only the first time I mention them outside of a citation.

ter to improve the accumulation of insights and the coherence of the book. In these mini-chapters I return the reader to the larger aim of the book and help orient them on the progression of the argument with regard to the findings, insights and research questions, and what remains to be learned next. In Chapter 7 I develop a framework that conceptualises the entities and processes involved in technological decline, and that can be useful as methodology to study future cases of decline. In Chapter 8 I conclude with a discussion of the overall scholarly and societal use of this study, its limitations and a research agenda.

Chapter 2. **Literature review**

2.1. **Accounting for technological decline in literature**

As noted in the chapter above, in academic literature dealing with technologies and innovations, just as in mainstream policy making, it seems that new technologies are both more desirable and interesting phenomena than their decline. Since the 1960s, the topic of the end of life of technologies has been (periodically) gaining attention and studied in economics and management. This literature, however, suffers from a lack of granularity in terms of timescales and unit of analysis (e.g. Ayres, 1987; Tushman & Rosenkopf, 1992; Meckling & Nahm, 2019), thus remaining somewhat abstract regarding technological decline. In addition, despite the observability and complexity of technological decline, processes of decline tend to be conflated with mere substitution, as in literature on disruptive innovation (e.g. Ayres, 1987; Yu & Hang, 2010; Taylor & Taylor, 2012) and in climate models (as critiqued by Kevin Anderson and Glen Peters (2016)). Decline is also seen as an unappealing topic altogether (Smith et al., 2010; Stegmaier et al., 2014) because of perceived connotations with failure and a greater interest in markets and competition (Polanyi, 1944; Vinsel & Russell, 2020) as the nexus of both social life and technological development[4]. Bruno Turnheim and Benjamin Sovacool (2020) in their comprehensive literature review write that disciplinary takes on decline and failure (e.g. in economics, policy and governance studies, engineering) tend to frame decline as system weakness, anomaly and disappointment to be corrected as soon as possible. By contrast, in some of STS, innovation studies, transition studies, management studies and history of technology, technology and its decline tends to be appreciated as an important process and a learning opportunity (Turnheim & Sovacool, 2020). Because this stance towards the topic of this thesis aligns with the goals elaborated in Chapter 1, I will focus on the latter body of literature in the following review.

The literature review below is qualitative and conceptual. To conduct it I searched the Web of Science search for the terms “technology” in combination with (variants of) “destabilisation”, “control”, “discontinuity”, “dismantling”, “convergence”, “extinction”, “loss”, “disappearance”, “death”, “abandonment”, “termination” and “phase out”. I compiled a list of literature of the first 600 most cited items, and manually screened their titles and abstracts for relation to the topic of the thesis, after which 43 relevant entries remained. The number of dropped entries was so high because the

[4] Eugene McCarraher (2019) suggests that such central positioning of the market is a quasi-religious belief, an enchantment by the market as the fairest force of nature.

search terms are rather popular words found in articles that had nothing to do with the topic of technological decline. In fact, additional search using the snowballing method (where I identified key sources and bodies of literature with the help of other literature reviews and research agendas (e.g. Köhler et al., 2017, 2019; Kanger et al., 2020; Turnheim & Sovacool, 2020; Rosenbloom & Rinscheid, 2020)) revealed more entries: namely, 107. The final list included exactly 150 academic sources. As I closely read them, I used an Excel table to note if and how the authors define and address technology, technical change, and technological decline and adjacent concepts. The literature searches were conducted in 2018.

In the following I present how technological decline is discussed in the literature. Instead of discussing each of the 150 sources separately, I highlight the main approaches, themes and concepts. I will order my review in a list of 'key approaches', discussing their research interests, central concepts and, when relevant, noted weaknesses.

2.2. Key approaches

Kondratiev waves

Technological decline was first studied systematically and in detail more than a century ago by Nikolai Kondratiev (Kondratiev, 1999; Freeman & Louçã, 2002; Köhler, 2012). Kondratiev was among the first to discuss phases 'life' of technologies and observed wave-like rises and falls: invention, demonstration, growth, maturity and slowdown (Köhler, 2012). In Kondratiev's wave theory decline is typically conceptualised as "[m]aturity, leading to a (smaller) continuing role of the technology in the economy or slow disappearance" and "[s]lowdown, as the technology is challenged by new technologies, leading to the next crisis of structural adjustment (with unemployment and social unrest)" (Köhler, 2012, p. 5). Kondratiev thus adopts a systems view, and studies the dynamics by examining firms, policy instruments, statistics and key events. His main point was the cyclicality of a technology's "life" and, thus, inevitability of decline. This point was taken up, or developed independently, by Joseph Schumpeter (1942) to study macroeconomic and price cycles, but it was primarily the first part of the innovation—decline pair that was later taken up by mainstream economics.

Technology life cycle

Technology life cycle literature (e.g. Tushman & Anderson, 1986; Ayres, 1987; Taylor & Taylor, 2012) is linked to Kondratiev and Schumpeter and draws from evolutionary economics. Here firms and their management are the subject of empirical analysis as well as target audience. This literature is concerned with regularities in the emergence and maturation of technologies (Markard, 2020). Although this literature does not focus on decline (rather on emergence of discontinuous, or disruptive, innovation (Markard, 2020)), it offers insight on the latter stages of a technology's "life".

For instance, a 'senescence' life stage is characterized by high standardisation, a more or less settled price for the technology (low price elasticity), no national identity of the technology, mergers and failures on the market, and unstable competition with many original leaders starting to drop out (Ayres, 1987). And, from the firm's perspective: major sunk costs into a given technology (i.e. capital intensity), firms trying to sell assets related to the technology, major bureaucratisation of the firm that uses or produces the technology (Ayres, 1987). While it touches upon an important topic of maturing, aging systems, we do not learn much about the actual dynamics of decline from this literature, i.e. what happens as a result of the senescence. Moreover, literature on technology life cycles has been critiqued for a lack of attention to institutional change and to public policy, and for an exclusive focus on firm management (Markard, 2020). Here technology dynamics is in the background of firm organisation and activity.

However, ways to consider technological decline from a management perspective, even though not explicitly linked to technology life cycles, have come in the form of the concept of "exnovation". The term exnovation was originally coined by John Kimberly (1981), who places it as a last phase in his life cycle of innovations: invention, adoption, use, exnovation. Kimberly conceptualises exnovation as conscious work to withdraw support and to reorient it for other purposes (Hermwille, 2017). More recently, Martin David (2018a) emphasised that physical dismantling is required to achieve exnovation, and Dirk Arne Heyen and colleagues (2017) propose three dimensions of importance in exnovation: actor interaction, policy instruments and time horizon. The theoretical and empirical focus in works on exnovation is given to preparing and starting decline (David, 2018a), and, overall, work on exnovation has so far been suffering from lack of empirical studies.[5]

Social Construction of Technology

In Social Construction of Technology (SCOT) (Bijker et al., 1987; Bijker, 1995a) the cultural role, appearance and function of a new technology is a product not of technical rationality and engineering logic, but of competition and mutual transformation

[5] The term "exnovation" has been also prominently used by Jessica Mesman (Mesman, 2011; Mesman et al., 2019) in patient safety studies with a completely different meaning than Kimberly: that of illuminating the invisible/hidden.

of expectations from the given technology of different groups of users and non-users. From the perspective of SCOT, individuals and organisations are engaged in a network of collective sense-making of technologies. This sense-making is guided by evolutionary processes as the initial variety of meanings is reduced through selection processes and processes of creation of a shared cognitive frame (Geels, 2020a). Once interpretive flexibility closes, the technology reaches stabilisation, e.g. discussions of what a bicycle or plastics is, how and by whom it is used subside (Bijker et al., 1987; Bijker, 1995a). Trevor Pinch (2001) equates closure and stabilisation processes with innovation studies concepts of path creation and path dependence.

In SCOT technological decline is not the interest. In fact, David Edgerton (1999) critiques Wiebe Bijker for ending his studies of the bicycle, plastics and lighting shortly after the diffusion stage. Logically, however, decline could be interpreted as processes of destabilisation or re-opening of the interpretive flexibility.

Among other critique of SCOT Benjamin Sovacool & David Hess (2017) list three that the analyst of technical change should be aware of: a tendency towards voluntarism and heroic actor narratives, which may obscure certain power dynamics; a lack of interest in the longitudinal impacts of technology on society, due to the preoccupation with the emergence of technology; and, similarly, a lack of adequate explanation of larger system-wide patterns beyond local practices.

Large Technical Systems

The Large Technical Systems (LTS) approach was originally conceived to explain the emergence and development of socio-technical systems steered by system builders. It "offers an approach to explaining how humans organize and consolidate disparate materials or functions to maximize the efficiency of a given technique, process or goal" (Sovacool & Hess, 2017, p. 716). In LTS technology is understood as physical artefacts made up of different physical components as a socio-technical system, or seamless web, of interacting and interdependent social and technical elements (Hughes, 1986).

LTS theory operates with several key concepts: momentum, reverse salients, system builders, and technological style. "Mature", or established, systems become institutionalised which ensures a certain persistence or 'momentum'. Sometimes LTS may encounter reverse salients, or bottlenecks—certain critical problems (from the perspective of the system) that constrain system's enlargement. Often in LTS studies such reverse salients are technical issues such as physical or chemical limitations or unavailability of cheap alternative materials, or institutional, such as regulation or public opinion (Ewertsson & Ingelstam, 2005). System builders are the entrepreneurial actors or groups of actors who are in a position of power in an LTS. These could be inventors, managers, investors, politicians, firms, agencies, etc. who steer the development of an LTS (Ewertsson & Ingelstam, 2005). A system will vary in technological style depending on geographical, political, economic, social, cultural, historical or other conditions external to technology (Hughes, 1983).

Sovacool and colleagues (2018) point out several major attributes of LTS. First, LTS are socio-technical: they include artefacts and infrastructures, but also institutions and actors. Second, they are large-scale: a traditional illustration of an LTS is the (American) electricity system with its vast infrastructure of equipment, specialists and users, and huge capital investment. Third, LTS are coordinated to fulfil a function (e.g. provide electricity).

Sovacool and colleagues (2018) proposed a way for LTS theory to engage with decline explicitly. Through processes of reconfiguration, contestation, drift and crisis, that may be iterative, a mature LTS may turn stagnant and declining. Reconfiguration would be a process of adaptation to instabilities or challenges. If it is unsuccessful, it may lead to contestation and loss of control of the system builder over the system. Contestation can happen slowly through external pressures or counter-productive steering of the LTS ("drift"), or quickly, through crises or major accidents. Contestation may lead to decline. Decline is thus gradual: from adaptation to pressures, to slow or fast contestation, to decline. These stages are not sequential and the LTS can recover and become stronger than before. Sovacool and colleagues propose to measure phase-out as the slowing of growth, decreasing volume or quality of service provided by the LTS, or shrinking geographic scale of the system (2018). The authors provide historical examples of French trains having lost ground to cars (in terms of market share, but also literally), British coal-based energy sources—to oil and gas, and electric trams in the US—to buses.

LTS has been criticised for vagueness. The terms "systems", "technical" and "large technical" are not well-defined (Ewertsson & Ingelstam, 2005), and the social and the technical are conflated to an extent which may imply that "everything is in everything" (Gingras, 1995, as quoted in Sovacool & Hess, 2017). LTS has also been criticised for its tendency to focus on heroic actor narratives with the concept of system builders, and for technological determinism by using the concept of momentum (Ewertsson & Ingelstam, 2005; Graham & Thrift, 2007; Sovacool & Hess, 2017).

Actor Network Theory

A different kind of systems approach is the Actor Network Theory (Callon, 1984; Latour, 1999). According to ANT, technology (also science and the rest of the world, for that matter) is a network of actors. The actor is "[a]ny element [that] makes other elements dependent upon itself, and translates their will into a language of its own"

(Callon & Latour, 1981, p. 286). The network is steered by these powerful actors into stability, control and extension (Radder, 1992). It does not matter if an actor happens to be not a human: in ANT the actor's power may come from a door or a car seatbelt both of which dictate certain behaviours delegated to them by human intentionality (Latour, 1992).

Thinking in networks offers several advantages, according to Bruno Latour (1996b): it eliminates distance, as geography becomes one of the connections; scale is replaced by the metaphor of connections, as all that matters is the intensity of connections in a network; there are no *a priori* assumptions of an hierarchy among the elements of a network; and the dichotomy of the outside versus the inside becomes irrelevant, as a network has no boundaries, only connections between its elements. Networks are permeated by politics and any kind of permanence is temporary and as robust as the actors' work to keep resistance and variation under control (i.e. translation work). According to Mike Bourne, "all translations, however apparently secure, are in principle reversible" (Bourne, 2016, p. 12).

ANT critics question the value of the core proposition to treat human and non-human actors equally, as well as ANT's complicated methodology (Bloor, 1999). ANT is also accused of reintroducing Whig history: ANT analyses have the tendency to focus exclusively on successful network builders, and forget the "losers" (Radder, 1992). Similarly, ANT is critiqued for being ahistorical: it is preoccupied with the present and the local, but does not account for the past (nor predict the future) (Radder, 1992), nor is it able, critics assert, to include any study of social conflict (Feenberg, 2003).

Although classic ANT scholars hardly ever discussed decline explicitly[6], there seems to be only a small step to make to apply ANT for this purpose. For instance, in ANT persistence of given technology is explained as the strength, robustness and vastness of the network of actors. Empirically, perhaps, this persistence may manifest as social embeddedness, sunk costs, lock-ins, etc. Decline could be conceptualised as the weakening and shrinking of the actor network, or the growth of a competing actor network. Theoretical articulation (e.g. is decline the weakening of a network, or building an alternative one?) and empirical testing of this claim could be the topic of future research, especially if it can address some of the critiques of the ANT.

A different extension of the ANT into the sphere of decline was proposed by Frédéric Goulet and Dominique Vinck. They diagnose the emergence bias in ANT and write that "from the standpoint of this sociology the two processes [i.e. construction of new associations and breaking of existing ties] go hand in hand" (Goulet & Vinck,

6 The unaccomplished French train project Aramis, studied by Latour (1996a), did not go through decline as it did not even rise up the S-curve (see section 2.3).

2012, p. 120). According to Goulet and Vinck, withdrawal is rearrangement, redefinition and/or detachment of entities from a network; and it involves delegitimisation of entities to be withdrawn ("centrifugal association"), reinforcement of existing ties that avoid inclusion of said entities and association of new entities, and making certain associations invisible (Goulet & Vinck, 2012). This idea of decline actually making a system stronger has gained more traction in recent years (e.g. Newig et al., 2019).

More recent research followed in filling the attention gap to decline in ANT. Martin David and Nona Schulte-Römer (2021) mobilise ANT's problematisation, interessement, enrolment and mobilisation as processes of phase-out: actors promoting phase-out problematise existing relationships in a network, they use "interessement devices" such as legislation, they ensure the opposite of enrolment—dissociation, and, in the end, actor relations are redefined in accordance to a new network configuration ("mobilisation to let go" (David & Schulte-Römer, 2021, p. 4)).

Dynamics of social practice

Theories of practice, which aim to explain the behaviour of people, the users of technologies, are most widely known from Pierre Bourdieu's work (1977, 1990). Later authors, such as Andreas Reckwitz (2003), Inge Røpke (2009), Elizabeth Shove, Mika Pantzar and Matt Watson (2012), developed the theory further. The latter source is particularly interesting as it discusses the dynamics of practices.

Shove and colleagues (2012) propose a focus on the later stages in life of practices and technologies. They suggest that practice is best understood as an interlinkage between 'materials', 'forms of competences' and 'meanings'. Or, in other words, "objects, infrastructures, tools, hardware and the body itself", "know-how, background knowledge and understanding", and "mental activities, emotion and motivational knowledge" respectively (Shove et al., 2012, p. 23). Their conceptualisation of the three elements is useful to trace the dynamics of practices, but Shove *et al.* are first to acknowledge the simplification that they commit to when they unite and unify complex and varying categories into the three elements (Shove et al., 2012; Sovacool & Hess, 2017).

Shove and colleagues focus on the dynamics of practices: as long as the three elements are stable, their interactions in time and space produce the dynamics in practices. Practices can decline, in which case the elements will travel apart. With time some elements are left behind, replaced by other (e.g. the change in special clothing for chauffeurs, or collective forgetting of how to read a map) (Shove et al., 2012). In fact, three things may happen to elements after disruption of links: disappearance with little or no trace, becoming "dormant", or becoming part of other practices (Shove et al., 2012, p. 35). In case of complete or near-complete disappearance, artefacts are not used anymore and become rubbish, what was before common knowledge turns into a little-known secret, and previously widely shared meanings are forgotten and become obscure hints (Shove et al., 2012). The conceptualisation of dynamics of social practices bears many commonalities with how uninvention of nuclear weapons unfolded according to Donald MacKenzie and Graham Spinardi (1995) and Bourne (2016), but also with how the processes of domestication are conceptualised (Lie & Sørensen, 1996; Sørensen, 2006).

How is social practice theory relevant to technological decline? The gap between practice and technology is being bridged in recent literature. By emphasising interlinkages between elements and one of them being "materials", Shove *et al.* brought practice and technology conceptually closer together, which was not the case before in theories of practice (Sovacool & Hess, 2017). A further bridging, relevant to the topic of decline, was suggested by Paolo Magaudda and Sergio Minniti (2019) who link their study of declining media ("retromedia") with Wanda Orlikowski's (2000) focus on investigating technology in organisational practices. Magaudda and Minniti write that studying retromedia-in-practice allows "both to address the processual nature of retromedia and to propose an interpretation that keeps together media materiality, their meanings and also the embodied activities and behaviours that are attached to them" (Magaudda & Minniti, 2019, pp. 678–679).

Among the most common critique of social practice theory is a tendency to treat practices as unchanging across time and space and a lack of attention towards structural, systems dynamics (Sovacool & Hess, 2017).

Technological Innovation Systems

The functional dynamics of Technological Innovation Systems (TIS) (Hekkert et al., 2007; Bergek et al., 2008) was relatively recently expanded to conceptualise phase-out and destabilisation (Kivimaa & Kern, 2016). TIS is a firm-centred innovation studies approach that is aimed to advise policy intervention for diffusing new technologies (Coenen & López, 2010). TIS functional dynamics allows to produce snapshots of the networks that support the emerging technology, and to assess the relative strength of given technology's grip in an industry. TIS can be seen as LTS engrained with more evolutionary analysis (Markard & Truffer, 2008).

The core of a TIS functional analysis is mapping seven processes, or "functions", that make up a TIS: knowledge development and diffusion, influence on the direction of search, entrepreneurial experimentation, market formation, resource mobilisation, legitimation, and collective learning (typically labelled as "positive externalities") (Bergek et al., 2008, p. 411). Paula Kivimaa and colleagues (Kivimaa & Kern, 2016;

Kivimaa et al., 2017) suggest complementing this classic view on TIS with additional five processes that would enable to analyse the processes of destruction of incumbent regimes[7]: control policies (taxes, import restrictions, bans), significant changes in regime rules (e.g. changes in economic paradigms, such as privatisation and market liberalisation), reduced support for dominant regime technologies (e.g. cutting R&D funding, removing subsidies, removing tax deductions), changes in social networks and replacement of key actors, and new organisational or institutional practices and routines.

Jochen Markard (2020) links TIS and technology life cycle literature. He argues that TIS decline can be measured by: a decrease in (research, entrepreneurial, etc.) activity of actors, actors leaving the TIS, and a shrinkage of markets; a decrease in coherence and formalisation of its institutes (de-institutionalisation); contestation of technology designs and performance parameters; and break-ups of networks and network ties. As a result, Markard claims that "[a]t the end of the life cycle […], the focal technology may either cease to exist as in the case of video recorders, or it may survive in some small remaining niche application (e.g. vinyl discs)" (Markard, 2020, p. 10).

TIS has been critiqued for the implicit growth narrative (also shared by much of the reviewed literature, as can be noticed by now) and its national focus. According to Ulrich Petschow and colleagues (2020), TIS implies that decline is a weakness that needs to be fixed to maintain the strength of the innovation system. In fact, Jochen Markard and Bernhard Truffer demarcate a TIS between its formative phase and "some point in the growth phase" (Markard & Truffer, 2008, p. 611). Petschow and colleagues (2020) also point out that international or environmental effects are generally not considered in a TIS analysis.

Multi-Level Perspective

Finally, the Multi-Level Perspective on socio-technical transitions (or just MLP) (Rip & Kemp, 1998; Geels, 2002; Geels & Schot, 2007; Smith et al., 2010) is a conceptual model used to explain changes of socio-technical systems through the processes of technology adoption, substitution and/or diffusion, and the interactions between niches, regimes and landscapes (i.e. the levels). Technology is understood as a socio-technical configuration or system that is aimed to fulfil a major societal function (transportation, food production, etc.).

The MLP has been predominantly used to explain the history of socio-technical

7 Paula Kivimaa and Florian Kern (2016) also modify the seven functions by removing "positive externalities" and adding "price-performance improvements". This alteration is not critical to discuss in present work.

transitions. Niches are understood as protected creation and testbed spaces for "various technical, social and organisational innovations" (Kivimaa & Kern, 2016, p. 206). Niches generate variation of technological trajectories, which in turn are stabilised by regimes—common ways of problem-solving activities by engineers, designers, users, policy makers, scientists, bankers, suppliers, etc. who search for solutions in the same direction (Geels, 2002). These common ways of thinking are embodied in rules, standards, institutions, lifestyles, competences, infrastructures and sunk investments in machines (Geels, 2007b). Forces not under immediate control of actors make up the socio-technical landscape: shared cultural beliefs, symbols and values, wars, demographic shifts, economic collapses, etc. (Geels, 2004). An important characteristic of MLP is that no single cause or factor drives transitions. Instead, transitions occur when the dynamics at different levels align and reinforce each other (Geels & Kemp, 2007).

Decline is implicitly present in the MLP as a phenomenon concomitant to the breakthroughs of niches, but not explicitly conceptualised. An attempt to address this was taken up by Stefan Vögele and colleagues (2018). The authors conceptualise two pathways for decline once an innovation is dropped by the regime: either continued existence in a niche (i.e. not in a regime) or disappearance. They further differentiate between a pathway of continued existence in a "nutshell", i.e. in narrow, special applications (e.g. vinyl records), and of continued existence with a new meaning/design, i.e. revised application (e.g. airship).

MLP has been criticised, among other, for downplaying agency and human needs, for inadequate explanation of politics and power, for over-emphasising niche-regime interactions, for its problematic predictive value (Geels, 2011; Sovacool & Hess, 2017), and for vagueness (Goulet, 2021). Vögele *et al.* (2018) may be adding to this list of issues by *a priori* assuming decline as a reversal of the processes of emergence: "[t]he phase-out process of a technology can be described by reversing the order of these stages [of niche development]" (Vögele et al., 2018, p. 6), they claim, whereas this could be an empirical question instead. A case in point is David's countering argument that any removal of an established technology "fundamentally differs from processes introducing such innovations" (David, 2018b, p. 340).

Discontinuation and destabilisation

Besides the core STS approaches and innovation and transition studies discussed above, emergent frameworks of discontinuation and destabilisation have appeared in literature. Although lacking the same empirical support as the theories above, these new frameworks offer to conceptually expand existing theories to a study of decline.

Literature on governance of discontinuation is aimed to study policy-making processes of technological decline (Stegmaier et al., 2014; Stegmaier, Visser, et al., 2021). The authors draw from the US-centred multiple-streams framework (Kingdon, 1984) to understand how a technology is problematised, how decline solutions are proposed, fleshed out and selected, and how decline is performed. Peter Stegmaier and colleagues look at decline at a macro scale in which governance actors (government, parliament, firm, industry association, group of countries, etc.) take the lead in interpreting issues, facts and values, turn them into problems to be solved, and prepare and orchestrate withdrawal of associated resources (e.g. programmes, organisations, infrastructures). Discontinuation entails withdrawing support from specific policies, but also undermining the inertia of the incumbent system that is associated with the technology. A critique by Köhler and colleagues (2019) of governance and policy-oriented frameworks could also be applicable to work on discontinuation: namely, a tendency to focus more on policy outputs, rather than on policy outcomes.

Technological decline is discussed in detail in literature on regime destabilisation (Turnheim, 2012; Turnheim & Geels, 2012, 2013). Here, technology is implied to co-evolve with industry, and its trajectory to be dependent on the stability of industry regime. The loss of faith in the regime, triggered by inability to cope with the problems, occurs gradually, and may ultimately lead to complete dissolution of established regime. In this case the industry downsizes, exits, or 'milks' the assets (Turnheim, 2012; Turnheim & Geels, 2013). According to Turnheim, the strategies depend "on the severity of the problems in relation to the industry's core competence and the ability of industry actors to enact radical change" (Turnheim, 2012, p. 62). Regime destabilisation is thus a process of "weakening of external sources of stability and [weakening of] actor commitment to established regime rules" (Turnheim, 2012, p. 56).

Bruno Turnheim and Frank Geels (2012, 2013) discuss in detail the destabilisation of coal industry in the 20th century, as do Phil Johnstone and Sabine Hielscher (2017), but other future-oriented studies have focussed on the prospects of regime/industry destabilisation in the port of Rotterdam (Bosman et al., 2018), food industry in Finland (Kuokkanen et al., 2018), coal in Germany (Leipprand & Flachsland, 2018; Vögele et al., 2018), pulp and paper industry in Sweden (Scordato et al., 2018), and other.

The concept of regime destabilisation is not without criticisms. Importantly, the assumption that seems to be made is that industry is the nexus of socio-technical change, a view that has been criticised (e.g. Polanyi, 1944; Hughes, 1994; Soete, 2011; Upham et al., 2015). Secondly, the notions of industry destabilisation and regime destabilisation seem conflated[8], whereas it is not self-evident that regime

8 For example, in Turnheim (2012) "regime destabilisation" is mentioned in the title, but only

(norms and cognitive rules) and industry (economic activity or a collection of firms) are one and the same. Thirdly, David critiques the value of the concept of regime destabilisation in explaining complete removal of a given technology (David, 2017).

To sum up, in literature the later stages of technology's 'fate' is not conceptualised with as much degree of granularity and detail as the earlier ones. The discontinuation and destabilisation frameworks do advance the understanding of and bring more empirical evidence on decline. I argue that it is productive to build on these emerging frameworks to advance the knowledge of the dynamics of decline, and in the next section I explicate how.

2.3. Concepts and themes

Above I briefly reviewed the most influential theories and approaches on technical change in innovation studies, transition studies and STS, and beyond, as well as emergent literature. One of the most obvious points of difference between the various approaches is what stage of 'life' they accentuate relatively more: emergence, dynamic stability or decline. Most approaches suffer from this emergence bias, i.e. a tendency to focus conceptually and empirically on the beginning of technologies' life cycle. This leaves the later stages underconceptualised. The area of knowledge on phase-outs is slowly expanding with emerging theorisations, but existing knowledge remains largely fragmented. For further comparison I mobilise the concept of 'technological trajectory'.

The concept of technological trajectory comes from economics where trajectories are used for technological and financial foresight. According to Arie Rip and René Kemp, "[t]he main motivations for mapping techniques have been the need of policy-makers to assess the present and future state of technologies (and sectors) and the need of firms and technology organizations to forecast developments (in technology, but actually also in markets or even in society)" (Rip & Kemp, 1998, p. 360). Coined by Richard Nelson and Sydney Winter (1982) and, initially, developed by Giovanni Dosi, technological trajectory refers to a framework for problem solving, formed by common ways of thinking and common choices of engineers and designers (Dosi, 1982) (e.g. early cars resembled and were modelled after horse carriages because of a design trajectory). Later authors have expanded the concept of trajectory to mean predictable pathways of incremental innovation that result from problem solving activities not only of engineers and designers, but the larger society: users, policy mak-

three times in the rest of the text, while "industry destabilisation" is mentioned 81 times.

ers, scientists, suppliers, etc. who search for solutions in the same direction (Geels, 2002). For the purposes of this book, trajectory is *not* seen as autonomous or predetermined. It is rather seen as a direction that is expected from a given technology by actors (Van Lente & Rip, 1998; Borup et al., 2006), subject to change through the actions of actors.

Elizabeth Shove and Gordon Walker referred to “trajectories of erosion, decay, and fossilisation” as “processes that parallel those of innovation” (Shove & Walker, 2007, p. 767). Their concept of “trajectories of erosion” is instructive to refer to technological trajectories losing momentum and shrinking or dissipating, and thus deviating from trajectories that were anticipated in the past.

The ‘S-curve’ is the traditional mental image to represent trajectories. To stylise technological development, the S-curve is typically presented as a linear sequence of pre-development, take-off, acceleration and stabilisation phases (cf. Foster, 1985; Rotmans et al., 2001). The Y-axis for the S-curve is usually undefined, or at best it marks quantity or quality of technological output, or the density of linkages between actors and activities (structuration). When discussing trajectories of phase-out, I align with Svante Lindqvist (1994) who suggested the inverse U-curve as a development of the S-curve. The S-curve, Lindqvist writes, provides a mental image of only “half or less of the history of technology” (1994, p. 284) and it exaggerates the importance of this first half. Lindqvist’s inverse ‘U-curve’ produces a more full and accurate stylisation of technological development because it includes trajectories of decline. Drawing on Lindqvist, an inverse U-curve, or bell curve, would include the usual S-curve elements, but add shocks or ‘eras of ferment’ (P. Anderson & Tushman, 1990), i.e. periods of instability that may lead to phase-out (Figure 1). If the processes of decline are completed, only remnants of a technology survive. Of course, the figure below should not be over-interpreted as a definitive prediction of each and every technology’s life cycle, but rather as an ideal-type, schematised representation.

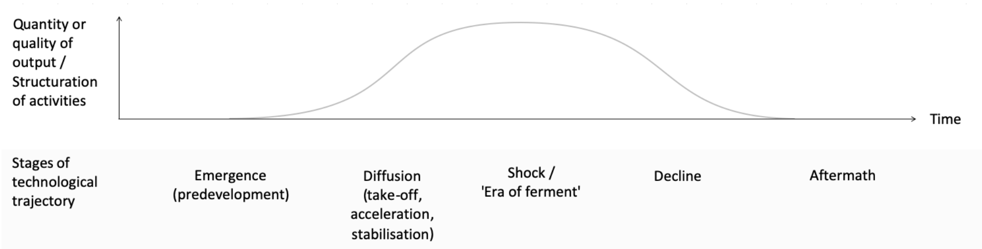

Figure 1. The technology bell-curve and its phases. Source: own.

In most of the reviewed approaches, theoretical and empirical focus is predominantly on the S-curve: emergence, stability and era of ferment (Table 1). There is, thus, both an empirical and conceptual bias towards technology emergence. This has been noticed by other researchers and Debra Davidson colourfully writes about the possible reasons: innovation "is far more politically palatable [...] because it does not threaten any vested interests in the current regime. Innovations are [...] the stuff that wins awards, launches careers and stimulates stock markets" (Davidson, 2019, p. 255). New studies started to build up on the 'grand theories' and explore decline with their help, other emergent literature started from elsewhere (e.g. discontinuation).

Configurations (Rip & Kemp, 1998; Shove et al., 2012), networks (Callon, 1984; Latour, 1999) and systems (Hughes, 1983; Geels, 2002; Geels & Schot, 2007; Hekkert et al., 2007; Bergek et al., 2008) often appear as focal entities in the analysed literature. They are understood as heterogeneous ensembles of artefacts, individuals, infrastructures, scientific knowledge, cultural categories, industry structures, markets (i.e. application domains), norms and laws, cultural/symbolic meaning, consumption patterns, and natural resources (Geels, 2004; Shove et al., 2012; Hess & Sovacool, 2020). Here, society and technology, humans and things are "mutually constitutive and hopelessly mangled" (Garud & Gehman, 2012, p. 983), i.e. co-constructed or co-produced, "with no single dimension dictating change by itself" (Sovacool & Hess, 2017, p. 31). In this literature decline tends to be understood as break of reproduction and of ties within and shrinkage of the network/system/configuration. The concepts of configuration, network and system inform us that it could be productive to look for their disruptions when tracing and conceptualising decline.

A key mechanism of change in the literature is the co-evolution and co-design of the elements within the configuration, network and system. Material objects are often key here (David & Schulte-Römer, 2021). Frank Geels (2020a) writes that STS scholars brought to mainstream sociological discussion about agency and structure the discussion of the pervasive influence of material and technological dimensions. Michel Callon (1987) famously suggested that technology is a way of studying "society in the making", and Bruno Latour (1991) saw technology as "society made durable", arguing that artefacts provide ways of anchoring new routines and practices (Geels, 2020a). In synthesising approaches such as the MLP or TIS materiality is included as infrastructures and resources.

A lot of attention in literature is given to meanings and sense-making, drawing from symbolic interactionism and structuration theory (Giddens, 1984). There is a dichotomous relationship here between, on the one hand, structures of rules and meanings, and, on the other hand, the agency of actors, who are free to interpret and enact these structures and rules. Such interpretations are discussed in Bijker (1987) with his concept of 'interpretive flexibility'. Interpretive flexibility foregrounds that scientific knowledge and technological design require a negotiation between interpretations and the concomitant social processes. Harro van Lente and Arie Rip (1998) further argue that expectations and promises structure actions: researchers, engineers and firms propose technology options, and claim promises, when accepted such promises are taken as requirements to be fulfilled. In this way technological and economic activities are mobilised. Transition theory has taken up expectations, promises and symbolic/cultural meanings of technology in general as performative forces of a socio-technical system (Geels, 2002; Geels & Kemp, 2007).

Networks, systems and configurations are dynamic and actively and continually formed and reformed according to the intentionality of the human actors, and constrained, according to a position found in transition studies, by an accumulated 'momentum', inertia or 'frame'. In ANT this (re)formation work is referred to as performance, in the sense of reproduction, "making and remaking groups" (Latour, 2005, p. 35). Similarly, John Law writes about the processes of "heterogeneous engineering" in which actors try to "maintain some degree of stability in the face of the attempts of other entities or systems to dissociate them into their component parts" (Law, 1987, p. 248). Some authors in theories of practice also refer to performance, seeing it as the reproduction of the connections between material, cognitive and symbolic dimensions of a practice (Shove et al., 2012; Welch & Warde, 2015). For studies of decline it might be productive to mobilise the concept of performance as a representation of use value (Marx, 1976) (high use value = intensive performance) to partly describe the dynamics of the configuration.

An important process in performance and work is learning, or creation, retention and transfer of skills, knowledge and competences. Learning is emphasised in transition theory as an indicator of success of an innovation, and is something that is protected in niches (Loorbach et al., 2017). In STS, learning is involved in processes of appropriation and domestication of technology (Sørensen, 2006). Learning involves processes of reframing that may result in a change of perspective among stakeholders on the problem, upon which they will try to collectively find a solution (Grin et al., 2010). In practice theory, activities related to learning and other forms of competences co-constitute configurations, together with materials and meanings (Shove et al., 2012).

Prior literature already started pushing these shared concepts of configuration, co-evolution, sense-making, performance, etc. into analyses of decline. Much of the literature discusses decline of a configuration via processes of delegitimation or competition with other configurations, to which the configuration may readjust (reconfig-

Theory/Approach	Term used	Mechanism of decline	Focal part of trajectory	Unit of analysis	Unit of observation
Kondratiev waves	Slowdown	Technology maturity leads to either a (smaller) continuing role of the technology in the economy or its slow disappearance. During a slowdown the technology is challenged by new technologies, leading to a crisis of structural adjustment featuring unemployment and social unrest.	Emergence, stabilisation, ferment, decline	System	Events, firms, policy instruments, statistics
Technology life cycle *(early literature)*	Senescence	High standardisation, a more or less settled price for the technology (low price elasticity), no national identity of the technology, mergers and failures on the market, and unstable competition with many original leaders starting to drop out	Ferment, decline	Firm	Firm activity, statistics
Technology life cycle *(emergent literature)*	Exnovation	Withdrawal and reorientation of support; absence of use of technology due to the removal of its physical infrastructure, framing of technology as obsolete and unattractive.	Ferment	Product, practice	Policy instruments, policy outputs
SCOT	No specific term	*(Logically:)* destabilisation/reversal of closure, re-opening of negotiations.	Emergence, stabilisation, ferment	Artefact, network	Artefact, social groups, their frames
LTS	Decline: unsuccessful adaptation to pressures, system growth erodes	Momentum of mature system encounters critical problems (reverse salients) that prevent its enlargement. Eventually, the system builder may lose control over system which leads to its shrinkage.	Emergence, stabilisation, ferment	System, industry	Activities of key industry actors
ANT *(early literature)*	No specific term	Weakening of connections in the network, shrinking of network.	Emergence, stabilisation, ferment	Network	Activities of actors

Table 1. Mapping theories of technical change and how they engage with technological decline.

ANT *(emergent literature)*	Withdrawal	Rearrangement, redefinition and/or detachment of actors, artefact, substances, practices, modes of organisation; centrifugal association, reinforcement of existing ties, association of new entities, and making invisible certain associations.	Ferment, decline	Network	Entities in a network
Dynamics of social practice	No specific term	Break in links between constituting elements of practice and subsequent break of reproduction of practice.	Emergence, stabilisation, ferment, decline, legacy	Practice (routinised behaviour), retromedia-in-practice	Individual's activity and sense-making, number of participants of practice
TIS	Decline	Decrease of actor base, size and activity in TIS, breakup of ties and networks, delegitimisation of technology designs and performance parameters. Weakness in one or more TIS processes that prevent maintenance or enlargement of TIS.	Stabilisation, ferment	System	Events, discourses, policy instruments, statistics
MLP	No specific term	Decrease of structuration, niche-fication of an innovation, loss of dominant position within regime.	Emergence, stabilisation, ferment	System, regime	Events, discourses, policy instruments, statistics
Discontinuation	Discontinuation	Misalignment of constituting relations of a socio-technical trajectory and a loss of the trajectory's distinctive character. Governance actors frame problems and direct withdrawal of resources.	Ferment, decline	Regime	Discourses, frames, policy instruments, policy outputs
Regime destabilisation	Regime destabilisation	Process of exposure to significant challenges that have a potential to threaten normal functioning. Shrinking or changing markets, failure of industry to adapt to external and internal pressures.	Ferment, decline	System, regime, network	Firm: responses, frames

Table 1 (continued). Mapping theories of technical change and how they engage with technological decline.

ure) or 'drift' into a declined, 'dormant' state. Such mechanisms are discussed across studies of industries and firms in LTS, technology life cycle and regime destabilisation literature, TIS, social practices and discontinuation. Case studies of dissociations, disconnections and de-alignments have been emerging lately with work on withdrawal and exnovation. There, more attention is being paid to framing and creation of competing configurations. Other approaches, such as MLP and SCOT, have not yet developed a body of empirical work on decline and remain somewhat theoretical in their descriptions of decline mechanisms.

Overall, I draw five insights from the reviewed literature for studies of decline:

- decline is a systems process constituted by technical and symbolic dynamics;
- these dynamics tend to involve a weakening of an element of the system (i.e. it becomes less stable, reliable, resilient, flexible compared to its previous condition);
- in addition, system connections may weaken, too;
- when declining, systems shrink and their role in the environment decreases;
- due to an emergence bias that has dominated studies of technical change for so long, but also due to differing units of analysis and of observation (with, I would claim, superfluous focus on industry and firms), there is not enough empirical granularity in existing studies of technological decline (yet).

Based on these insights, I claim that a good characterisation and theorisation of the dynamics of technological decline (research questions 1 and 2) will need to meet the following criteria. They will need to: (a) to focus, of course, on the decline of technology, not earlier phases, (b) be grounded in empirical studies of detailed granularity of analysis (Murmann & Frenken, 2006) (to follow the middle-range theorisation logic (Chapter 1)), (c) appreciate the complexity and messiness of the socio-material dynamics of decline, and (d) appreciate the developments outside of market and industry, as not the only arenas of socio-technical change (e.g. Polanyi, 1944; Hughes, 1994; Soete, 2011; Upham et al., 2015).

Below I draw on these insights and formulate the methodology to structure the empirical analysis of the phenomenon of technological decline.

Chapter 3. **Research design**

3.1. Conceptual framework: configurations and strands

Unless he or she wants to engage in crude empiricism, it is implausible, if not impossible, that the researcher should begin analysis with no presuppositions (Kuhn, 1962). In this chapter I present the research design and methodology I used in the empirical cases (Chapters 4-6), in which I draw from the insights obtained from the literature review discussed in the previous chapter to guide my data collection and analysis.

From the literature on technical change it appears that the basic starting point of an analysis of technologies is the acknowledgment of a strong interrelatedness of artefacts and society, economy and culture, institutions and practices. In other words, the connectedness of material and socio-cognitive entities and their relations in a configuration are often the unit of analysis, and so they are in the present thesis.

Within this unit of analysis units of observation need to be established[9], without which the configuration will be very difficult to study with a high degree of granularity. In an attempt to avoid a critique that analysing the intertwined socio-technical dynamics amounts to concluding that "everything is in everything" (Sovacool & Hess, 2017, p. 15 quoting Gingras, 1995), the units of observation need to be analytically distinguished from each other and analytically separated to an extent that this is possible. I draw from STS literature that analytically separates the 'strands' of the entangled sociotechnology: Shove and colleagues (2012) who discuss materials, meanings and forms of competence; literature on domestication (e.g. Lie & Sørensen, 1996; Sørensen, 2006) where symbolic, practical and cognitive work is distinguished; MacKenzie & Spinardi (1995) where "tacit knowledge, control over materials, and the translation of interests form […] a necessary three-sided approach to […] uninvention" (MacKenzie & Spinardi, 1995, p. 88); and Latour and Callon who distinguish between human and non-human actors (Callon, 1984; Latour, 1999). Borrowing the terminology—though not the ontology—used by Shove and colleagues (2012), I thus operationalise the 'strands' that co-constitute the configuration as materials, meanings and forms of competence. When talking about these I will mean, respectively:

- objects, tools, hardware, infrastructures, production facilities, market, resources;

[9] The distinction between unit of analysis (key focal entity of the study (Sheppard, 2020)) and unit of observation (entities to be observed, measured or otherwise studied to learn more about the unit of analysis (Sheppard, 2020)) is more typical in mainstream sociology, and here I find it useful for the clarity of methodology.

- laws, rules, public discourses, competing narratives of supporters and opponents before and after the decline and changes in cultural meanings and regulatory regimes they may (have) lead to; and
- tacit, codified and other knowledge on design, manufacture and use, as well as labour relations[10] (Table 2).

Such separation into three strands is an analytical move and not an ontological claim, and a simplification that I commit to as an operationalisation strategy (cf. H. Klein & Kleinman, 2002; Geels, 2007a).

Unit of analysis ('strands' of a configuration)	**Units of observation**
Materials	Objects, tools, hardware, infrastructures, production facilities, material resources
Meanings	Public discourses, narratives, laws
Forms of competence	Tacit, codified and other knowledge on design, manufacture and use, labour relations

Table 2. Units of analysis and units of observation in the present book.

The three strands are not monolithic and are themselves networks of different entities, co-existing and competing (Callon's 'punctualisation' (1984)). The dynamics within the strands can be expected to be driven by the same rules as other networks, e.g. they are dynamically stable as long as there is alignment (Goulet, 2021) and they can become unstable if there is too much internal contestation. I will consider that meanings, competences and materials are associated, entangled in a configuration as long as the configuration is performed, i.e. the technology is participating in manufacture or routine use. Every time the given technology is manufactured or used, the associations are reproduced and entangled tighter. This is a state of continuity, dynamic stability, and the absence of decline.

3.2. Methodology

I opted for a case study approach as it allows to observe deep causal links, although at some expense of generalisability (Yin, 2012). I conduct the investigation to answer the research questions with a small selection of cases to study. I opted for multiple

[10] Forms of competence can also be understood from the economics perspective as 'intellectual capital'.

cases since they allow to develop a more robust, generalisable and testable theory than single-case research (Eisenhardt & Graebner, 2007). The case selection criteria are: an observable decline of technology in a given period of time compared to an earlier period, variation in the outcomes of a decline (at a given point in time), i.e. 'polar type' cases[11], geographic variation, data accessibility, and personal curiosity in a case. Following Eisenhardt and Graebner (2007), I am not overly concerned with how representative the cases are as the current thesis is aimed to build, not test theory. The selected cases are, then: the re-emergent cloud seeding (the US), the contracted incandescent light bulb (the EU), and the abandoned *Ural* computer (Russia).

Since the aims of this book lie in contributing to the acceleration of sustainability transitions, purposeful decisions matter in the cases I study. As also already touched upon in previous chapters, this is warranted because a traditional focus in transition studies on emergent outcomes of co-evolutionary behaviour has been critiqued (Smith et al., 2005; Geels, 2011; Feola, 2020) for downplaying the role of deliberate human action in change. Gert Spaargaren and colleagues write that it should be recognised that "(intentional) human behavior is fundamental to the analysis of social change and should be given a more central position in the conceptual models used in transition studies" (Spaargaren et al., 2013, p. 9)[12].

Throughout its history, a given technology rarely stays the same. Many alternative designs emerge along the dominant one (e.g. Ayres, 1987), so a big methodological question is to track the 'same' technology throughout its history. Instead of mapping all or most of the possible configurations, in my cases I pragmatically traced the focal one (determined during case selection) by tracing documented utterances of the stakeholders. Decline is then traceable through processes of dissociation (Goulet & Vinck, 2012) of the strands from the configuration, processes that I will further study empirically and attempt to characterise in the following chapters.

To trace the strands, I followed a representations approach by Paul Upham and colleagues (2015), who themselves draw upon social representation theory (Moscovici, 2001). Representations are psychological processes of attributing meaning to phenomena, artefacts and abstractions based on previous knowledge and cognitive frameworks (Upham et al., 2015). Upham and colleagues propose to collate representations of technologies gathered from texts. To follow representations means to follow how technologies are rendered familiar and tangibly understood (Upham

[11] Eisenhardt and Graebner might classify the first two criteria as 'theoretical sampling' which, according to them, means that "cases are selected because they are particularly suitable for illuminating and extending relationships and logic among constructs" (Eisenhardt & Graebner, 2007, p. 27). Polar types refer to extreme cases in order to more easily observe contrasting patterns in the data (Eisenhardt & Graebner, 2007, p. 27).

[12] I return to emergent and purposeful change in Chapter 7.

et al., 2015).

In empirical cases I follow a reactive sequence methodology (Mahoney, 2000) commonly used, implicitly or explicitly, in historical sociology (Clemens, 2007; Haydu, 2010). Reactive sequences are a useful way to study trajectories and paths narratively, i.e. as a sequence of causally linked and temporally ordered events. Key in reactive sequence analysis is to demonstrate the causality of event chains from a (contingent) key antecedent event to the studied final event (Mahoney, 2000). Analysis of reactive sequences is possible with narrative explanation (Abell, 2004; Clemens, 2007; Haydu, 2010), which goes beyond mere chronological documentation of events but orders them into a causally linked storyline. James Mahoney (2000) quotes Jack Goldstone's (1998) case of invention of a first coal-powered steam engine, developed to pump water out of flooded coal mines, as an example of reactive sequence: "it was just chance that England had been using coal for so many centuries, and now needed a way to pump clear deep mines that held exactly the fuel needed for the clumsy Newcomen pumping machine" (Mahoney, 2000, p. 535). Similarly, with the aim of explaining the casual linkages in the event chains in my cases that lead to decline, I structure my empirical material as narratives from antecedent events to final events. In my cases the final event is decline, observed as abandonment, re-emergence or downscaling (see Chapters 2-4). A narrative approach is also productive for comparison of historical cases, which is a non-trivial issue for historical studies using variables, but is more amenable in narrative explanations[13].

Although the present work is based on historical cases, it should not be read as, and would probably not be interesting for, a historical account of the covered cases because this is not the aim. The aim is rather, as explicated in Chapter 1, to understand the dynamics of decline and learn how to intervene in it. To maintain the focus on these objectives, I structured the narratives following Andrew Pettigrew's (1990, 1997) analytical chronology approach, well suited for historical research when reconstructing a chronology of events and their causal links (e.g. Verbong et al., 2008). William Sewell (2005) notes that historical processes have multiple temporal and special causes which need to be studied in interaction. The rationale of the analytical chronology approach is to provide an explicitly interpretive historical narrative, based on the sequence, timing and conjunctures of events (Verbong et al., 2008; Geels, 2011). With this approach the aim is not to provide the 'true history', but a selectively focused narrative explanation, e.g. a heuristic device. Thus, my focus of the narrative explanation in the empirical chapters is oriented towards configurations of materials, meanings and forms of competences, as formulated above, the dynamics of which I

13 A theoretical explanation of this point may be found in Haydu (1998) and Mahoney (2000).

trace and structure the case descriptions around.

I will be discussing the detailed methods of each case in the respective empirical chapters. Overall, I used archival data as primary sources, and academic literature, grey online literature and the press as secondary sources. In one of the cases it was possible to conduct interviews with some of the stakeholders. I collected the data between 2018 and 2020, inclusively. The data consist of literature review, media review, studies of archived material and recorded interviews. All collected data, except interviews, were gained from publicly accessible sources (archives, books, journals). For the interviews permission to use the data was given by the interviewees. All data, except interview transcripts, were stored in Maastricht University's standard facilities for storage and backup. The data collected can be accessed via DataverseNL (Koretsky, 2022).

I present the cases by the outcome of decline: re-emergence, contraction and abandonment. As said, these are not (only) historical accounts, but contain much analysis aimed to develop the argument of the book towards answering the research questions. In the empirical chapters I return iteratively to the research questions of the thesis, instead of dedicating one chapter to one aspect or question. The empirical chapters have been published or submitted to academic journals through the course of my PhD trajectory (I note this in footnotes in each of the chapters in question). This was done prior to the publication of the present thesis and they thus reflect earlier stages of development of this book's conceptual framework. I give this disclaimer to minimise the confusion of the reader who will notice conceptual differences. Notably, Chapter 4 singles out social practice theory as the primary conceptual basis for the adopted heuristic, whereas in the current thesis there is no such emphasis, as discussed earlier in the present chapter; or in some of the empirical chapters I use 'phase-out' synonymously to 'decline', whereas there is a difference, as discussed above. The 'final version' of the conceptualisation should be sought in the present chapter and Chapter 7.

I have not adjusted the text of the empirical chapters, so they may appear disjointed. Thus I include "Intermissions" between the empirical chapters that build upon the publications' conclusions and expand them towards the goals of the present book. Another function of the Intermissions is to increase coherence of the thesis argument in its progression from a methodology (Chapter 3), used for empirical exploration, to a framework in Chapter 7. In Chapter 7 I bring together the different analytical threads and formulate the framework on technological decline.

Chapter 4. **Decline and re-emergence: cloud seeding**[14]

4.1. **Introduction**

Technology phase-outs are aspirational targets, as well as real-world phenomena. In this paper we understand technology phase-outs as a process of scaling down production, use and/or research and development of particular equipment, processes and associated practices to the point of their abandonment in wider society through a process of unravelling of the socio-technical configuration that makes up a technology.

Deliberately phasing out technologies is increasingly recognised as a necessary and viable measure to foster sustainability (Goulet & Vinck, 2017; David, 2017; Rogge & Johnstone, 2017; Geels et al., 2019). Recent examples are the Paris Agreement pledges of China, Denmark, Spain and the Netherlands, among other countries, to stop building new coal plants and phase out old ones, the emergence of the Powering Past Coal Alliance[15], Germany's commitment to phase out nuclear and coal power, a 2019 discussion in the UN to ban lethal autonomous weapon systems (Gayle, 2019), a 2019 OECD summit on regulating artificial intelligence (Murgia & Shrikanth, 2019), and increasingly common cities' policies to ban cars from city centres. In 2020, the UK government called for advice on a petrol, diesel and hybrid cars phase-out (UK Department of Transport, 2020).

The opposition to phase-out is diverse, too. Upham and colleagues specify four causes for reluctance of decision-makers to support change: sunk costs, locked-in learning, certainty of coordination in the status quo, and adaptive and self-fulfilling expectations (Upham et al., 2015); and Meadowcroft (2011) adds to this low priority of change in a pre-existing list of things to do. Such barriers to change enhance 'lock-in' mechanisms (Geels et al., 2015) and path dependence (Mahoney, 2000; Garud & Karnoe, 2001). Phase-outs, indeed, may have far-reaching consequences. Historical examples are oil shortages in the West in the 1970s (e.g. Burnett, 1991; Rüdiger, 2014), controversial coal mining curtailment in the UK (Turnheim, 2012; Turnheim & Geels, 2012), disruptive pushing-out of traditional hand weaving in India (Mamipudi, 2016), or discontinuation of popular products (e.g. Tushman & Anderson, 1986;

14 This chapter was originally published in *Environmental Innovation and Societal Transitions* (Koretsky & Van Lente, 2020), co-written with Harro van Lente, hence the use of pronouns "we" and "our" in the chapter and some repetitions with the preceding chapters in this book. I preserve the use of the term 'phase-out' here, even though the difference between 'phase-out' and 'decline' is acknowledged in Chapter 1. Minor adjustments were made in this chapter to format figure and table references and footnotes for consistency.

15 https://poweringpastcoal.org/ [Accessed on October 13, 2021]

Ehrnberg, 1995; Levain et al., 2015), such as older computer versions.

In innovation studies and science and technology studies (STS) several scholars have argued that more insight is needed on how phase-outs unfold, start, are steered and finalised (Lindqvist, 1994; Edgerton, 2007; Shove, 2012; Stegmaier et al., 2014; Levain et al., 2015; Goulet & Vinck, 2017; Rogge & Johnstone, 2017; Russell & Vinsel, 2018; Markard, 2018). These studies show that technology phase-outs *are* complicated and may occur for all kinds of reasons. For instance, some technologies were phased out in a less directed manner, while others were more guided (ice harvesting industry in the US (Utterback, 1994) vs. coal mining in the UK); some were more complete, others less (space shuttle vs. incandescent light bulb (Stegmaier et al., 2014)); some phase-outs were caused by substitution, while others by obsolescence (fountain pen (Shove et al., 2012) vs. kamikaze attack aircraft). Studies exploring the phenomenon of technology phase-out are necessary precisely because gaps in this knowledge prevent decision-makers to act.

Yet, innovation studies and STS approaches, with their focus on emergence and early stages, do not have much to say about the phenomenon of phasing out, as we show in the following section. This raises the question: how to explore phase-outs of technology? We address this question in two ways: conceptually, by looking at phase-out as an unravelling of a socio-technical configuration; empirically by studying a particular case, cloud seeding in the US. Interestingly, cloud seeding is an unsuccessful phase-out which resurfaced several decades later as a proposed geoengineering technique. The case thus allows to see how phase-out unfolded, how it was unsuccessful and how re-emergence took place.

Below we first review how phase-out has been studied thus far and argue that social practice theory offers a promising heuristic (section 2). Next, we delineate how we study the historical case of cloud seeding in the US (section 3). We then present (section 4) and discuss our findings (section 5), and return to the theoretical and empirical questions on phase-out in the concluding section.

4.2. **Studies on phase-out**

In this paper we conceptualise technologies as ‘socio-technical configurations’, which are networks of intertwined heterogeneous elements (Geels, 2002; Shove et al., 2012). In this, we draw on the concept of ‘seamless web’, emphasised in both transitions and STS literature, which encompasses heterogeneity, plurality and co-evolution of science, technology and society (MacKenzie & Wajcman, 1985; Hughes, 1986; Callon, 1987). In transitions literature this is conceptualised as ‘socio-technical system' (Rip & Kemp, 1998; Geels, 2002, 2011).

The phenomenon of phase-outs of socio-technical configurations is not widely studied, although literature on the topics of destabilisation and discontinuation is growing. In most innovation studies and STS literature the topic has been overshadowed by traditional interest in innovation and emergence of novelties. Yet, there is pioneering work, which varies by objects of study—technology, industry, governance conditions, etc.—and studies aspects of phase-out, such as preparation or enactment.

In transition studies, for instance, Turnheim and Geels (Turnheim, 2012; Turnheim & Geels, 2012, 2013) discuss regime destabilisations, seen as loss of stability of established systems. In this approach, technology is de-emphasised and is implied to co-evolve with industry. The industry regime comprises knowledge and capabilities, cognitive frames, values, and formal regulations. Destabilisations are explored from the perspective of firms in the industry regime: how they respond to pressures on the regime from economic and socio-political environments.

Another approach addressing decline is Technological Innovation Systems (Hekkert et al., 2007; Bergek et al., 2008), particularly, its more recent expansion by Kivimaa and Kern (2016). TIS is also a firm-centred approach that is aimed to advise policy intervention on diffusing new technologies (Coenen & López, 2010). Technology is seen as a system of knowledge, expectations, markets, resources, culture and other elements (Bergek et al., 2008). Kivimaa and Kern (2016) explore the destruction of incumbent regimes (such as old building designs or lighting) via control policies, significant changes in regime rules, reduced government support for dominant regime technologies, and changes in the composition of key actors.

The Multi-Level Perspective on socio-technical transitions (Rip & Kemp, 1998; Geels, 2002; Geels & Schot, 2007; Smith et al., 2010) explicitly addresses the transition from one socio-technical system to another (Coenen & López, 2010). It is successful in explaining the emergence of novelties and the accompanying regime dynamics, but it has relatively little to say about processes of decline (Shove & Walker, 2007; Hargreaves et al., 2013; Geels, 2019).

Stegmaier and colleagues explore attempts to induce technology phase-out, or discontinuation (Stegmaier et al., 2014). Drawing from the multiple-streams framework (Kingdon, 1984), Stegmaier and colleagues look at how governance actors (government, parliament, firm, industry association, group of countries, etc.) take the lead in defining problems to be solved, and guide the phase-out by withdrawing support from specific policies. Technology here is seen, similarly to MLP, as a configuration of policies, actors and artefacts.

In STS, recent work on the classic Large Technical Systems (LTS) approach discusses how systems like electricity supply or telecommunications reconfigure, get contested and decline under pressure (Sovacool et al., 2018). Decline is conceptualised here as a halt and reversal of growth of the system and decline of sales or quality of service. Since the emergence of transition studies and the MLP approach, LTS somewhat fell out of fashion. One of its proclaimed limitations is its emphasis on 'heroic actors', usually company heads (Ewertsson & Ingelstam, 2005; Sovacool & Hess, 2017).

The term 'exnovation' has been coined to explore phase-out when "a given technology is currently no longer used because its physical infrastructure has been deliberately removed" (David, 2017, p. 138). The theoretical and empirical focus here is on preparing and starting a phase-out, but not on its enactment. Other work in STS on phase-outs is less specific, but is important in its early calls for attention to the topic of phase-outs (Goulet & Vinck, 2012, 2017).

The list above is not exhaustive, but shows how the most recognised approaches (Köhler et al., 2017; Sovacool & Hess, 2017) address the phenomenon of phase-out. Some of them focus on stages in the trajectory of a socio-technical configuration that precede phase-out, like emergence or destabilisation; others focus on parts of socio-technical configurations, like governance conditions. Despite their strengths, these approaches do not fully address the phenomenon of phase-out of socio-technical configurations, and they do not provide a convincing heuristic to *trace* phase-outs and to study *how* they unfold in time and space, which is the knowledge gap identified in the introduction and which we aim to address in this paper.

Phase-out from the perspective of social practice theory

The overview above showed that emergence, stabilisation and decline of socio-technical configurations are multifaceted phenomena, including material, cognitive and cultural aspects. To study a socio-technical configuration phase-out, a framework is needed that allows heterogeneity and change. We think social practice theory offers a productive perspective because it acknowledges diversity, while not limiting itself to novelty and emergence in the first place.

Transitions research, indeed, has paid increasing attention to social practice theory (Shove & Pantzar, 2005a; Røpke, 2009; Gram-Hanssen, 2011; Spaargaren, 2011; Watson, 2012; Halkier, 2013; Welch & Warde, 2015; Liedtke et al., 2017), including attempts to bridge it with other prominent approaches such as the MLP (McMeekin & Southerton, 2012; Hargreaves et al., 2013). In general, social practice theories (Schatzki, 1996; Schatzki et al., 2000; Reckwitz, 2002; Røpke, 2009; Schatzki, 2016) study practices as "organized, and recognizable, socially shared bundle of activities that involves the integration of a complex array of components" (Welch & Warde, 2015). Spaargaren and colleagues (2013) point out that theories of practice emphasise centrality of routinised (as opposed to only conscious) human action, and this routinised action is manifested in the flow of everyday practices. Theories of practice are aimed to turn away from dualisms of agency-structure or micro-macro. They enable policy solutions that are not tied to changing individual behaviour and beliefs only (Watson, 2012).

According to Shove and colleagues, practices are "configurations that work" (Shove et al., 2012, p. 41), they are "a necessarily provisional, but relatively consistent, relatively enduring integration of elements" (Shove et al., 2012, p. 82). In this reading, practice theory has a nuanced, specific and simple view of change, as the interaction of three elements: materials, competencies and meanings (Shove et al., 2012); or material, cognitive and symbolic elements (Watson, 2012). The first encompasses "objects, infrastructures, tools, hardware and the body itself", the second one is "know-how, background knowledge and understanding", and the third one "mental activities, emotion and motivational knowledge" (Shove et al., 2012, p. 23). In this way, phase-out is to be understood as a disruption, or unravelling, of the linkages between these three elements.

When practices decline, elements become disconnected and diverge, for instance reading a map becoming a rare skill now that there are GPS navigators (Shove et al., 2012). In principle, three things may happen to elements after the disruption of links: disappearance with little or no trace, becoming 'dormant', or becoming part of other practices (Shove et al., 2012). In case of complete or near-complete disappearance, artefacts are not used anymore and become rubbish, what was before common knowledge turns into a little-known secret, and previously widely shared meanings are forgotten and become obscure hints (Shove et al., 2012).

Conceptual framework

In this paper we formulate our own conceptual framework and view phase-out as *the unravelling of materials, competencies and meanings in socio-technical configurations*. This framework is inspired by practice theory but does not apply it in a strict sense, because we are not interested in practices, but in socio-technical configurations. We thus adapt the approach of social practice theory in two ways: the unit of analysis and the scale of analysis. Regarding the first, we follow Shove, Pantzar and Watson (2012) in their discussion how social practice theory is relevant for the study of socio-technical configurations (Sovacool & Hess, 2017). Secondly, we expand the usual focus of social practice theory on "routinized type of behaviour" (Reckwitz, 2002, p. 249) to the temporal and spatial scales appearing in sustainability transitions research (Köhler et al., 2017).

We emphasise that in this paper we do not aim to adopt the entirety of social practice theory with all its assumptions – we are instead only intrigued by the lessons offered by this approach and its lack of emergence bias. Yet, by exploring the unravelling of the socio-technical configuration and by expanding its conceptualisation to include systemic phenomena, we also address two critiques of social practice theory: the simplification of reducing socio-technical configurations to three elements (Shove et al., 2012; Sovacool & Hess, 2017); and the neglect of broader, systemic phenomena (Sovacool & Hess, 2017).

4.3. **Methodology**

Cloud seeding is a technology of injecting a chemical compound into the atmosphere with the aim of changing the properties of the atmosphere (Simspon & Dennis, 1972; Weather Modification, 1974; Fleming, 2010; Baumgart, 2017), such as causing precipitation or reflecting sunlight. It can be used either with ground-based or aircraft-mounted generators. Sometimes equated with a broader label of weather modification, cloud seeding has been researched and developed by at least American, British and Soviet governments and private actors starting in the 1950s (Fleming, 2010; Baumgart, 2017). The effectiveness of cloud seeding has been debated since its invention. Today it is generally accepted that cloud seeding works only under certain, almost laboratory, conditions, such as the right air moisture, wind speed and direction (Spinrad, 2009; Baumgart, 2017).

We opted for a case study approach as it allows to observe deep causal links, although at some expense of generalisability (Yin, 2012). Since the aim of the paper is to bring forth the dynamics of phase-outs, a case with dynamic interactions between and within materials, meanings and competences was needed. We opted for cloud seeding because it is a contested technology, but, perhaps surprisingly, also widely practiced across time and space. We chose the US because of its historically leading role in cloud seeding R&D: today most international cloud seeding initiatives date back or rely on experience gained during the US experiments of the 1950s and 1960s and later technology transfers abroad. We chose a historical study of several decades to create a rich case description and trace the temporal dynamics between materials, meanings and competences and draw lessons from the unfolding of the phase-out. The exact composition of what counts in our case study as materials, meanings and competences was our choice based on our operationalisation from theory. The types of primary data we searched for is summarised in Table 3. We see the original conceptualisation of materials too limited to material objects, therefore we expanded it to also include funding and markets (cf. Shove, 2016). To trace these elements, we followed a representations approach by Upham and colleagues (2015), who propose to collate representations of technologies – which, according to Upham *et al.*, shape both social and physical environment – gathered from texts. To follow representations means to follow how technologies are rendered familiar and tangibly understood (Upham et al., 2015).

Element of configuration	**Descriptors from theory**	**Operationalisation for case study**
Materials	Objects, infrastructures, tools, hardware and the body itself	Aircraft, chemical compounds, delivery systems, meteorological models, funding infrastructure, market
Meanings	Mental activities, emotions, motivational knowledge	Public discourses, laws, perspectives (e.g. control, drought relief), emotions
Competences	Know-how, background knowledge and understanding	Chemistry, flying, modelling, assessing location/time, number of graduates in field

Table 3. Operationalisation of data for case.

We collected the data from primary sources using archival research and media analysis. We used publicly available digital archives of the USA Library of Congress[16], the Hathi Trust Digital Library[17] and the CIA digital archive[18], all of which offer rich digital collections. For a focused approach, we limited ourselves in this paper to aircraft-based cloud seeding, which is a more widespread form of cloud seeding; we also do not cover the history of pre-WW2 cloud seeding.

We searched for these terms: "cloud seeding", "weather modification", "rainmaking", and "geoengineering", and supplemented the results using the snowball method. This returned, overall, about 30,000 hits, which we scanned and filtered to identify relevance to the topic of cloud seeding phase-out. We closely read and analysed the remaining 49 government and congressional reports, published recollections, and other documents. The media analysis was conducted using ProQuest and LexisNexis databases using the same search terms as above and focused on three largest US newspapers: *The Washington Post*, *The New York Times* and *The Wall Street Journal*. We limited our search to years 1945-2018. Out of the 1,250 hits, which we manually screened titles of, we filtered out 1,035 unrelated to cloud seeding (i.e. search term mentioned in passing or not discussed in any meaningful way), and closely read the remaining 215. The main secondary sources used for background knowledge and

16 https://www.loc.gov/collections/ [Accessed on March 3, 2020]

17 https://www.hathitrust.org/ [Accessed on March 3, 2020]

18 https://www.cia.gov/library/ [Accessed on March 3, 2020]

contextualisation were the books *China lake: A journey into the contradicted heart of a global climate catastrophe* by B. Baumgart (2017), *Make it rain: State control of the atmosphere in twentieth-century America* by K. Harper (2017), and *Fixing the sky: The checkered history of weather and climate control* by J. Fleming (2010).

To make sense of the collected historical data, we conducted content analysis and created a reconstructed analytical chronology, following an analytical chronology approach by Pettigrew (1990, 1997). This approach is well-suited for historical research when reconstructing a chronology of events and of their causal links is needed (Verbong et al., 2008). The rationale of the approach is to provide an explicitly interpretive historical narrative, based on the sequence, timing and conjunctures of events (Verbong et al., 2008; Geels, 2011). The aim is not to provide all of a 'true history', but a selectively focused narrative explanation (Verbong et al., 2008). This focus of the narrative explanation in this paper is oriented towards materials, meanings and competences, the dynamics of which we trace and structure the case description around. During content analysis we manually coded the framings of the search terms and the context of each source. These codes informed the categorisation of various meanings of cloud seeding discussed in the next section. For example, we predominantly coded MacDonald (1968) as 'dangerous technology' and 'unacceptable ethical hazard' because the text places cloud seeding in a group of other harmful 'environment modification' technologies: "Intense interest in this form [i.e. seeding] of weather modification […] is likely to lead to effective cloud modification within the next five to fifteen years. […] As economic competition among many advanced nations heightens, it may be to a country's advantage to ensure a peaceful natural environment for itself and a disturbed environment for its competitors. Operations producing such conditions might be carried out covertly. […] Such a *'secret war' need never be declared or even known by the affected populations*" (1968, pp. 184, 205, emphasis added). Another example is a hearing in the US Congress (Weather Modification, 1966) which we coded 'welcome forest fire relief' and 'welcome water supply control': "We have performed experimental seeding operations in an instrumented test area during three *lightning storm* seasons" (p. 257, emphasis added); and "I continue to believe that man can solve many of his *water supply problems* through weather modification techniques" (p. 16, emphasis added). We provide further examples for most primary sources which we have used in the next section.

Figure 2 summarises the case based on the collected available data. It shows the rise of federal funding for cloud seeding up to 1972, some fluctuation and a drop of funding between 1973 and mid-1980s, and a sharp rise in seeding area starting from 1998-2000. The latter period also saw 'geoengineering' using cloud seeding becoming a debated technique (see also Figure 3, Figure 4 and Figure 5). Based on the figure, we identify three distinct periods of cloud seeding history: emergence, phasing-out and re-emergence. Although in the following section we present these periods as rather strictly limited to certain years, this is just an analytical simplification, tied to certain events that we take as key for the respective period.

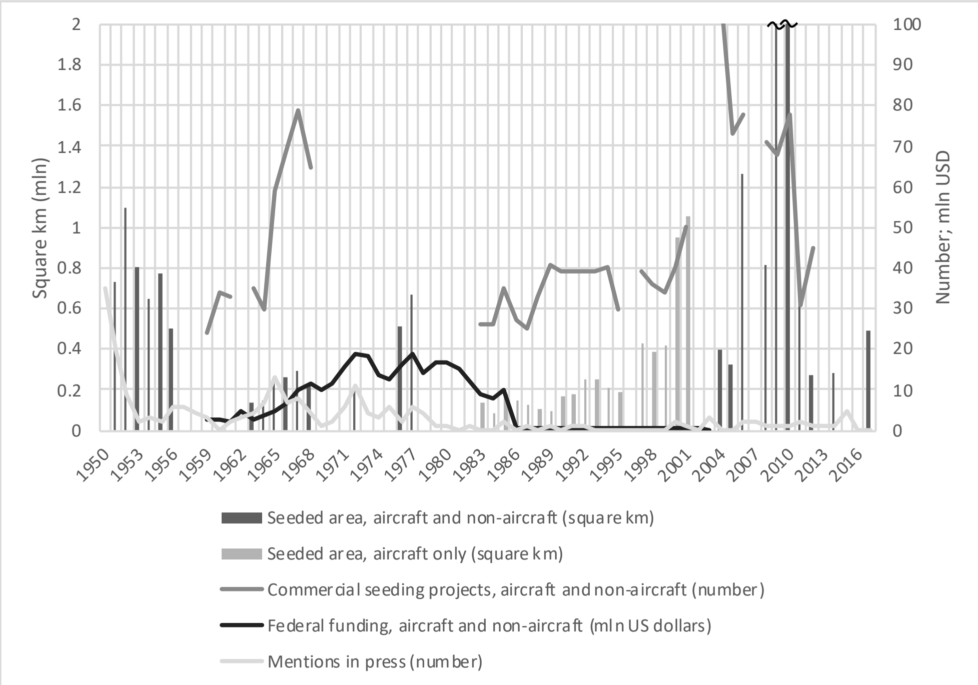

Figure 2. Different indicators illustrating performance of cloud seeding between 1950 and 2018. Sources on funding: weather modification reports to US Senate (Weather Modification, 1964, 1966, 1974; Congressional Research Service, 1978)*, Changnon and Lambright (1987), and NRC (2003). Sources on seeded areas and commercial projects (incomplete data): NSF "Weather Modification" annual reports (e.g. National Science Foundation, 1968), NSF (1968), WMO reports "National Weather Modification Projects" (e.g. World Meteorological Organization, 2002), and NOAA weather modification annual reports (e.g. 2008). Sources on mentions in press: own calculations based on newspaper archives. For a coloured version of this image please refer to the digital version of this paper.*

4.4. Case study: cloud seeding in the US (1946-2018)

4.4.1. Emergence (1946-1971)

This period saw the foundation and peak of both R&D and field cloud seeding in the US. Most notable events are first experiments, a series of droughts which brought water supply control high on the public agenda and led to project Skywater – one of the first large-scale cloud seeding projects, and the Senate's inquiries into classified funding related to weather modification, anti-hurricane project Stormfury and military project Popeye. In this period, the meanings were connected with the materials and competences to form cloud seeding.

Materials

The materials foundation for cloud seeding was established in 1946 and did not significantly change with time or with application. One needed an aircraft (usually Douglas DC-6, Lockheed WP-3D, WC-130 and lighter planes), a chemical compound, its delivery system (burner, flares, hoppers), photo cameras, water gauges and/or sensors, and, preferably, a meteorological model of sorts. From the beginning, carbon dioxide (dry ice) and silver iodide were established as main chemical agents to create ice crystals out of air moisture.

Fuelled by the promises of the technology (see "Meanings" below), federal and private funding rose consistently (Figure 2). The first large-scale project was Cirrus (1947-1952) by General Electric and the US Army (Havens, 1952). Research and test project Skyfire (1953-1978) by Department of Agriculture, and projects Artificial Cloud Nucleation, Scud and Shower (1953-1954/55) by the military followed (Harper, 2017). A decade later, a lot of resources were drawn to project Stormfury (1962-1983) (Willoughby et al., 1985), run by the Navy and the National Oceanic and Atmospheric Administration (NOAA), project Skywater (1966-1980) by the Department of the Interior (Rogers & Gahan, 2013), and project and operation Popeye (1966-1972) by the military (Weather Modification, 1974; Fleming, 2010; Baumgart, 2017). Several universities ran smaller projects (Congressional Research Service, 1978).

The growth of private cloud seeding market was sudden in the early 1950s and immediately caused problems as rivalling farmer-seeders sued each other for stealing rain. Multi-year commercial projects counted by the dozens and total seeding areas reached 0,5-1,1 mln km^2 yearly (Figure 2).

Meanings

The meanings of cloud seeding voiced by the developers (e.g. General Electric, the US government) and users (mostly the same actors, but also, prominently, farmer associations, municipalities, and utility companies) can be grouped into optimistic ("water supply control", "hurricane mitigation", "forest fire relief", "diplomatic tool", "weapon") and cautionary meanings ("dangerous technology"). Actors aligning with the optimistic meanings were more active during the time of the socio-technical configuration's emergence, despite the lack of conclusive evidence for the efficacy of cloud seeding to affect any precipitation. In 1951, General Electric advertised the promises of cloud seeding, hoping for government financial support of (their) commercial cloud seeding R&D, and so did the Departments of the Interior and Agriculture, who hoped to lead the management of present and future shortages of water (Weather control and augmented potable water supply, 1951). Policy reports were also openly optimistic about future results and called for continuous support for research and application (e.g. Newell, 1966). Even the US presidents Kennedy and Johnson contributed to the discussion, as illustrated by Lyndon Johnson's phrase: "he who controls the weather controls the world" (Wilkison, 1962).

Owing to a long tradition to commodify nature (e.g. Mrozowski, 1999; McCauley, 2006; Bermejo, 2014), the desire to control the weather was seen by some actors as a self-evident objective (Fleming, 2010). **Water supply control** represented a belief that seeding a cloud with chemicals would produce rain. This idea was propagated by Irving Langmuir (1948) and picked up by farmers, hydropower companies, ski resorts, but also the US Bureau of Reclamation (of the Department of the Interior). Secretary of the Interior commented that there are "enormous rivers of water flowing over us in the atmosphere; of huge pools of moisture poised above our heads" (Weather Modification, 1966). This was topical in light of a series of severe droughts in the first half of 1950s and in mid 1960s. The move to expand the Bureau's control over natural resources materialised in the form of project Skywater in 1966.

The meaning of **hurricane mitigation** was advocated first by Langmuir, and then by meteorologists Joanne (Malkus-)Simpson and Robert Simpson (Malkus & Simpson, 1964). The idea of hurricane control was the basis for project Stormfury. **Forest fire relief** was an adjacent idea. Project Skyfire was started by the Forest Service (of the Department of Agriculture) to find out how to decrease the threat of lightning-caused fires to forests using cloud seeding. Cloud seeding was also seen as **diplomatic**, or ideological, **tool** within the confrontational mentality of the Cold War. Vannevar Bush called to use cloud seeding to improve crop-growing conditions in other countries and thus "extend our favorable influence over the free world" (Weather control…, 1951).

Cloud seeding was also attractive for the US Army as photoreconnaissance aid, as a way to reduce enemy troop morale, damage harvests, trigger precipitation to expose camouflage and reveal signs of enemy activity on supply routes (Harper, 2017). The Navy, Air Force and Army had their own projects to **weaponise the weather**. The head of weather modification R&D at the US Navy, Pierre St. Amand, told in 1965 Senate hearings that "[w]e regard the weather as a weapon" (Taubenfeld & Taubenfeld, 1969).

Some actors did see cloud seeding as **dangerous technology**. The Weather Bureau and some others contested cloud seeding on scientific grounds, and other critical voices joined (e.g. MacDonald, 1968; C. F. Cooper & Jolly, 1970). The science advisor to the president Donald Hornig warned president Johnson of "serious political implications involved with using weather control techniques" (Harper, 2017, p. 217).

Public attitudes were split. The press reported a great variety of opinions: support (e.g. urging to make use of "rivers in sky" ("Udall Urges…," 1967)), disillusionment (e.g. titles like "Farmers Map War on Cloud Seeding" (1964)), law suits (e.g. "Rain-Making Suits Showering on City" (1951)), and concerns (e.g. the exposure of Vietnam cloud seeding (J. Anderson, 1971)). Cloud seeding was often blamed for bad weather, and cloud seeders were being sued for damage to crops. For some time cloud seeding remained a legal grey area, but by 1958, thirteen states introduced regulations on cloud seeding (Harper, 2017).

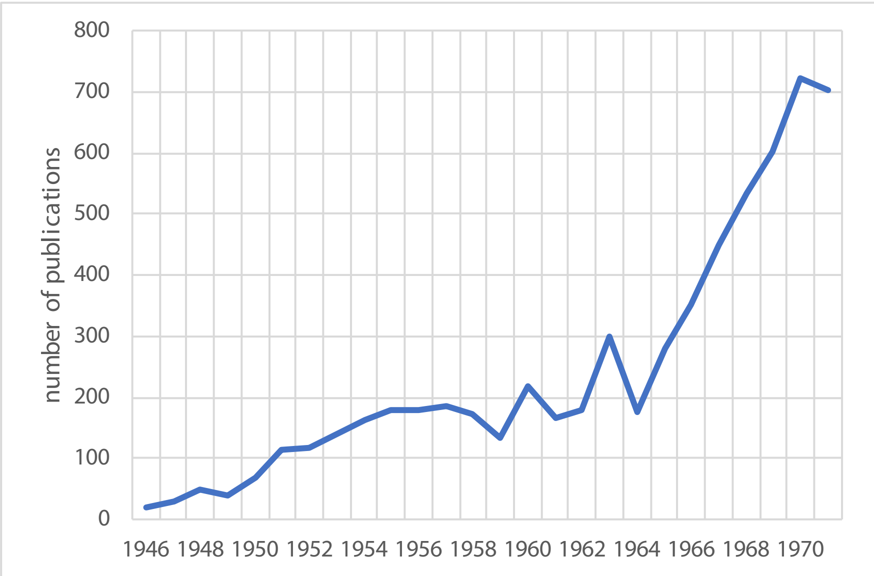

Figure 3. Academic interest in cloud seeding between 1946 and 1971 illustrated by keyword frequency in academic texts. Created by authors combining Google Scholar searches for terms discussed in the methodology section.

Competences

Cloud seeding required certain skills and competences in, e.g. chemistry and microphysics – for developing the seeding agent; piloting – for manoeuvring the clouds, assessing speed, etc.; meteorology – to know where to fly; and modelling. Recollections of US pilots about military cloud seeding in Asia state that pilots and crews were required to obtain a special qualification to seed clouds[19]. Some pilots' skills and experiences during cloud seeding turned out so unique, they were able to pursue academic career in meteorology (Baumgart, 2017).

19 http://www.awra.us/gallery-jan05.htm [Accessed on March 3, 2020]

Government actors attempted to build up theoretical and applied expertise so they funded or called to fund R&D programmes to increase the number of graduates and professors in relevant fields – mostly meteorology. Federal funding into meteorology grew throughout the 1960s (Horn, 1974). The numbers of undergraduate, graduate and post-graduate degrees increased steadily during the 1960s, but levelled off in early 1970s as the growth of funding stopped (Orville, 1978). The number of publications on the topic grew sharply, as illustrated in Figure 3[20].

4.4.2. **Decline (1972-1984)**

The period of decline was characterised by exposure in the media of secret military cloud seeding by the US during the Vietnam war, which caused a public outcry and the 1977 signing of the international "ENMOD" treaty prohibiting the use of "environmental modification techniques" as weapons. Both of these resulted in the peaking and then dropping of cloud seeding funding and the closing down of many cloud seeding projects in the US. In this period, connections between the three elements disrupted. A strong 'counter'-meaning emerged and damaged the legitimacy of other meanings. As a result of lost legitimacy, the diversity of cloud seeding applications shrunk, weakening meanings as an element of the configuration, and the amount of government funding decreased, weakening the material element. Both of these threatened the existence of the configuration as a whole.

Materials

The government supported cloud seeding and other weather modification R&D up to 1972 (Figure 2), when federal funding reached its highest point – 18,7 mln dollars (Changnon & Lambright, 1987). By 1975, in the context of anti-Vietnam war and environmentalist protests, funding dropped to 12 mln, whereas other R&D funding continued to grow (Changnon, 1975). Funding increased again in 1977 due to the Departments' of Defence and of Interior expenditure in years leading up to ENMOD (it seems that both were trying to spend as much as possible before the international ban entered into force), before gradually falling in the 1980s to the 1966-1967 levels. The market's precise reaction is unclear for the 1970s as there are no reliable or complete data. Judging by the number of projects alone, by the 1980s the market stabilised at the level of early 1960s.

Most materials for cloud seeding were always fairly easy to acquire as they were

[20] We take this illustration with a grain of salt, however, since the corpus of older books may not have been digitised to the same degree as newer books.

not exclusively used for cloud seeding. When governmentally funded cloud seeding projects such as Stormfury and Skyfire closed, the aircraft used for cloud seeding were either scrapped, destroyed or repurposed.

Hurricanes, or rather their absence, can also be seen as a material element that hampered the continuation of Stormfury, a project *for* seeding hurricanes, but there were none during the precarious for cloud seeding years 1970-1972 (Willoughby et al., 1985).

Meanings

Those who neither developed, nor used cloud seeding, played a key role in the decline of cloud seeding during the 1970s. Investigative journalist Jack Anderson of *The Washington Post* broke the first news about Vietnam cloud seeding in 1971 (J. Anderson, 1971), which was later picked up by others (V. Cohn, 1972; Hersh, 1972a, 1972b; Wilford, 1972). It turned out that between 1967 and 1972, cloud seeding was used to prolong the monsoon season, disrupting the movements of North Vietnamese troops with whom the US was at war at the time. The actual effects on precipitation are still under debate, unlike other technological warfare used in the Vietnam war, such as "crop killers" (e.g. Hamblin, 2014). Regardless, the military defended against critical reporting by framing dropping rain as a morally better alternative to dropping bombs (see title of a satirical piece in *The Washington Post* "The Rain Humane Falls Mainly From the Planes" (A. Buchwald, 1972)).

Thus, two meanings became dominant and pushed all the rest into background: **weapon**, which suddenly became very visible, and **unacceptable ethical and environmental hazard**, which was a development of the connected earlier meaning "dangerous technology". The meaning "dangerous technology" was not confined anymore to academic texts, but turned over to activists and policy-makers, transforming into a more hard-line and vocal meaning of unacceptable ethical and environmental hazard. Apart from the press, Senator Claiborne Pell played a big role by persisting to bring up cloud seeding for public Senate hearings during 1971-1975. The critique of cloud seeding overlapped with earlier intellectual discussions on the dangers of technology and science (e.g. Marcuse, 1964; Illich, 1973), and the environmental and pacifist movements.

Water supply control was still a popular purpose for cloud seeding, defended by commercial operators and farmer associations in West and South of the US, as well as by the Bureau of Reclamation and the Department of Energy (the latter was considering cloud water as "alternative means for water supply" as late as 1981 (National Archives…, 1981, p. 35064)). To be sure, commercial seeding largely lacked scientific foundation and even simple measurements, and, as Fleming (2010) suggests, was mainly done as an inexpensive probabilistic risk management strategy. Commercial seeders were apparently comfortable with continuing seeding, whether it actually worked or the rain was nature's doing. Commercial seeders were increasingly attacked in court (Standler, 2006) and in the US Senate (Weather Modification, 1976).

Other meanings were also increasingly contested. Cloud seeding was seen as promising **hurricane mitigation** technology only by a decreasing circle of scientists (Willoughby et al., 1985; Fleming, 2010; Woodley et al., 2010; Baumgart, 2017), who were not able to persuade the government. A case in point is the history of project Stormfury which was finally defunded in mid-1980s. Cloud seeding as **forest fire relief** (project Skyfire) died out earlier, in 1978 (Harper, 2017).

Overall, "Congressional support for the entire subject of weather modification [...] declined steeply after 1973", writes Kwa (2001, p. 157), and so one by one federal agencies withdrew their support from cloud seeding programmes. Policy and budgeting agendas were increasingly diverted from cloud seeding or any other weather modification to dealing with a more pressing oil crisis and less controversial R&D, such as atmospheric research (Changnon, 1975). After this, not much cloud seeding R&D remained apart from spin-off meteorological modelling at NOAA, NASA, Department of Homeland Security, Office of Naval Research (the Navy), and the universities. Polarising discussions in press went on till 1978 (e.g. Weisman, 1975; Herron & Johnston, 1975; Large, 1978), after which their interest waned.

Competences

Skills requirements for cloud seeding did not seem to change much and knowledge steadily grew during this period, in contrast to declining academic interest in the topic (Figure 4). Stormfury staff, waiting for suitable hurricanes, had to turn to theoretical research on cloud microphysics and meteorology (Willoughby et al., 1985; Fleming, 2010; Woodley et al., 2010). A lot of accumulated theoretical knowledge around cloud seeding was applied in weather modelling once operational cloud seeding closed down, as was the case with NOAA.

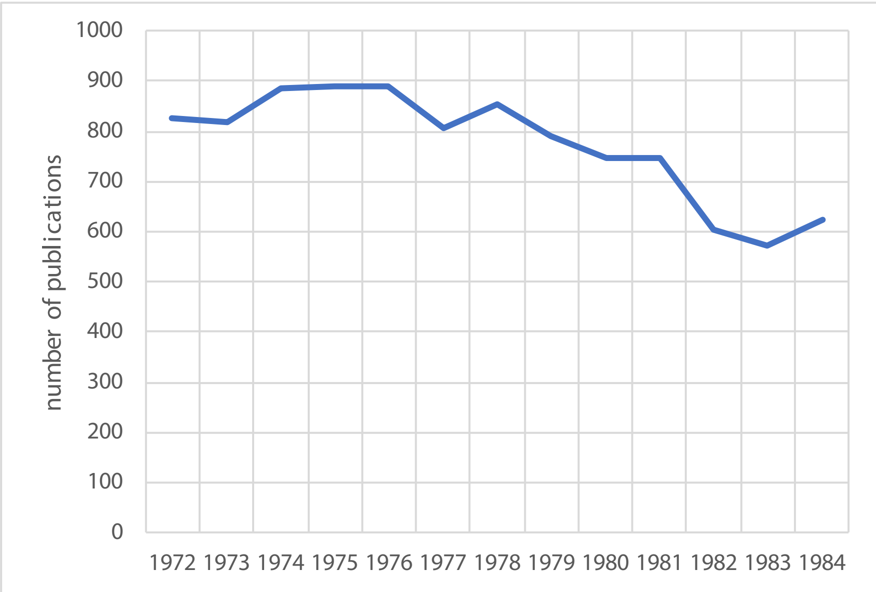

Figure 4. Academic interest in cloud seeding between 1972 and 1984 illustrated by keyword frequency in academic texts. Created by authors combining Google Scholar searches for terms discussed in the methodology section.

4.4.3. **Re-emergence (1985-2018)**

This period is characterised by a long pause in publicly visible activity related to cloud seeding (Figure 2). During the 1980s, NOAA turned away from seeding clouds to studying them. In the 1990s, cloud seeding was briefly explored by the US Air Force academic institutions, without much publicly visible effect. However, by early 2000s, cloud seeding saw a reintroduction in both academic and political circles. By the beginning of 2010s, cloud seeding featured in Congressional debates over a new possible application: geoengineering, prompted by scientists suggesting it as a ‘fix’ to global warming and hurricanes. These efforts strengthened the meanings element, as interested actors linked the new meaning of geoengineering with old and new materials and competences, and then revitalised the configuration.

Materials

Between 1985 and 2003, and by 2010, federal funding of cloud seeding R&D went down below 0,5 mln per year (National Research Council, 2003; Government Accountability Office, 2010) (Figure 2). The relatively level number of commercial seeding projects in 1980s-1990s (Figure 2) suggests a steady market, which started to grow in the late 1990s, as indicated by the rising size of seeding areas (World Meteorological Organization, n.d., 2002). In 2017, cloud seeding was conducted by four non-profit associations, three cloud seeding operators, two energy companies, one state, and one university (K. Boyd[21], personal communication, November 23, 2018). By 2018, more than 12 mln dollars of private funding were raised for a geo-engineering (see "Meanings" below) research and testing project SCoPEx (Tollefson, 2018). The meaning of geoengineering for global warming mitigation was in turn fuelled by the global warming itself and a new linking of cloud seeding competences. The main delivery systems used the same technology as in the 1960s: flares and burners[22].

Meanings

As the US emerged from the 1980s, the environmentalist and pacifist protests, including against unethical manipulation of weather (providing the 'counter'-meaning), became a thing of the past. In 1991, the National Academy of Sciences (NAS) proposed geoengineering as an option to mitigate and adapt to climate change. NAS made a case for, particularly, aircraft-delivered "dust or soot [...] in the atmosphere" and "emissions of particulate matter" into clouds (Institute of Medicine et al., 1991, p. 81), effectively proposing cloud seeding. The following year, David Keith (today an outspoken advocate of geoengineering at Harvard) and colleagues started to propose cloud seeding, among other methods, for solar radiation management as a way to prevent and undo further global warming (Keith & Dowlatabadi, 1992). If previous periods saw calls for 'improving' the climate from academic, military and science-fiction writers' circles, now deliberate **global warming mitigation**, allegedly more realistic through cloud seeding (and other means) than rainmaking, was being discussed in Congress on several occasions as a viable tactic (Weather Modification and S. 517, 2005; *Weather Mitigation...*, 2007; Geoengineering, 2010, 2017).

Small-scale geoengineering experiments such as SPICE[23] and SCoPEx[24] were being developed, although by the end of 2019 no publicly announced experiment has been conducted by the US, at least partially thanks to some critical voices seeing geoengineering as an irresponsible and **dangerous practice** (e.g. Fleming, 2010; N. Klein, 2012; Hamilton, 2015).

As in the previous period, actors, such as utility companies and farmers, were still using cloud seeding[25] for what they saw as **water supply control**. They had to

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21 Dr. Kandis Boyd was deputy director of NOAA's Office of Weather and Air Quality in 2018.

22 E.g. https://www.weathermodification.com/cloud-seeding-aerial.php and https://www.flintoff.org/cirrus-artists. [Accessed on March 3, 2020]

23 https://www.spice.ac.uk/ [Accessed on March 3, 2020]

24 https://projects.iq.harvard.edu/keutschgroup/scopex [Accessed on March 3, 2020]

25 https://www.google.com/maps/d/viewer?mid=1ro7JIEMX3R2dZZ0-JYGQBqN4W-

operate within legal boundaries introduced by most states (Standler, 2006). Other meanings of cloud seeding were not prominent. The US Air Force briefly discussed **weather as a weapon** in the 1990s, largely repeating the forty year old expectations (Air University, 1994; Coble, 1996; House et al., 1996). During this time period, NRC and NOAA claimed that intentional weather modification has been proven to not be effective and cloud seeding should be put to rest (National Research Council, 2003; Spinrad, 2009). NOAA also distanced itself from any **hurricane mitigation** (Spinrad, 2009).

In press any mentions of cloud seeding, be it for geoengineering or not, were limited during this time period compared to previous periods. Mainly new curbs and tests were discussed (e.g. Ray, 2000).

In 2010, the UN Convention on Biodiversity explicitly banned geoengineering. While the US technically did not ratify it, it had been adhering to it in practice.

Competences

During this period, cloud seeding continued to require specialised skills. As in the previous periods, pilots worked together with meteorologists who were often at a ground station and informed them of the heading and when to release chemicals.

Specialised knowledge was also required to conduct cloud seeding and interest in the topic grew sharply (Figure 5). Key figures of American cloud seeding held such knowledge, e.g. Pierre St. Amand and Joanne Simpson. Both were influenced by the decline of operational cloud seeding. St. Amand's publicly available biographies do not mention his direct involvement in cloud seeding after 1988, but his expertise with water vapour and chemistry was clearly still relevant even after retirement: he conducted consulting work on water resources for the World Bank, was a consultant to a large chemicals producer American Potash and Chemical Company, and served as a vice president and technical director of an oil spill-cleaning Muetal Corporation.

In 2019, NASA still used meteorological models designed in project Stormfury, further developed by Simpson's colleagues into the Goddard Cumulus Ensemble model – a modelling tool for weather analysis and forecast. Joanne Simpson's, former head of Stormfury, work was picked up by NASA, where Simpson led cloud modelling efforts and "space-based meteorological experiments" (NASA Earth Observatory, n.d.). Other theoretical knowledge also advanced, as evidenced by a rise of popularity in the topic (Figure 5), e.g. by 2005 meteorologists had learned to track the direction of the flow of seeded particles in a cloud (Weather Modification and S. 517, 2005).

The rise of the internet has expanded access to information about cloud seeding

bE&hl=en&usp=sharing [Accessed on March 3, 2020] with standardised cloud seeding kits and separate components available for purchase online[26]. Relatively low-skill manufacture of components was possible as well.

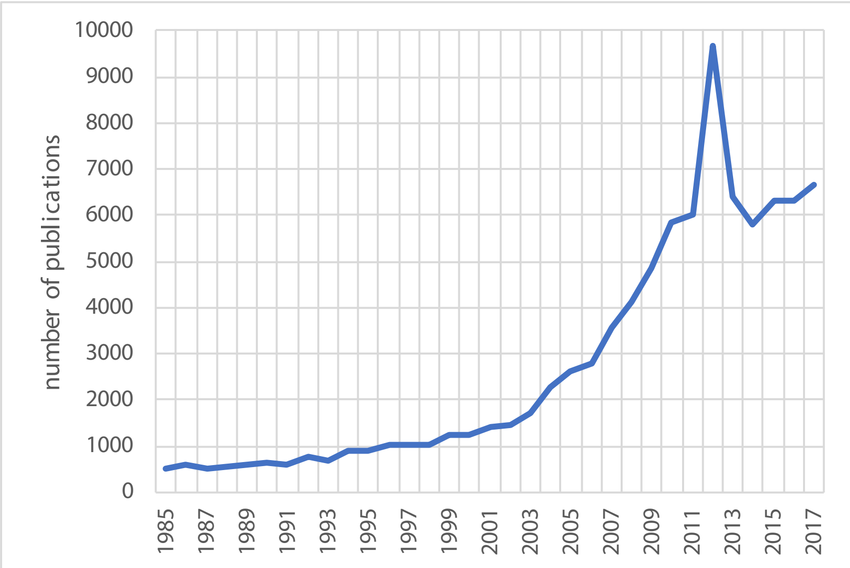


Figure 5. Academic interest in cloud seeding between 1985 and 2018 illustrated by keyword frequency in academic texts. Created by authors combining Google Scholar searches for terms discussed in the methodology section.

4.5. **Analysis**

Cloud seeding proved to be a case of incomplete phase-out, as evidenced by its later re-emergence when commercial seeding expanded and the closely adjacent meaning of geoengineering became highly visible. The phase-out of cloud seeding is a case of abandonment and revival, separated by intervals; hence it can be qualified as incomplete only with reference to the time of writing. It is interesting how the phase-out failed: even during phase-out, cloud seeding was never seized in commercial operations. In other applications it was not used after the phase-out, but it was also not entirely thrown out of the window. For instance, NOAA preserved institutional memory of cloud seeding, even if it did not perform cloud seeding anymore.

For some fields, phase-out even brought along innovation and knowledge spillover. For instance, after NOAA's cloud seeding was shut down, Joanne Simpson brought her knowledge and competences to meteorology, advancing the field's expertise in weather system computer simulations and hurricane computer modelling; and

26 E.g. http://iceflares.com/ [Accessed on March 3, 2020]

Pierre St. Amand transitioned to oil spill clean-up. This shows that after a period of phasing-out, competences, previously concentrated in high-profile R&D projects, can become free to spill over to other, less contested fields.

To better see the mechanisms of (an incomplete) phase-out, it is instructive to observe the differences between emergence and re-emergence of cloud seeding, which came down to the ability of involved actors to mobilise elements and (re-)establish links. The period of re-emergence both benefitted from and was disadvantaged by previous cloud seeding developments:

- material elements were widely available. Before the emergence of cloud seeding, many materials, such as the seeding compound, advanced sensors, delivery systems, computer models and satellites, did not exist and were developed only later. During the re-emergence, all of these materials were already present and widely used in various applications;
- the legal status of cloud seeding was more limiting during re-emergence. During emergence, cloud seeding was legally allowed with some limitations, whereas during re-emergence, there was an infrastructure of national and international regulations (although we may question their efficacy): ENMOD, the UN Convention on Biodiversity, and US state regulations;
- the diversity of meanings of cloud seeding was far smaller during re-emergence: only geoengineering, water supply control and their contestations, whereas during emergence many applications were being seriously discussed and some funded;
- the availability of knowledge differed significantly. Before the emergence there was no advanced knowledge of particle behaviour in the atmosphere. The different skills, expertise and knowledge grew slowly during the emergence. A lot of this expertise and knowledge accumulated in scientific articles, conference proceedings, cloud seeding companies and associations, and became embedded in meteorological models by the time of re-emergence, and the interested actors could easily benefit from this.

Overall, the amount of work needed for the re-emergence was lower than for emergence. For re-emergence, elements of cloud seeding were readily available to be reconnected, and in some fields, like commercial cloud seeding, there was no disconnection in the first place. Even when cloud seeding was no longer performed, cloud seeding was 'stored' in institutional memory, in manuals and tacit knowledge. Here, re-emergence was possible because the materials, meanings and competences, although disconnected, still existed, and they did not have time to turn to dust, be forgotten or become unfamiliar. Finally, successful re-emergence was also facilitated by having a precedent for connecting the elements.

The phase-out was triggered by shifts in one of the elements: meanings. During the years 1971-1972 dominant meanings ('water supply control', 'weapon', etc.) came under pressure and eventual silencing of most of them by a strong counter-interpretation: 'unacceptable ethical and environmental hazard'. In a way, this was a destructive counter-meaning that posed an existential threat to cloud seeding (thus illustrated by red colour in Figure 6). Most other meanings were defeated by this counter-meaning and this weakened the configuration. As Van Lente and colleagues found in a study of hypes and disappointments, diversity of meanings allows more possibilities for recovery in cases of problems: "[t]he more specific an envisioned application is, the more difficult it becomes to reorient expectations after disappointment" (Van Lente et al., 2013, p. 1617). Should the remaining meaning of 'water supply control' not have survived, no more meanings would be linked to materials and competences and cloud seeding would phase out. In such case, re-emergence would have required more work and time to prepare required knowledge, expertise, equipment, etc. The connections between elements were the weakest around 1985 (as visualised by 'hollow' vertical lines in Figure 6), so the potential for a more complete phase-out was the strongest then.

The potential for a complete phase-out weakened as the dynamics *within* elements developed. In the period of re-emergence, entrepreneurial actors connected new, although pre-existing (illustrated by horizontal lines in 'materials', Figure 6), material elements to cloud seeding: 'global warming' and 'reflective particles'; as well as to new meanings: 'global warming mitigation' and, briefly, 'weapon'[27]. The new elements (whose novelty in the configuration is emphasised by blue colour in Figure 6) were successfully linked up with the older elements of 'water supply control', 'severe droughts', 'computer modelling', 'aircraft', etc. As a result, not only were clouds still being seeded commercially, but now new cloud seeding R&D was being conducted with the aim of geoengineering. Thus, for cloud seeding, the dynamics *within* an element have been crucial, i.e. when various meanings, materials and competences do not immediately substitute each other, but co-exist, compete with or complement one another. Figure 6 summarizes our analysis.

Some final remarks about the case. One may argue that cloud seeding is not a valid case of phase-out because it never actually 'phased in', and it never worked anyway. In these two respects cloud seeding differs from, say, fossil fuel-based technology

27 Although these materials existed, they were not always linked at the right time and at the right place. For instance, the unavailability of hurricanes at the right time and at the right place prevented the Stormfury project, which hosted a large part of cloud seeding R&D, to continue performing cloud seeding.

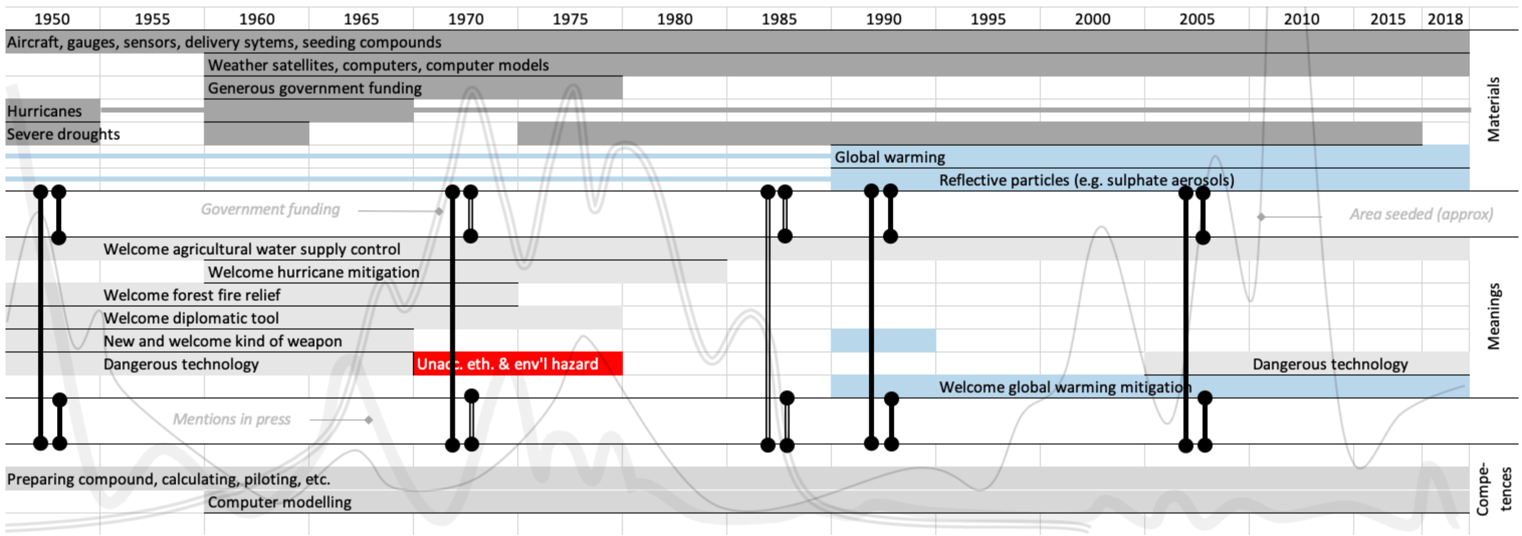


Figure 6. Actively connected elements of cloud seeding (bold vertical lines), in schematised dynamics of emergence (1946-71), phasing-out (1972-84) and re-emergence (1985-2018). Red indicates the element that weakened the socio-technical configuration. Blue indicates newly-connected elements. Government funding (double line), seeded area (thin line) and mentions in press (thick line) are overlaid in grey and introduced in more detail in Figure 2. For a coloured version of this and other graphics please see the online versions of the publications.

or plastics. Yet, it was institutionalised enough to see a lot of commercial activity, federal funding, press coverage, and embedding in legislation. The question whether it 'actually' worked is less relevant than what key actors decided and were prepared to act upon. In a sense, a technology 'works' only if key actors agree amongst each other that it does (Bijker et al., 1987; Latour, 1992; Van Lente & Rip, 1998). US citizens, cities, states and eventually the federal government for a time funded not only cloud seeding research, but also operations. For a time they clearly agreed that it worked, even though there may well have been a "collective delusion" (Hamblin et al., 2011) of deliberate control of weather.

4.6. Discussion and conclusions

Much attention in innovation studies and STS, as well as in policy-making, is paid to emergence and scaling up of technologies. To support sustainability transitions and 'just transitions', studying the phase-out of technologies is equally important, yet receiving less scholarly attention. We developed an understanding of phase-out as the unravelling of materials, competencies and meanings in socio-technical configurations. With a heuristic inspired by social practice theory, we studied a historical case of American cloud seeding.

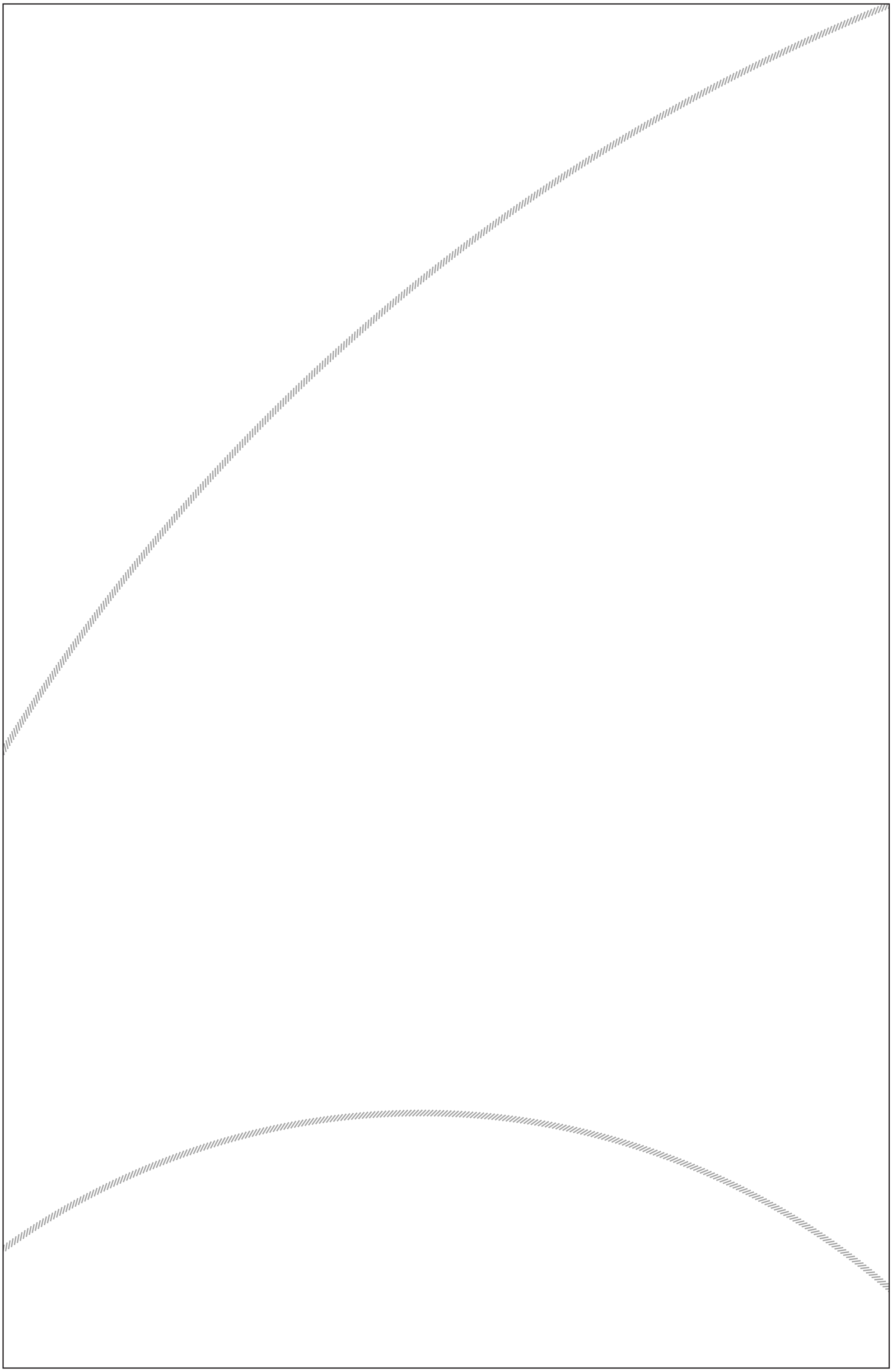
We found that cloud seeding is an incompletely phased-out socio-technical configuration in which the links between material, cognitive and symbolic aspects were strained, but never fully disrupted. Moreover, it is a case of a re-emerging configuration. We found that the competition between meanings and counter-meanings had first weakened most of the meanings attached to cloud seeding by mid-1980s, but then receded, allowing cloud seeding to re-emerge in the 1990s and beyond. When a new meaning of 'geoengineering' emerged, new entrepreneurial actors came into play, as well as new seeding competences and new problems to be solved (global warming) with old cloud seeding techniques. We thus argue that phase-out, while disruptive, is not necessarily destructive. Despite challenging the status quo and 'unlocking' the lock-ins, it may generate innovation via knowledge spillover and free up the previously occupied resources. Thus, for instance, meteorology, an adjacent field, benefitted from the weather models and hurricane simulations developed previously in cloud seeding projects.

In this paper, we adapted a heuristic from social practice theory to study technologies and sustainability transitions. An important reminder is that we did not study practices, but socio-technical configurations. Where practice theory would see different practices of cloud seeding, say, agriculture or firefighting, in this paper they all fall under one socio-technical configuration with competing meanings. However, our work shows that insights from practice theory may be applicable to other units of analysis and other scales than the local. With this, the paper contributes to bridging closer practice theory and transition theory, and supports such suggestions by, for instance, McMeekin and Southerton (2012) and Hargreaves and colleagues (2013). The potential of other theories and approaches to study phase-outs is far from exhausted. Further research could study how established theories of innovation can explain phasing-out and differences between different kinds of phase-outs, including reversible and irreversible ones. Finally, the trajectory of cloud seeding may be part of a larger phenomenon that is cyclical (emergence—decline—re-emergence), so a fruitful research direction may be to link the study of unravelling with larger patterns, such as hype cycles (Van Lente et al., 2013) or long waves (Kondratiev, 1999).

More empirical studies and dedicated policy studies are needed to offer policy advice on phase-outs from the perspective of unravelling. Still, we attempt to formulate at least some preliminary practical advice for 'just transitions' based on our findings. First, the lessons of social practice theory apply for technologies as well: since phasing out implies the disruption of links between the materials-meanings-competences triad, it appears that losing one of them would be enough. Thus, governance actors interested in phasing out could target one element only. However, they would need to carefully examine the ramifications. If, for instance, the element is part of other technologies or other configurations, it might not be safe to disrupt it. In the case of cloud seeding, phase-out could have been more complete if it was subjected to more pressure when the socio-technical configuration was most vulnerable, that is, when the links between the elements were the weakest in mid-1980s. Had there been more concerted effort to, for instance, continue raising concerns on many governance levels regarding cloud seeding as a weapon, or, more broadly, the morality of commodification of nature, perhaps cloud seeding would not have re-emerged, or at least this would have taken more work. More research is needed on the actual policies to be implemented, however, since unintended consequences may follow.

Second, governance actors should not be in principle overly reluctant to initiate phase-outs of technologies. As shown, phase-outs could produce innovation and knowledge spillover, both of which could be harnessed to mobilise political support for phase-out policies. In addition, for a just transition, phase-out policy does not have to mean nor should it necessarily aim for absolute eradication, say, a universal ban. Significant scaling down may be enough via awareness raising, reduction of funding or regulation and monitoring. Thus, the objective of phase-out could be fulfilled, and room will be left for those with interest to continue working in a niche. The downside is a potentially easier re-emergence.

A final lesson might be that cloud seeding phase-out started with investigative reporting and Congressional debates – neither party was a developer or a user of the given technology. This confirms that an opposition to a technology does not need to be closely involved with its design or even use to start or support a phase-out.



Intermission I: gains thus far

The goals of the present thesis are broader than the goals of the empirical chapters. To expand into these broader goals and to explicitly integrate the cloud seeding case into the book, it is useful to recall the book's research questions: how to characterise, understand and intervene in the processes of technological decline?

Mobilising the metaphor of strands, that co-constitute the given socio-material configuration as long as the configuration is used and/or produced (Chapter 3), I draw the following theoretical and practical lessons from the cloud seeding case for the goals of the thesis. These may help to characterise and understand the processes of technological decline:

- a decrease in intensity of performance of the configuration seems to coincide with a decrease in variety of one or more strands. In other words, a technology seems to decline when it becomes less embedded, or useful in fewer applications. This is supported, but only in relation to meanings and to new technologies, by Van Lente and colleagues (2013) who suggest that re-legitimising a technology is easier when its interpretive flexibility is (re)opened: "emerging technologies with generic applications can be linked to a more diverse set of expectations associated with different paths of social embedding" (Van Lente et al., 2013, p. 1617). This implies that there may be a link between the unravelling within the strands and a lower resilience of the configuration[28];
- unravelling in one strand may be enough for the unravelling of the configuration to start;
- during unravelling of the configuration, some forms of competences seem to travel to other configurations and technology fields (e.g. from cloud seeding R&D to meteorology), thus, potentially, ensuring their continuity (and the jobs for the individuals involved), even though they may change in the process.

With regards to lessons for interventions into processes of technological decline (research question 3), I observe from the cloud seeding case that a technological decline policy does not have to mean nor should it necessarily aim for absolute eradication, say, a universal ban. Thus, the objective of decline could be fulfilled, and room will be left for those with interest to continue working in a niche. The downside is a potentially easier re-emergence.

28 An analogy comes to mind of a thin stack of spaghetti being easier to break than a thick one. (For the peace of mind of Italian chefs among the readers—this is only a hypothetical analogy, not meant to endorse breaking spaghetti in half for cooking.)

Governance actors interested in decline should examine which dimension of the technology in question would be safe and ethical to target first: materials, meanings or forms of competences. For example, firing the workforce without compensation or prospects for re-employment would obviously be a bad move. On the other hand, as in the cloud seeding case, governance could target the meanings. Supporting strong, independent investigative media, as well as having a receptive and active parliament, matters for decline, as do international agreements (such as the ENMOD) that can be used to leverage other countries' decline of the given technology.

Since in my empirical chapters I iteratively explore the research questions of the thesis, the lessons above remain to be confirmed and explored with other cases before they can be generalised.

With these intermediate insights from the cloud seeding case in mind, I now turn away from the American cloud seeding case to a different context with a much more recent case of the European light bulb ban. I will continue to observe the strands of the configuration, and explore the links between changes in one or more strands and the changing resilience of the configuration to withstand shocks like competitors and regulation.

Chapter 5. **Decline and contraction: incandescent light bulb**[29]

5.1. **Introduction**

Technology phase-out is commonly understood as a process of decline of production and/or use of a given technology from large scale to small scale or even to complete abandonment. Technology phase-out is increasingly seen by policy-makers and in academia as a viable exit strategy for an unsustainable technology (e.g. petrol cars in the UK[30]) or for an unpopular one (e.g. nuclear power in Germany (Johnstone & Stirling, 2020)) (Goulet & Vinck, 2017; David, 2017; Rogge & Johnstone, 2017; Green & Denniss, 2018; Geels et al., 2019; Markard, Geels, et al., 2020), whereas previously a focus on nurturing novelties dominated.

Phase-outs are real-world phenomena and they show great variation in how much they are steered (e.g. ice harvesting in the US (Utterback, 1994) vs. coal mining in the UK (Turnheim & Geels, 2012)), how long they take (e.g. incandescent light bulb (Stegmaier et al., 2014) vs. cigarettes (Oreskes & Conway, 2010a)), how long the technology stays phased out (e.g. space shuttle vs. vinyl records (Magaudda, 2011)), how disruptive they are (e.g. coal mining curtailment in the UK (Turnheim, 2012; Turnheim & Geels, 2012)), and more. Exploring these and other questions has gained academic interest in recent years, including studies on technology discontinuation (Stegmaier et al., 2014; Stegmaier, Visser, et al., 2021), destabilisation and failure (Turnheim & Geels, 2012; Turnheim & Sovacool, 2020), withdrawal (Goulet & Vinck, 2017), exnovation (David, 2017) and more (e.g. Shove, 2012; Koretsky & Van Lente, 2020; Markard, Bento, et al., 2020)[31]. This is refreshing in the context of the prior dominant focus on emergence and novelties (Lindqvist, 1994; Edgerton, 1999; Stegmaier et al., 2014) in innovation studies, science and technology studies (STS) and history studies. In this paper I view phase-out to be equally important to emergence because decline of a given technology is to be expected at some point in time (MacKenzie & Spinardi, 1995) or is desirable, especially in cases of market failure (Rogge & Johnstone, 2017; C. Roberts et al., 2018; Rosenbloom & Rinscheid, 2020), thus it is important to prepare for it (Kivimaa et al., 2021).

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29 This chapter was originally published in *Energy Research and Social Science* (Koretsky, 2021), hence some repetitions with the preceding chapters in this book. I preserve the use of the term 'phase-out' here, even though the difference between 'phase-out' and 'decline' is acknowledged in Chapter 1. Minor adjustments were made in this chapter to format figure and table references and footnotes for consistency.

30 https://www.gov.uk/government/consultations/consulting-on-ending-the-sale-of-new-petrol-diesel-and-hybrid-cars-and-vans/consulting-on-ending-the-sale-of-new-petrol-diesel-and-hybrid-cars-and-vans [Accessed on April 10, 2021]

31 See Rosenbloom and Rinscheid (2020), Kanger and colleagues (2020) and Turnheim and Sovacool (2020) for comprehensive reviews.

In this paper I revisit the case of the incandescent light bulb phasing-out. My starting point is the puzzling observation that it concerns an iconic technology so ubiquitously used and produced, and yet the phasing-out occurred relatively swiftly. I ask: what processes were involved in the phasing-out of the incandescent light bulb after the phase-out regulation entered into force? With this research question I pursue both a theoretical aim, to gain insight in any emerging patterns of the fast phasing-out of this embedded technology, and an empirical aim, to learn more about any disruption caused by phasing-out to the stakeholders after the regulation entered into force, since much prior literature on technology phase-out tends to focus on developments that precede such regulation.

While the light bulb phasing-out has been studied before, the present study differs in its approach and analytical focus. Stegmaier and colleagues, for instance, study the light bulb discontinuation "as a problem of interpretation and action for governance makers" (Stegmaier et al., 2014), revealing moves by governance actors, such as adapting policy and standards. In this paper, however, I aim to go beyond a focus on governance actors and look at the overall phasing-out dynamics, including the moves and strategies of other stakeholders. Opening up these dynamics is important to advance the knowledge about phase-outs, how to navigate them (Kivimaa et al., 2021), how to speed them up (Sovacool, 2016) and how to ensure justice (e.g. Jasanoff, 2018) – all pressing topics in energy transitions.

The incandescent light bulb is an interesting case because it was a very common, mature and culturally established technology. This makes the speed of its phase-out, ten years, somewhat exceptional (Negro et al., 2012; cf. Sovacool, 2016). In addition, the phasing-out, while meeting dissent at the time (Stegmaier et al., 2014), in hindsight is evaluated positively, with disruptions largely forgotten. For example, European consumer association BEUC recently reported that consumers saved on average around 1,330 euros over the years due to the phasing-out (Quack, 2019). There is an alleged positive economic change for low-income communities (EP, 2018), and the press has been, generally, writing positively about the phasing-out (e.g. Edis, 2017; Simon, 2017). Previous studies have shown that there was limited resistance to the light bulb phasing-out; in fact there was an alignment of stakeholder interests (Kierkegaard, 2014; Stegmaier et al., 2014; Edge & McKeen-Edwards, 2008). These converging interests may have been the reasons for both the speed and the welcomed outcomes of the light bulb phasing-out. It almost seems like an exemplary phasing-out, thus worth investigating.

I discuss my analytical framework and methods in more detail in section 5.2. In section 5.3 I review the case of the incandescent light bulb in Europe. In section 5.4 I further analyse the case and draw further empirical and theoretical conclusions.

5.2. Studying technology phase-outs

5.2.1. Theory

Among the emergent literature on phase-outs and adjacent concepts (Kanger et al., 2020; Turnheim & Sovacool, 2020; Rosenbloom & Rinscheid, 2020), two dominant approaches in transition studies are particularly advanced in explicitly conceptualising technology decline and phasing-out. These are 'discontinuation governance' by Stegmaier and colleagues (Stegmaier et al., 2014; Stegmaier, Visser, et al., 2021) and 'regime destabilisation' by Turnheim (Turnheim, 2012; Turnheim & Geels, 2012). The former focuses on discontinuation as policy-society-technology dynamics. The authors look at how powerful actors (policy-makers, firms, industry associations, group of countries, etc.) take the lead in defining problems to be solved and guide the phasing-out by withdrawing support from specific policies. In turn, in literature on regime destabilisation, destabilisation is studied as a phenomenon of accumulation of external pressures, internal performance problems and a weakening commitment of firms to the industry regime. Turnheim describes firm strategies to deal with regime destabilisation. In destabilisation, technology is de-emphasised and is implied to co-evolve with industry.

Both these approaches are instrumental in understanding what different actors do when trying to prepare, steer or oppose phase-out. However, their foci are not on tracing *the effects* of the developments that constituted the downward trajectory of the phasing out technology *after* governments decided to phase out. These developments are important to trace to open up phase-out of an embedded technology and any of the phase-out's disruptive dynamics. Second, the two approaches tend to focus on a relatively narrow selection of actors, usually those in power to frame issues and steer the direction of phase-out: policy-makers, firms, industry associations, etc. These stakeholders are crucial, as I will confirm, particularly in shaping the design of phasing-out technology, but more stakeholders participate in the dynamics of phasing-out technology and are affected by it (Oudshoorn & Pinch, 2003). To answer my research question and to complement both discontinuation and destabilisation approaches, I take an explicit focus on the empirical developments in phase-out during the next ten years *after* the European phase-out regulation entered into force, focusing on the roles of and effects on industry and policy-makers, but also *more actors* such as the users and industry employees.

5.2.2. **Methods**

I opted for a case study approach as it allows to observe deep causal links, although at some expense of generalisability (Yin, 2012). Research on energy often is limited to a single national context, whereas, like previous analysts of the incandescent light bulb (ILB), I look at the EU scale, which was the scale of the light bulb's phasing-out. I limited my analysis to the main target of the EU phase-out policy, the classic, incandescent light bulb[32].

For this study I conducted content analysis of primary literature, reviewed secondary literature, conducted a media analysis and two in-depth interviews. For the literature analysis I searched for texts with Google Scholar and Web of Science[33]. For the media review I have analysed seven English-language sources taken as proxies to European debates on the phase-out: *Euronews, Radio Free Europe, Euractiv, The Guardian, The Times, The Irish Times* and Irish *Examiner*. I used the LexisNexis database to search for any mentions of the ILB, not only its phase-out. Only the last five media sources produced any hits.

To validate my findings I held interviews with two key actors. I interviewed a representative of a Dutch sectoral labour union FNV Metal and representatives of lighting company Signify, formerly known as Philips Lighting (together with Osram, Signify is one of the two largest lighting companies in Europe). I treat the FNV Metal source for illustrative purposes to specify and illustrate a national perspective around phasing-out and labour.

I manually coded the material, accounting for the framings of the searched terms and the context of each source, conducted content analysis, searching for emergent themes, and compared data from my sources. I conducted case analysis according to the analytical chronology approach by Pettigrew (1990, 1997). This approach is suited well for historical research when reconstructing a chronology of events and of their causal links is needed (Verbong et al., 2008). The aim is not to attempt to present 'objective' history with all of the minute details, but to provide an explicitly interpretive, selectively focused historical narrative, based on the sequence, timing and conjunctures of events (Verbong et al., 2008; Geels, 2011). The focus of the narrative explanation in this paper is guided by materials, meanings and competences, the dynamics of which I trace and analyse.

32 Commonly called the Edison light bulb, classic light bulb, A-type bulb or general lighting service (GLS) lamp.

33 Search term used: Europe AND (incandescent OR filament) AND (lamp OR bulb) AND ban OR phase-out.

5.2.3. **Case background**

It is tempting to explain the history of the ILB in hindsight and claim that the preconditions for the phasing-out were obvious before it started. I aimed to avoid this pitfall by tracing the history of the ILB from its position of strength and solid societal embeddedness. Much has already been written about the emergence and embeddedness of the European light bulb, such as reviews of the history of its invention and development (e.g. Israel, 2002; Burghart et al., 2006; Stross, 2007), and technical comparisons with other bulb types (halogen, fluorescent, etc.) (e.g. Montoya et al., 2017). Extensive technical reviews of the European ban were made for the European Commission (EC) before (VITO, 2009) and after (VHK/VITO, 2013) it entered into force, as well as for the IEA (Waide, 2010). The results of the ILB phasing-out have been evaluated both favourably (Chappin & Afman, 2013) and unfavourably (Frondel & Lohmann, 2011; Perino & Pioch, 2017) compared to other policy options (taxation, subsidies) from an economic and ecological perspectives. One assessment statistically showed negative effects on economic equality (Mills & Schleich, 2010), and another found that the ban was not effective in lowering the number of used ILBs by 2014 (Cabrera Santelices et al., 2015). Jensen (2014), Mills and Schleich (2014) and Blum and colleagues (2018) showed the complex and shifting attachments some European users have towards the ILB. Moseley and Ferguson (2011), Runkle and colleagues (2012), and Haans (2014) showed negative biological effects of compact fluorescent lighting (CFL) compared to ILBs. Socio-economic and governance studies of Edge and McKeen-Edwards (2008), Deters (2018), Kierkegaard (2014), and Stegmaier and colleagues (2014; Stegmaier, Visser, et al., 2021) emphasise how the ban was a fast, easy and attractive solution for a coalition of actors whose strategy, however, lacked transparency and consumer participation.

Below I present the analysis of the case of the light bulb phasing-out. After data collection and a preliminary analysis, I identified three stylised periods in the history of ILB phasing-out: widespread acceptance up till 2005, a short period of contestation between 2006 and 2008, and phasing-out between 2009 and 2020. I structure the case analysis in the next section along these periods. This strict periodisation is only an analytical simplification, tied to events that I take as key for respective periods.

5.3. Case analysis

5.3.1. The ILB is widely manufactured and used (up till 2005)

By the 2000s, the start of the assessed period, the *meaning* of the traditional Edison light bulb was solidified as a very common object (Figure 7) in households and the ILB had firmly become part of the culture. It was, for instance, the symbol of innovation and bright ideas (Brant, 1988) and, at one point, was popular in jokes of a varying degree of offensiveness[34] (Kerman, 1980). One psychology study found that the light bulb has a traceable psychological and cognitive effect (Elmore & Luna-Lucero, 2017)[35]. In 2006 alone 2.1 billion out of 5.1 billion bulbs installed in EU households were ILBs (EC, 2009c). On average in 2007, a household had twice as many ILBs than other bulb types (EC, 2009c) due to its comfortable light colour, dimmability and low price (IEA, 2006).

The *material* element of the ILB was straightforward in this period. In the first half of the 2000s, European ILB market was mature. Sales were stable (VHK, 2019), or, according to Eurostat, on the rise (Figure 8)[36]. During the 1960s-1980s, Philips[37], at the time one of the two largest lighting companies in Europe (alongside Osram), had fourteen ILB manufacturing centres in Europe with hundreds of employees each (Harry Verhaar[38], personal communication, October 2, 2020). Foreign trade and installed capacity were also fairly stable (Figure 9, Figure 10).

The assembly of an ILB required a high-investment industrial base because the parts are being produced and processed (heated up, formed, melded, mounted, soldered, sealed) on the production line (Bas Klawer[39], personal communication, October 2, 2020). All of this required strict process control and a lot of *competence* (Bas Klawer, personal communication, October 2, 2020). Since the development of the ILB in 1878, new types of light bulbs were introduced (e.g. fluorescent and halogen lamps around the 1930s (Bijker, 1995b)) and used next to ILBs.

34 "How many [insert name of identity group] does it take to change a light bulb? – Three: one to hold the bulb, and two to turn the ladder" (Kerman, 1980).

35 Elmore and colleagues write that "exposure to an illuminat[ed] light bulb enhances participants' performance on insight-based problems […] whereas exposure to a burnt-out bulb reduces creativity" (Elmore & Luna-Lucero, 2017).

36 Accurate data on the use of light bulbs is notoriously not trivial to acquire or interpret, hence the diverging estimations in models and Eurostat statistics.

37 Philips formed a separate company Philips Lighting for its lighting business in 2016, renamed Signify in 2018.

38 Mr. Verhaar worked as Head of Global Public & Government Affairs at Signify (formerly, Philips Lighting) at the time of personal communication.

39 Mr. Klawer worked as Head of Global Manufacturing at Signify at the time of personal communication.

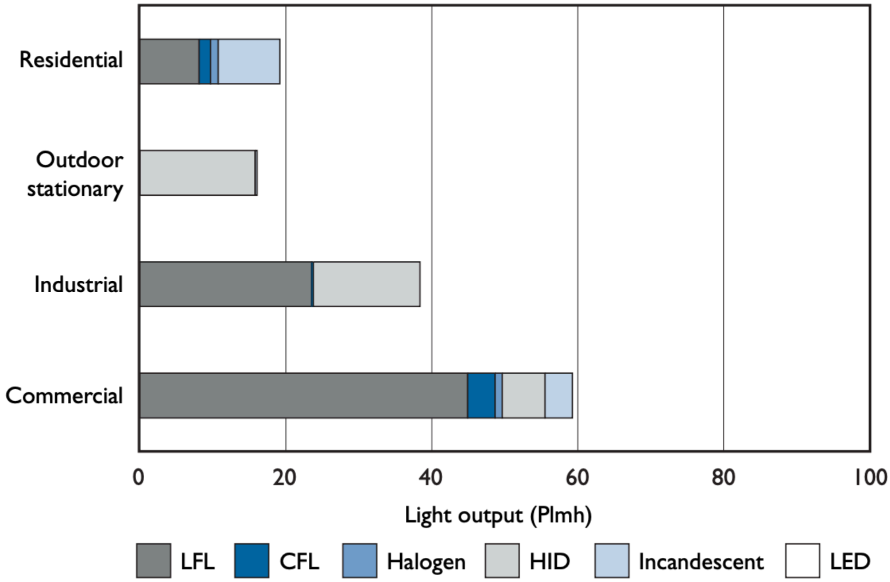

Figure 7. Estimated global average share of electric light production by lamp type and end-use sector in 2005. LFL = linear fluorescent lamp, CFL = compact fluorescent lamp, HID = high-density discharge lamp, LED = light-emitting diode lamp. Source: IEA (2006). *Reproduced with permission. For a coloured version of this image please refer to the digital version of this paper.*

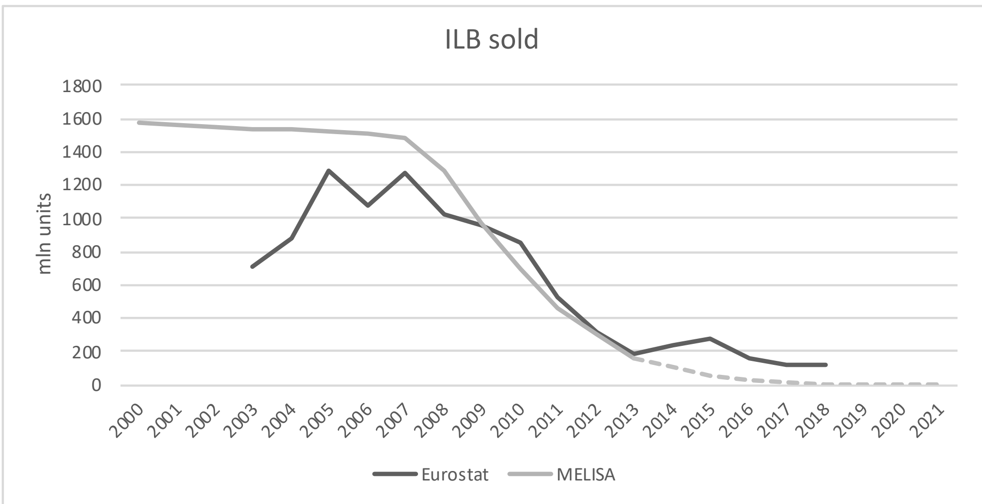

Figure 8. Incandescent light bulb sales in Europe (dashed line indicates projection). Data sources: Model for European Light Sources Analysis (MELISA) (VHK, 2019) *and Eurostat* (2020).

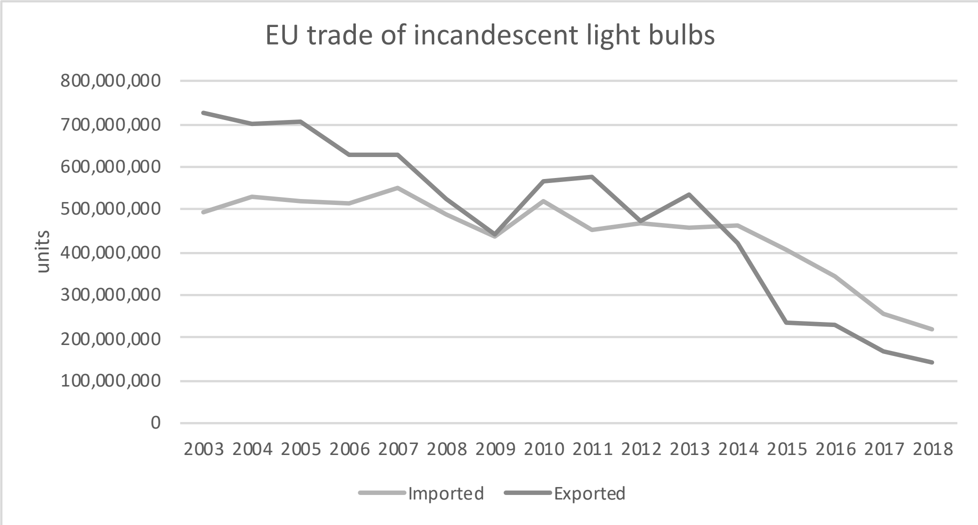

Figure 9. EU trade of incandescent light bulbs. Data source: Eurostat (2020).

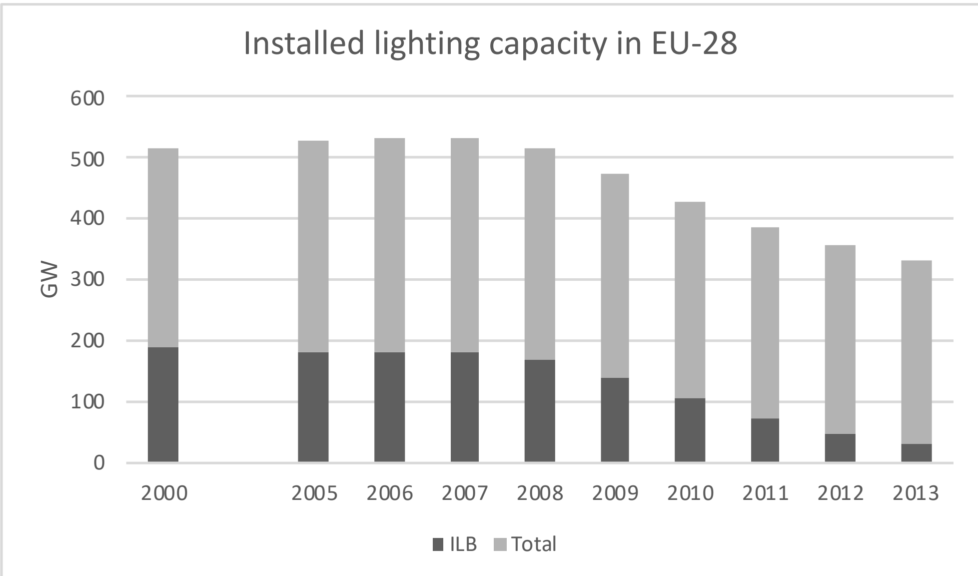

Figure 10. Installed lighting capacity in the EU. Data source: VITO (2015).

The user was not expected to have complex *competences* to use the ILB. The use and disposal of ILBs was more straightforward than alternatives available in early 2000s, such as compact fluorescent lighting (CFLs) or the early light-emitting diodes (LEDs). The latter two required user instructions regarding their disposal: CFL contained dangerous mercury and both CFLs and LEDs were considered e-waste and had to be recycled accordingly (VITO, 2015). The use of CFLs was also tricky: although great design effort was spent on achieving a familiar bulb-like shape (Kanellos, 2007) to fit in the place of the ILB, CFLs needed to be handled extra carefully for fear of breaking and one needed to get used to their cold light, slow ignition, flickering, especially with earlier CFLs[40].

Overall, by the 2000s, the ILB was very well embedded physically and culturally, although it did already co-exist with other types of lamps. During the 2000s, major manufacturers were selling CFL bulbs for niche markets, alongside the dominant ILBs, but were expecting the latter to continue to dominate at least in the short term (Kelly & Rosenberg, 2016). The longer-term expectations were linked with the LED (Franceschini & Alkemade, 2016). As I will discuss below, the infrastructural and cultural embeddedness of the ILB was exactly the reason policy intervention became an attractive option.

5.3.2. **Wide support for ILB phase-out (2006-2008)**

The speed of the events that had led to the beginning of the phasing-out of the ILB in Europe was remarkable and is usually attributed to the alignment of the interests of the EC, who had climate targets to meet, a part of consumers, who wanted to save on energy costs, and the industry (Stegmaier et al., 2014; Deters, 2018; Stegmaier, Visser, et al., 2021; Edge & McKeen-Edwards, 2008). This topic was covered in prior literature, but here I investigate the material, discursive and competence-based dynamics key for the analysis of the subsequent phasing-out.

It has always been well known that the ILB is the least energy-efficient lamp type due to its low ratio of consumed energy to produced light (5% (IEA, 2006)). However, only during the mid-2000s was this characteristic of the light bulb's materiality mobilised as a framing strategy by the industry and the governments to form a negative public opinion of the ILB. A 2006 International Energy Agency (IEA) report on lighting industry which called the ILB a "symbol of waste"[41] (IEA, 2006). The IEA advised more countries to phase out the ILB (IEA, 2006). ILB phase-out was appealing to policy-makers and large consumers (Kierkegaard, 2014), as it did not require extra costs or considerable behavioural change from them (Edge & McKeen-Edwards, 2008). Most EU countries backed up the recommendation (Zissis, 2007; Howarth & Rosenow, 2014). The press reflected the change from a pre-2006 positive image of the

[40] More on adoption of CFL can be found in Franceschini and Alkemade (2016).

[41] "[I]n today's world, where rapidly rising demand for energy (including that required to feed billions of incandescent light-bulbs) is contributing to equally rapid growth in greenhouse gas emissions, the incandescent light-bulb should rather be a symbol of waste" (IEA, 2006, p. 64).

ILB to the 2006-2009 lively debates about the downsides and benefits of both the ILB and its ban. Notably, critique from groups who opposed the ban was hardly visible.

The industry in Europe (i.e. Osram, Philips and other smaller companies) was quick to support this change of *meanings*. If before 2006 manufacturers were content with focusing on selling the ILB, fast improvements in LED technology quickly changed that. LEDs were more attractive for producers than the ILBs: although they had a much slower replacement rate than the ILBs[42], LEDs had a higher profit margin (GE, 2007; Deters, 2018; Edge & McKeen-Edwards, 2008). In 2006 the industry announced support for global phase-out (Zissis, 2007; Howarth & Rosenow, 2014; Franceschini & Alkemade, 2016; Edge & McKeen-Edwards, 2008)[43].

In addition to reframing the meaning of the ILB, the industry has been for decades trying to bring the appearance of CFLs and LEDs closer to the ILB's. Both LED and CFL lamps stuck close to the ILBs design for technical reasons, as the new lamps had to be of the right shape to fit into lamp fixtures (Kierkegaard, 2014) and to emit light in a uniform way (Franceschini & Alkemade, 2016), and for psychological reasons, as the A-shape was already very familiar and thus easier to adopt (Bouwknegt, 1982; Maya et al., 2000). Here we see how certain *material* characteristics of the ILB were borrowed to benefit the CFL and the LED.

In sum, for the majority of the 20th century there was little interpretive flexibility of the ILB in Europe, whose low energy efficiency was always known. By year 2000, the bulb was still embedded in both cultures and ceilings. This interpretive *in*flexibility ended as global warming and the role of energy consumption debates gained steam throughout the 2000s. A controversy started forming around the ILB, primarily by national governments via the IEA and by lamp manufacturers. The different stakeholders were constructing a common frame of the political and technical problem of the ILB as an energy inefficient technology and shaping the physical characteristics of the LED. Their argument was that the market was too slow to drive the switch from the inefficient ILBs to CFLs and early LEDs. Evidently, the technical shortcomings of the ILB were not bothering energy consumers, and, in fact, many enjoyed the ILBs. Teaming up against the ILB, the anti-bulb stakeholders pushed further the reframing: is it really the dear and familiar light bulb or rather a "symbol of waste"? In the end,

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42 By 2009, replacement of ILBs accounted for more than 90% of Philips' and Osram's sales revenue (New Street Research, 2010).

43 Philips Lighting CEO said that "[i]t simply isn't realistic to ask manufacturers to make unilateral decisions to stop manufacturing incandescent bulbs. […] This needs to be done collectively and will probably need to be backed by legislation which sets minimum performance criteria" (Philips, 2006). Signify senior management retrospectively reflected on the rationale of the announcement: "we […] believe that you need to create your own future […]; if you don't phase out your own technologies, someone else will" (Harry Verhaar, personal communication, October 2, 2020). Osram had started to distance rhetorically from the ILB already in 2004 (Siemens, 2004).

as I discuss below, the opposition of groups with strong preferences toward the ILB was not powerful enough to persist.

5.3.3. The ILB production and use are downscaled (2009-2020)

Short-term effects of the ban

In 2009 the EC "Regulation 244/2009" (EC, 2009a), the sales ban, entered into force. Some lamps were exempted from the beginning, such as the coloured, low-voltage or low-luminosity ILBs, as well as ILBs for "special use" (LightingEurope, 2013), like those meant for industrial purposes (Kierkegaard, 2014) and horticulture (Signify, n.d.).

Following the ban, the ILB market started declining: import steadily decreased (Figure 9), the share of ILBs in installed lighting, as well as their absolute number, also fell (Figure 10). Sale estimations (Figure 8) show a drop starting in 2009, although the stockpiling of ILBs by shops (e.g. Jung, 2009) prolonged the phasing-out (Stegmaier et al., 2014).

The ban triggered structural changes in the lighting industry and caused a dip in turnover between 2009 and 2011 (Eurostat, 2021a). As Osram dismantled (Reuters, 2017) and Philips spun off (Halper, 2018) their ILB production capacities, smaller firms took up the opportunity to fill the shrinking European market. Signify, Innr, General Lamps and other smaller firms manufactured ILBs (General Lamps, n.d.) and ILB look-alikes (Innr, 2021). Retailers and numerous webshop businesses were offering often unbranded ILBs for sale, often claiming they were rough-service lamps, exempted from ban (Malnick, 2012; VITO, 2015).

As the ban rolled out, many dissenting voices were heard. They, however, did not end up having much influence on the phasing-out. I discuss below that this happened for two reasons: their voices were too weak to alter the downward trajectory of the ILB, and they retreated, accepting the advent of a new technology, the LED.

A controversy broke out as some groups, feeling excluded from prior negotiations, voiced their strong concerns regarding the phasing-out (e.g. Stegmaier et al., 2014; Deters, 2018). EU consumer associations, for instance, were angry of the prospects to find no ILBs in shops, while people with sensitivity to artificial lighting could not tolerate the flickering of the CFLs. Grievances towards the CFL also related to their perceived fragility and poisonousness, flickering, slow ignition times, and cold blue light tone (*Save the Incandescent Bulb*, 2009; VITO, 2015).

Multiple responses that aimed to challenge the now-dominant *meaning* of the ILB as a "waste of resources" appeared. The ILBs were praised for costing less, performing

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
EU28 (2013-2020)	-	-	158,6	153,9	154,8	153,4	155,6	163,2	165,1	168,5
EU27 (2007-2013)	161,6	158,7	-	-	-	-	-	-	-	-
Belgium	2,6	5,4	5,1	3,7	3,4	3,1	4	3,2	3,1	2,9
Bulgaria	1,2	0,9	0,9	0,9	1,1	1,2	1,2	1,2	1,2	1,3
Czechia	7,6	7,7	7,9	9,1	10,5	12,2	13,4	14,4	15	15,6
Germany	37,1	38	38	38,3	37,3	38	34,1	38,1	34,5	32,5
Estonia	0,3	-	0,3	0,4	0,3	0,4	0,4	0,4	0,5	0,5
Ireland	0,2	0,3	0,2	0,1	0,1	0,1	0,1	0,2	0,2	-
Greece	1,8	1,9	1,5	1,6	1,1	1,5	1,3	1,4	1,4	1,6
Spain	10,3	9,8	9,2	8,6	8,2	8,4	8,9	9,8	10,9	11, 6
France	-	16,4	15,9	14,9	16,2	11	11	10,7	11,3	10,4
Croatia	0,9	0,9	0,8	0,7	0,8	0,8	0,8	0,8	0,8	0,8
Italy	18,4	18	17,1	17	16,3	16	17,3	17,6	15,6	15,6
Latvia	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,2	0,2	0,2
Lithuania	-	0,3	0,4	-	0,5	0,5	0,5	0,7	0,9	1,1
Hungary	4,1	2,7	2,8	2,9	3,1	3,1	3,2	3,4	3,7	6,7
Netherlands	6,6	5,9	5,9	5,6	5,2	4,9	4,6	5,5	5,4	5,1
Austria	3,9	3,9	4,1	4,6	4,9	5	5,2	5,3	5,6	6,6
Poland	15,9	14,7	14,4	13,5	13,6	14	15,4	16,6	17,3	18,2

Table 4. Annual employment statistics for electric lighting industry for the EU and some of the Member States (in thousands). Source: Eurostat (2021a).

Portugal	2,4	2,4	2,3	2	-	-	2,1	2,1	2,1	2,1
Romania	3,8	2,8	2,4	2,1	2,3	2,4	2,3	2,4	2,6	3,1
Slovenia	1,3	1,3	1,4	1,5	1,5	1,9	1,9	2,1	2,3	2,7
Slovakia	5,3	5,6	5,8	5,8	6,2	7	7,5	8,3	8,6	8,9
Finland	1,5	1,4	1,4	1,4	1,4	1,5	1,5	1,4	1,5	1,6
Sweden	-	-	-	3	2,9	2,8	2,7	2,7	2,7	2,8
Norway	0,8	0,7	0,7	0,7	0,7	0,7	0,7	0,7	0,6	0,6
Switzerland	2,5	2,9	2,4	2,4	2,2	2,4	1,7	1,5	1,2	1,7
United Kingdom	-	14,4	-	-	14,2	13,4	-	13,4	16,4	15,4

Table 4 (continued). Annual employment statistics for electric lighting industry for the EU and some of the Member States (in thousands). Source: Eurostat (2021a).

better, being more aesthetically pleasing and easier to recycle (Jung, 2009; Howarth & Rosenow, 2014; Mills & Schleich, 2014). As one ophthalmologist put it, CFLs and LEDs were “a shame for the comfort and health of our eyes”, whereas the “good old incandescent bulbs” were not (Leid, 2016). The ILB was called by one frustrated designer a producer of more “natural” light (Haans & Olijve, 2012). In a consumers survey in Denmark respondents said they associated incandescent light “with ‘warm’ and ‘comfortable’ light, whereas light from CFLs and LEDs […] with ‘cold’ and ‘unpleasant’ light” (Jensen, 2014). These aesthetical preferences may be what Sarpong and colleagues call passionate nostalgia for “old-fashioned industries that focus on quality rather than quantity and heritage rather than novelty” (Sarpong et al., 2016). The supporters of the ILB were not convinced by the argument that a more energy-efficient light bulb is a better light bulb, and sought ways to preserve the ILB’s place in the culture, or at least in their homes.

These dissenting voices did not manage to alter the trajectory of the ILB. Instead, there are indications that by 2015 the previously dissenting groups have accepted the LED as the replacement for and improvement of the ILB. “They [LEDs] emit almost no UV, far less even than an incandescent bulb, which is a good point”, writes Lupus UK (2015), one of the original protesting patient associations. By 2018, European sales of LEDs dwarfed all other lamps (Zissis et al., 2021). Literature (K. R. Cowan & Daim, 2011; Leelakulthanit, 2014) shows that the promise of energy savings, better availability of LEDs and the belief that buying LEDs is more environmentally friendly were the leading factors of final acceptance of LEDs, at least outside of Europe. European energy users now preferred LEDs to CFLs because LED lighting looked more “natural” (Dangol et al., 2015). It would appear that the substitute bulbs have finally met the agendas of both producers and users: the latest LEDs looked and functioned like the “good old” ILBs, but secured a higher profit margin for the industry and were much more energy efficient. In fact, the industry had spent considerable effort to make the LED produce the kind of light similar to the ILB. Franceschini and Alkemade (2016) show that millions of dollars were spent over decades since the 1970s before bright white LED light was developed around the year 2000 and the industry was offering filament-imitating decorative bulbs which specifically copied and exaggerated the vintage look of the ILB.

In the end, the ILB configuration of meanings, competences and materials did not complete its unravelling, and thus cannot be said to be phase-out, because production and application continued in niches even by 2020, as new companies produced and/or re-sold the supposedly outdated and forgotten ILBs. ILBs did not disappear completely and are still used in, at least, niche industrial applications and horticulture. These fields of application had found irreplaceable certain key technical characteristics of the ILB (Signify, n.d.; Kierkegaard, 2014; VITO, 2015), e.g. in some industrial applications the LED electronics would fry. Thus, by the end of the observed period we see co-existence of the mainstream LED and a downscaled (or contracted) ILB configuration.

Long-term effects of the ban

By 2020 the exempted ILBs could be bought[44] after some googling as decorative lamps and so called ‘rough-service lamps’. However, on a wider scale a confident decline trend of the ILB is evidenced by analyses such as one by the EU’s Joint Research Centre (Zissis et al., 2021). Ten years after the beginning of the phasing-out, the outcomes were praised. For example, European consumer organisations BEUC and ANEC estimated that due to the ban, the average European household saved during these years up to 1,330 euros (Quack, 2019). And for Irish low-income households the economic effects were positive (EP, 2018). The media coverage, albeit very scarce, reflected a dismissal of the ILB (e.g. “How to Retrofit…,” 2013; “Scrapping EU Efficiency…,” 2017; “8 Things…,” 2018).

Deters (2018) writes that the phasing-out “chiefly affected lamp manufacturers and consumers” (see also Mills and Schleich (2010)), but I argue there was another crucially affected stakeholder group: the ILB labour force, which are the actors representing *competences*. The shrinking ILB market meant layoffs. In 2009, prior to the sales ban, the EC estimated that around two to three thousand jobs in the lighting industry would be lost in Europe due to the phase-out (EC, 2009b). The real number turned to be two or three times larger. Eurofound’s European Monitoring Centre on Change, which collects data on EU job dynamics per company, shows that around 6,000 lighting manufacturing jobs in the EU were cut by Philips and Osram together between years 2005 and 2019 (EMCC, n.d.) (Figure 11). Other accounts mention international figures of around 14,000 cut jobs: 6,700 in Philips (Noordhuis, 2012) and 7,300 in Osram (Weiss, 2012).

Of course, not all job cuts may be attributed to the phasing-out exclusively. Two other factors were key (Bas Klawer, personal communication, October 6, 2020): the 2008 financial crisis and an older trend of shifting labour from Europe to Asia. There are some indications, however, that phasing-out was a key one. First, at the time when European labour markets showed signs of stabilisation after the financial crisis (Eurostat, 2021b), in the lighting industry job shifts and cuts continued in 2010 (shifts from southern and eastern Europe to northern and central Europe, Table 4) and 2011

44 https://www.gloeilicht.nl/lampen/gloeilamp-standaard-100w-e27-230v-a55 [Accessed on April 10, 2021]

(cuts in Belgium, Spain, France, Italy and Poland, Table 4). Second, ILB production did move to Asia as expected by the pre-existing trend, but it did so specifically to regions[45] where sale of ILB was still allowed and popular, such as India: "India is one of the biggest markets […] where people cannot afford other lighting products yet" (Bas Klawer, personal communication, October 6, 2020). The latter indicates that the ILB ban in Europe was an important consideration for shifting labour. Additional research is needed to attribute the causes of job cuts empirically, but the job shifts and cuts by themselves already indicate disruption to the lives of the workers.

In some countries the labour force was successful in cushioning the layoffs. For example, according to Dutch labour unions, Signify (formerly Philips Lighting) workers managed to achieve a good deal: most either found another position within the company, retrained or left for other companies, while a quarter retired early (Hans Wijers[46], personal communication, October 9, 2020)[47]. Some ILB competences travelled, as workers switched to other positions, and some competences disrupted their continuous reproduction as workers retired. Staff retraining programmes also took place in other regions of Europe in preparation for layoffs (Bas Klawer, personal communication, October 6, 2020), although there is not enough data to draw stronger conclusions on the situation in other European countries.

By 2020, the lighting industry's turnover was, overall, rising (Eurostat, 2021a). The industry was one of the architects of the sales ban (supported by the EC who was aiming for climate targets) and it successfully and to its benefit switched to selling a substitute technology that was easier and cheaper to produce, and that had a higher price tag. To industry, the LED represented the progress that the lighting industry was striving for, and the ILB represented old technology and old business models (Harry Verhaar, personal communication, October 2, 2020). According to Signify, LED

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[45] For instance, country statistics (Table 4) show inter-EU movement of labour from e.g. the Netherlands, France, Italy and Spain to e.g. Austria, Czechia and Slovakia. According to Hans Wijers of FNV, "every [lighting] company looks to the countries where they can produce at lower costs. Sometimes it's a few years in India, then they go to China, then they go to Vietnam, Philippines. They transfer all the time their production locations. We've seen this also in Eastern Europe with Poland, then Hungary, then Romania. Every time after a few years the production is relocated to another country because the costs were lower" (Hans Wijers, personal communication, October 9, 2020).

[46] Mr. Wijers worked as Union Secretary at the Dutch trade union association FNV Metal at the time of personal communication.

[47] In the Netherlands, home country of Philips, labour unions first held internal discussions to decide the negotiation strategy with Philips (Hans Wijers, personal communication, October 9, 2020). The unions believed they had leverage over Philips as they could threaten with street protests which could damage Philips' reputation (Hans Wijers, personal communication, October 9, 2020). They then concluded that the phase-out and the accompanying layoffs in the Netherlands could not be stopped "because companies always seek the lowest-cost countries and they put out their production wherever it goes around the world" (Hans Wijers, personal communication, October 9, 2020). Instead, it was decided to use the leverage in negotiating better retirement and retraining plans (Hans Wijers, personal communication, October 9, 2020).

is the next logical step in lighting technology (Bas Klawer, personal communication, October 2, 2020), thus implying there is no room for political choice.

In sum, the unravelling of the ILB configuration occurred as a transformation in the ILB-related meanings and, subsequently, the competences and materials, and, at least by 2020, as downscaling of the ILB configuration. In 2013, the ILB was not the same configuration as pre-2009. It was now a configuration of reinforced, "rough service" materials, that for some evoked the feelings of nostalgia ("good old incandescent bulbs" (Leid, 2016)), and that required certain skill to find where to purchase. Strict national regulations, but also requirements of energy inefficiency and fashion are preventing the ILB to scale up again. In Table 5 I interpret some of the phase-out dynamics as attributions to three types of ILB stakeholders: the EC, the industry, the end users and the industry employees. The industry and policy-makers triggered change in the meanings, as the "good old light bulb" became contested by the industry and the policy-makers. Table 5 shows that the industry and the EC policy-makers weakened the elements of the configuration, the end users transformed them, while industry factory floor workers were relatively passive. Combined with the fact that European consumers, supposedly, saved on average around 1,330 euros over the years due to the phase-out (Quack, 2019), it would seem that the lighting industry employees bore a high cost for the phase-out as they had to go through retraining and job-hunting or move to another city or country. Additional ethnographic research could open up their experiences.

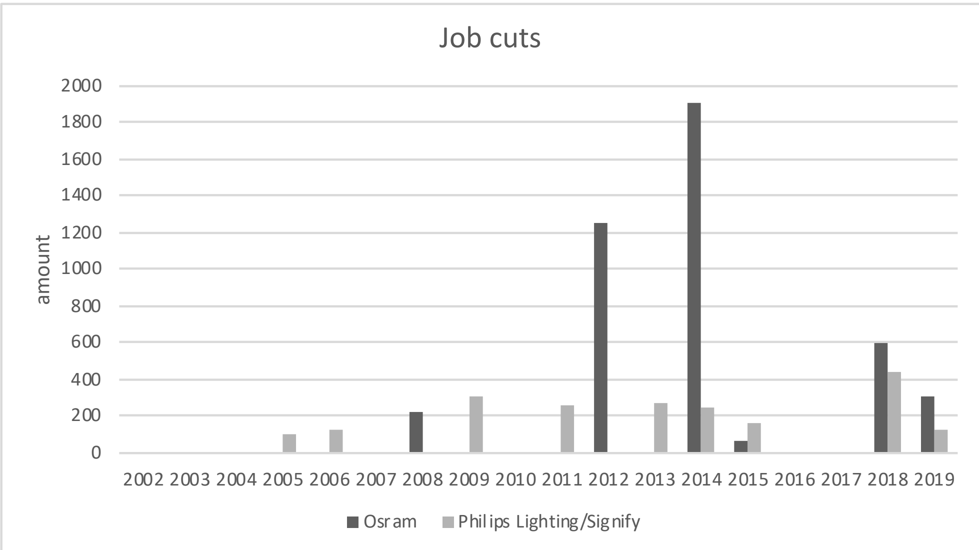


Figure 11. Job cuts dynamics in Europe at Osram and Philips Lighting / Signify since recording started by Eurofound's European Monitoring Centre on Change in 2002. Data source: EMCC (n.d.). *For a coloured version of this image please refer to the digital version of this paper.*

Stakeholders	Phase-out-relevant roles in configuration dynamics
European Commission	*Disrupted continuous reproduction* of meanings by promoting contestation of dominant frame; and of materials by supporting physical removal from stores (the ban)
Industry leadership	*Disrupted continuous reproduction* of meanings by promoting contestation of dominant frame; of competences by implementing layoffs as most EU-based ILB production closed; and of materials by supporting physical removal from stores (the ban)
End users	*Transformed* meanings by adding new ones ('rough service lamp', 'good old incandescent bulb') and removing destabilising ones ('energy inefficient lamp'); and *transformed* competences by adding new competences of finding the ILBs to buy
Industry factory floor workers	*Disrupted continuous reproduction* of competences as workers retired; and as workers switched to other positions competences *travelled*

Table 5. Roles of ILB stakeholders in the European ILB phase-out.

5.4. Discussion

On the surface, the ILB seems to have disappeared from the mainstream because it was outcompeted by LED. This is, at best, an incomplete evaluation since a simply 'better' technology would probably not need policy intervention on the same scale as the ILB did (see also Kierkegaard (2014)). Other processes were at play. In this paper I revisited the case of a fast phasing-out of a previously ubiquitous technology, the incandescent light bulb, to better understand what processes were involved in its fast phasing-out. In contrast to previous literature on the ILB phasing-out, I focused on the period after the sales ban had entered into force. I aimed to trace empirically the developments that constituted the downward trajectory of the phasing out technology, i.e. to open up the, often disruptive, dynamics of phase-outs. I traced materials, meaning and forms of competences, and the roles of key stakeholders in their dynamics. A second aim was conceptual, i.e. I aimed to formulate abstractions about technology phase-outs that rise above the details of my case.

The findings indicate that there seems to be no need for complete break-up of links of the configuration for a fast phasing-out. In other words, scaling down a configuration can be effective without eradication of materials, competences or meanings. I found that between 2000 and 2020 due to the alignment of stakeholder interests there were major destabilisations in all three elements. Key in these destabilisations was the intentional push for a destabilising meaning (energy inefficiency), resonant with powerful larger discourse (climate change), by a group of stakeholders. However, despite the overall downward trajectory, i.e. decrease in the intensity of interactions between producers and users (shrinking ILB sales)[48], these destabilisations did not lead to phase-out of the technology by the end of the observed period. In this sense, one cannot speak of this case as a case of phase-out of the incandescent light bulb. Instead, the three elements transformed, acquiring and dropping certain meanings, materials and competences to stabilize the configuration. Key in this downscaling, phas*ing* out of the configuration was the attachment of reinforcing meanings to the ILB by a group of stakeholders, the end users (nostalgic lamp, rough-service lamp).

Secondly, the contestation of CFL and support for LED shows that continuity of elements of the configuration matters and, in fact, can contribute to the speed of the phasing-out. In this case, it is the continuity of competences and materials: CFLs required changes in use practices, while LEDs did not, and LED was made to look like ILB in shape and colour output. The success of LEDs may have been in part based on the borrowing of these valued aspects of the ILB and integrating them. The phenomena of product and process imitation and hybridisation have been known since Joseph Schumpeter and are something that new market entrants do to catch up with successful actors (e.g. Pistorius & Utterback, 1997; Fagerberg, 2009). Here, imitation and hybridisation can also be observed in technology phase-out where they serve a stabilising function, ensuring closure of controversy and the establishment of a status quo of the substitute technology.

Third, in contrast to prior literature stressing that the ILB phasing-out affected the user and the manufacturer the most, I found that the processes of phasing-out were at least as disruptive for the workers of the lighting industry who experienced layoffs, re-skilling and jobs switches. Their role in phasing-out was more passive compared to that of the end users, who transformed competences and meanings, associated with the ILB. Although in the Netherlands, for example, labour unions and the industry seemed to have cushioned the hit, the numbers of job cuts were still two to three times larger than anticipated by the EC. Here future ethnographic studies of former ILB employees from across Europe will be useful to open up their experiences of the ILB phasing-out. This case thus is an example of the limits of *ex ante* assessments of societal costs of phasing-out. Making such technology-related assessments more inclusive is part of the larger discussion in literature on Responsible Research and

48 A similar mechanism was described by Shove and colleagues as downscaling of the reproduction of the configuration (Shove et al., 2012).

Innovation and Technology Assessment (e.g. Delvenne, 2017; Van Lente et al., 2017; Gerber et al., 2020).

Finally, three basic pathways could, in principle, be possible for the light bulb trajectory moving forward: re-emergence, further downscaling to complete abandonment, and the continuation of the current niche status. The phasing-out of the ILB is, in principle, reversible because all elements remain and are readily available, albeit as part of a downscaled configuration, i.e. with decreased sales and smaller-scale production. If a powerful new element is (re-)connected to it (an appealing new meaning, outperforming incandescence-based material or dominant competence), or if the LED is in turn phased out without a substitute, the ILB might re-emerge. In fact, the current niche status of the ILB might be an intermediary stage before re-emergence, as in the case of cloud seeding (Koretsky & Van Lente, 2020). Alternatively, the ILB might keep shrinking until it is seen only in museum exhibitions, or sustain the current status quo if it is still used by enthusiasts or in specialised applications. Further research may explore conditions for these and, possibly, more pathways.

5.4.1. **Limitations**

Apart from the usual generality limits of single case studies, this work is limited by the 'focused narrative approach'. That is, I presented the case of the light bulb as a rather clean story of a downward trajectory. In reality the processes I described and omitted are much more complex and implicated. The limitation is, however, a feature of any stylised history and, since I followed systematically the analytical chronology approach, I have captured key developments of the light bulb phasing-out.

Dedicated statistical and/or national case studies on the link between the ILB ban and the labour force changes are needed to confirm or disprove the present findings. Larger studies with access to sites of light bulb use and work practices could also be productive. It might also be interesting to conduct a meta-theoretical comparison of the ILB phasing-out using other theoretical perspectives and approaches to learn what they can offer for the study of phase-outs.

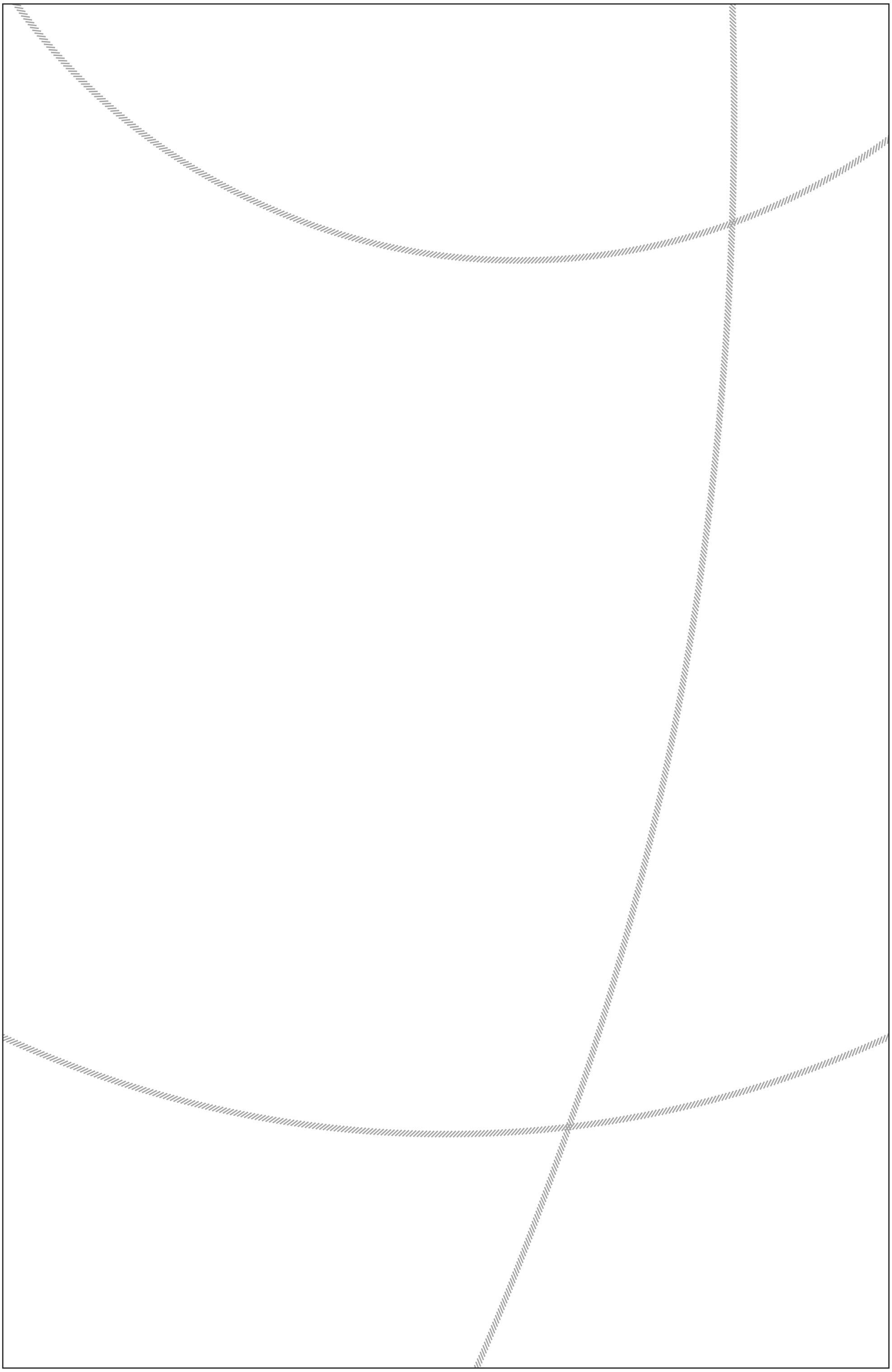
I acknowledge the limitations of the analytical framework adopted in this paper, and it should be treated as an exploration triggered by an interest in phase-outs, rather than a fine-tuned approach. Still, revisiting the story of the light bulbs' phasing out from the perspective of technology-in-practice is fruitful in tracing empirically the developments of the downward trajectory of the phasing-out technology from the perspective of the dynamics of heterogeneous interconnected elements (Magaudda & Minniti, 2019).

5.5. Conclusions

In this paper I asked what processes were involved in the phasing-out of the incandescent light bulb after the phase-out regulation entered into force. The aims were empirical and theoretical. Empirically, I revealed how the disruptive effects of the ILB phasing-out played out for the industry workers. Phasing-out caused layoffs, re-skilling and jobs switches to thousands, making the ILB ban fast but hardly exemplary. Looking at the example of the Netherlands, the negotiation of labour unions and the apparent involvement of the industry in the fates of the workers have made possible to cushion the worst effects of the ban and prevent large-scale opposition.

In addition, three theoretical conclusions can be made for the studies of phasing-out. First, the case of the light bulb confirms the existence of winners and losers in phasing-out, which implies similarities of phase-outs as phenomena to the (inverse) processes of innovation. Second, for a fast and effective phasing-out there seems to be no need to aim for eradication of the product and allowing exemptions is useful. Continuity of attractive features integrated in the substitute technology can contribute to a higher speed of the phasing-out. Third, phase-out is, in principle, reversible because of the non-eradication of the phased-out technology. A weakening of the substitute technology, an appealing new framing, a fitting competence, a new material could serve as catalysts for a revival.

The ILB phasing-out may be a case of a fast downscaling, however, its implications for energy transitions seem both hopeful and cautionary. They seem hopeful in that it appears to be possible to scale down a prominent and widely used technology, or at least one type of product, very quickly via downscaling it and nurturing a competing technology which would integrate some of the desirable characteristics that the old technology offered. And they seem cautionary because they show the uneven impacts of fast phasing-out.



Intermission II: gains thus far

I intermit the empirically heavy narrative for a brief stocktaking. The above case obviously differs from the cloud seeing one with regards to the context: different countries, different histories, different case temporality. By iteratively studying the research questions of the thesis in the chapters, I aim to build up the observations towards more generalised characterisation and understanding of technological decline, and towards a framework that could be useful for future cases in other contexts (insofar as it is possible with a small selection of cases, as discussed in Chapter 3).

In the chapter above I use the term 'phase-out' as a proxy for decline. Although the term 'phase-out' implies purposefulness, not all of the processes that mattered in the light bulb's unravelling were purposeful: for instance, the 2008 financial crisis or the reaction of the market to the sales ban. I will discuss the seeming dichotomy between purposeful and emerging processes involved in decline in Chapter 8.

To approach answering my research questions, from what has been discussed in the book so far, I formulate the following theoretical insights:

- there seems to be no need for complete unravelling of the strands for a fast unravelling of the configuration. In fact, it seems possible for a configuration such as the light bulb to remain in a state of decreased, niche performance for a long time;
- in Intermission I, I noted that some forms of competences seem able to travel to other configurations. I now find that materials can travel between configurations as well, leading to e.g. imitation, hybridisation and, in the end, continuity of style. In some cases such travelling entities of a strand cannot be shared by two configurations (e.g. funding or workforce). In this case, the variety of entities within a strand reduces in the older configuration, which then can contribute to lower resilience of the configuration and its unravelling;
- following the unravelling of the configuration, three basic pathways seem possible: contraction, seen at some point in both cases; re-emergence (a sort of 're-ravelling'), seen by the end of the observation of the cloud seeding case; and continuation of a niche status, seen by the end of the observation of the light bulb case.

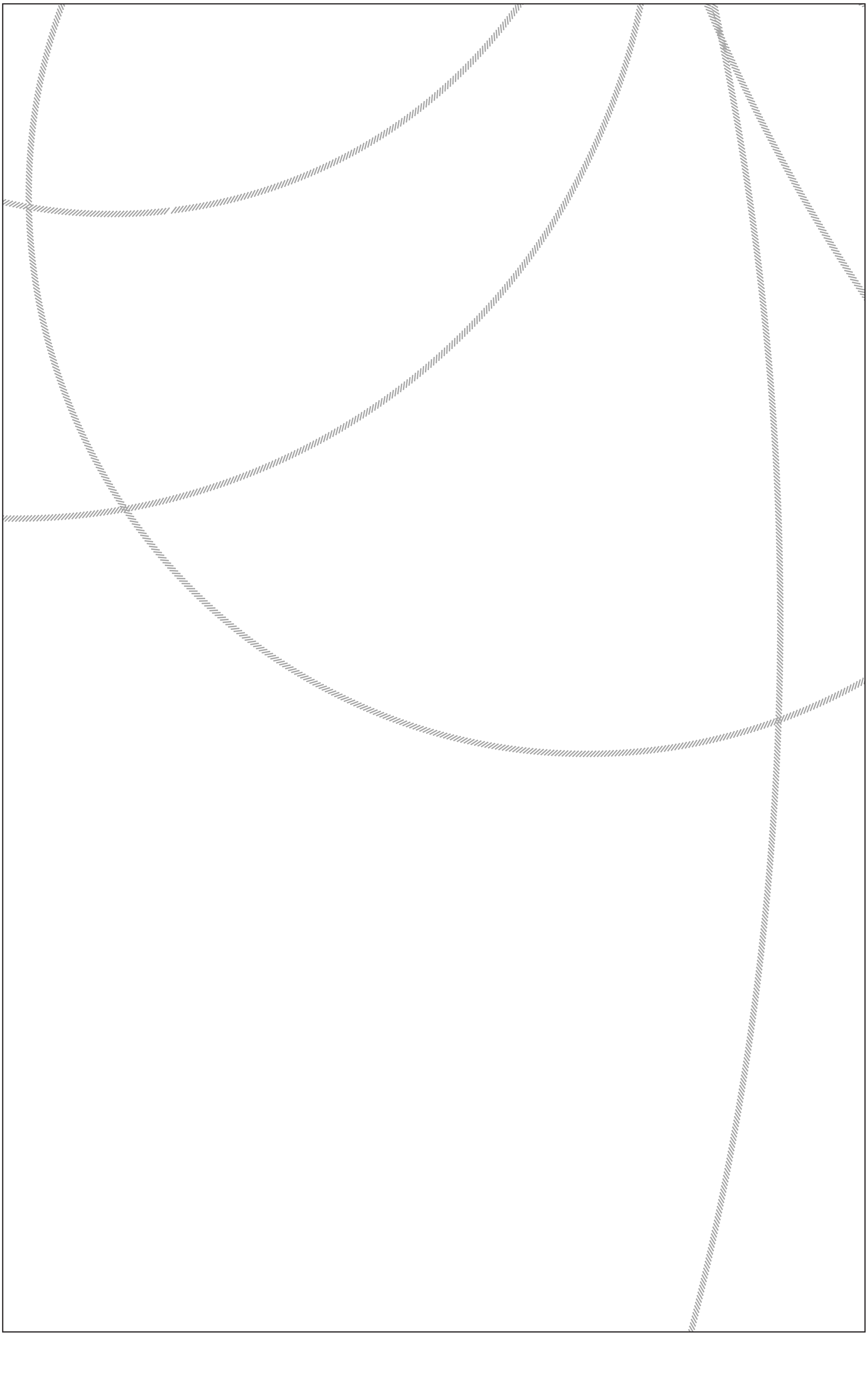
The unravelling of the light bulb is different from unravelling of cloud seeding: one contracted to a niche and survives there, the other is re-emerging. It appears that differences between technologies may also matter. After all, cloud seeding is very different than the light bulb: it is not a singular and compact artefact, it requires geographically and temporally dispersed expertise of multiple people to use, its efficacy and application contexts are more contested, etc. Perhaps, the complexity of technology can be characterised as variety of entities within the strands of the configuration. Thus, considering the finding above about the role of variety in unravelling (the lower the variety of entities in a strand, the lower the resilience of the configuration, the higher the chance for unravelling), less complex technologies (i.e. less resilient configurations) may be more susceptible to unravelling. I will come back to the role of the differences between technologies for their unravelling in Chapter 7.

Lastly, politically, the following proved useful for unravelling in the light bulb case (I will discuss these more in Chapter 8):

- a coalition of government(s), industry and (environmental) non-governmental organisations in favour of decline;
- strong labour unions that can cushion the damage of technology's decline for workers, but not too strong to stop or reverse the unravelling;
- support for and/or promotion of alternative existing or nascent desirable (e.g. more sustainable, ethically acceptable or less harmful to health) solutions or technologies that fulfil the same need as the unravelling technology. This could be done via offering subsidies, tax incentives, direct funding of R&D and (re)training, public relations efforts, and compensations to actors who stand to lose from technology's decline;
- ignoring or dismissing public concerns (the so called "decide-announce-defend" (DAD) policy[49]) also must be mentioned because of its efficacy in situations where public resistance is not expected, despite it going against the rationale of transparency and accountability of governance;
- trade and international agreements can be used to leverage other countries' decline of the given technology.

I now turn to my last case and this time invite the reader to the world of computers. Once again I will observe the strands of the configuration and explore the links between changes in one or more strands, as well as the changing resilience of the configuration to withstand shocks like competitors and regulation. This case is also interesting because it covers the computer industry in the defunct Soviet Union, of which relatively little is known outside of Russian and Soviet studies.

49 https://participedia.net/method/4831 [Accessed on November 12, 2021]



Chapter 6. **Decline and abandonment: the *Ural* computer**[50]

6.1. **Introduction**

Policy interest and demand for insight into decline of technology is on the rise. In 2020 the UK government requested public advice on phasing out petrol, diesel and hybrid cars (UK Department of Transport, 2020), and, in 2019, the Scottish government invited public views on the impacts of phasing out energy drinks for the consumption among young people (Scottish Government, 2019). Other plans and calls for deliberate decline, or phase-out, of specific products or technologies appeared for coal energy (PPCA, 2021), nuclear plants (e.g. Staudenmaier, 2017), and lethal autonomous weapon systems (Gayle, 2019). Observing a bias towards novelty, i.e. a focus on how technology emerges (Lindqvist, 1994; Edgerton, 2007), literature on technology and technologic change saw increased calls for phase-outs and their study (Shove, 2012; Levain et al., 2015; Goulet & Vinck, 2017; David, 2017; Rogge & Johnstone, 2017; Russell & Vinsel, 2018; Markard, 2018; Geels et al., 2019; Hickel & Kallis, 2020; Kanger et al., 2020; Turnheim & Sovacool, 2020; Rosenbloom & Rinscheid, 2020).

Technology decline can be defined as the scaling-down of production and/or use of particular equipment, processes and associated practices in a given geographical context to the point of their (intentional or unintentional) abandonment (Turnheim & Sovacool, 2020; cf. Kanger, 2021). Literature on decline is growing. We identify two knowledge gaps in it: a lack of empirical focus on the socio-technical processes after the stakeholders have committed to phase out a given technology, and a resulting under-conceptualisation of the involved processes and of the roles of stakeholders beyond governance actors. Opening up these processes and roles is important to advance the knowledge about decline and how to navigate it (Kivimaa et al., 2021), finding ways to speed it up (Sovacool, 2016) and ensure justice (e.g. Jasanoff, 2018), all pressing topics in sustainability transitions.

In the present paper we, first, aim to contribute to this growing literature by including an analysis of the socio-technical processes after a phase-out policy decision enters into force. Thus, we aim to go beyond a focus on the actions of governance actors (government, firms) prior to decline, and rather aim to trace empirically the so-

[50] This chapter was co-written with Ragna Zeiss and Harro van Lente, hence the use of pronouns "we" and "our" in the chapter and some repetitions with the preceding chapters in this book, and submitted to *Science, Technology, & Human Values* in 2021. Minor adjustments were made in this chapter to format figure and table references and footnotes for consistency.

cio-technical developments in the history of the technology. We ask: what socio-technical processes were involved in the decline of the *Ural* computer?

Our case of declined technology is a once prominent, but now largely disappeared Soviet/Russian computer *Ural*. We chose to study this particular case taking a post-development stance, which critiques the hierarchy of developed and developing countries (Sachs, 1990; Escobar, 2015), and due to a relative shortage of studies of that region. Thus, our aim with the present study is to expand the geography of cases in studies of technology and technical change and challenge the status quo of what Gibson-Graham (2008) calls "capitalocentrism", i.e. studies of cases in neoliberal economies. Gibson-Graham argues for economic diversity in case studies in order to re-legitimise contemporary non-capitalist modes of life. Although our case is obviously not contemporary, we, similarly, aim to help re-legitimise—not necessarily the Soviet system of governance—but the experiences of people who lived, worked, exchanged knowledge, dreamt, and produced physical and cultural legacies within an alternative politico-economic system[51].

There are certain difficulties with gaining insight from our particular case, the defunct Soviet Union, because it differs so much from any modern context. For this reason, our second research question is: which contextual factors related to the decline of Ural, if identifiable, were idiosyncratic to the Soviet Union? Thus, instead of *a priori* assuming a limited applicability of findings from a Soviet case, in this paper we pose it as an empirical question.

The paper continues in the following way. We discuss the methodology in the next section. In section 6.3 we document and analyse our case. We then offer points of discussion and concluding remarks on both the theoretical and empirical gains of the paper in section 4.

6.2. **Methodology**

In this paper, we are looking back to a past case of a computer series *Ural,* developed and produced in the former Union of Soviet Socialistic Republics (USSR) between 1955 and 1975[52]. Ural was an emblematic computer in the history of Soviet computer technology being the first of its class of Soviet computers to be revealed to the world at the 1955 Darmstadt Conference on Electronic Digital Computers and Information

51 This seems badly needed because a cursory look at just the titles of some of the studies on that region tend to be as depressing as they are dramatic: "Fallen Behind: Science, Technology, and Soviet Statism", "The Soviet collapse: Contradictions and neo-modernisation", "Armageddon averted: the Soviet collapse, 1970-2000", "A failed empire: the Soviet Union in the Cold War from Stalin to Gorbachev", etc. Such framings may be fostering avoidance of more studies of this region.

52 For brevity, we do not add "former" to "USSR" or "Soviet Union" in the rest of the text.

Processing, and being the oldest Soviet computer to be widely used in the country. Its designers are considered the first in the USSR to develop the idea of a cheap computer and start its production for the mass (industrial) user. This was unprecedented in Soviet computer industry, which prioritised internationally prestigious research-intensive projects, not consumer goods. Today the entire product series of Ural is abandoned, it is not used anymore and only found in museums.

Much has been written on the history of Soviet computing, particularly in the works of Tatarchenko (2017, 2019), Gerovitch (2004) and Peters (2016). The history of the Ural computer specifically, however, has not been the object of much analysis in either English or Russian-language literature, apart from the recollections and compilations by Malinovsky (1995), Smirnov (2005, 2014) and Smolevitskaya (2019). Thus, it remains largely an uncharted territory.

We use some quantitative data based on primary sources, but most of the collected data is qualitative. We have used several types of sources: Russian state archives, archives of the Moscow Polytechnic Museum (the largest Russian technology museum), CIA archives[53], academic literature in English and Russian language, newspapers *Pravda* and *Izvestia* (two largest newspapers in the USSR) and two popular science magazines *Znanie – Sila* ("Knowledge is power") and *Tehnika – molodeži* ("Technology for the youth")[54]. A useful source of information for us was the Virtual Computer Museum website (Proydakov, n.d.), which contains original articles and recollections on computer history. A key background source on the Soviet economy was the comprehensive review of secondary sources by Hanson (2003).

We searched[55] books, papers, articles and other documents on the Ural computer. We limited our search to 1954-1995: 1954 is the year when the Ural was invented, and 1995 is roughly the time of the final decline of the (post-)Soviet computer industry.

Data collection was conducted in 2019. We compared primary sources with secondary sources to cross-check information. Only some data could be triangulated. The data analysis and interpretation were done by the first author. Due to lack of publicly accessible data, we only managed to collect statistical data on the number of units produced and annual production value of computers.

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[53] As with other sources, we were reflective of possible bias in the CIA accounts of the Soviet computer industry due to possible lack of accurate data and/or Cold War-era biases. We use these sources in corroboration with each other or, where indicated, for illustrative purposes.

[54] Transliteration of most words and names from the Cyrillic script was done by the authors using the international ISO 9 standard. For more well-known names (e.g. *Brezhnev*) and words (e.g. *perestroika*) we preserved popularised transliterations for ease of reading.

[55] Search query in English and Russian, where appropriate: Ural AND comput*, electron*, cyber*, calculat*, radio, precision*, mathemat*.

The representations of materials, meanings and forms of competences are the central organising device in this paper. When tracing materials we followed technological artefacts, their production facilities and infrastructures. When tracing meanings we looked at situated cognitive activities, discourses and laws. When tracing forms of competences we looked at both the know-how and codified knowledge. We manually coded the collected material, accounting for the framings of the searched terms and the context of each source.

After data collection and coding, we conducted content analysis, searching for emergent themes, and reconstructed the timeline of the Ural using the analytical chronology approach by Pettigrew (1990, 1997). With analytical chronology, the researcher is not aiming to provide an objective history, but rather a selective, focused and explicitly interpretive historical narrative, one based on the sequence, timing and conjunctures of events (Verbong et al., 2008; Geels, 2011).

We *ex post* analytically split the history of Ural into four stages, which structure the case analysis in the next section: emergence, i.e. a period of growth of the Ural's production, crucial to understand the later phase-out; era of ferment, i.e. a period of emerging political and economic uncertainties; phase-out itself; and legacy left by the phase-out of Ural. Since our aims are to open up the case of the Ural and to identify Soviet contextual factors, we will be presenting the case from a position of emergence to phase-out.

6.3. The rise and fall of the Ural computer

6.3.1. Linking materials, meanings and competences (1955-1964)

Despite a popular misconception, viable pre-IBM computers were produced in the Soviet Union. "[A] scrounger's triumph over scarcity during a difficult economic recovery [from the war]" (Tatarchenko, 2017, p. 715), two models were presented in 1955 at an international conference in Darmstadt, West Germany. Those were the super-computer *BÈSM* and the middle grade Ural (Smolevitskaya, 2019). Early computers such as the BÈSM, M-1, M-20 and *Strela* were fit specifically for scientific calculations[56], and not for business purposes like process automation of repeatable, day-to-day tasks (Malinovsky, 2010). Cheaper and simpler middle grade computers

56 Early Soviet computers were mainly used in key nuclear weapons research, missile, missile defence and space projects, and, whenever possible, in scientific calculations in nuclear energy and chemical industry and theoretical physics research (Gerovitch, 2004). The press embraced mass computerisation and computers as "machines of communism" (Gerovitch, 2004; Peters, 2016).

for non-scientific purposes such as the Ural started to appear by the end of the 1950s and during the 1960s in aircraft and ship construction, medicine, meteorology and banking (Revič & Šilov, 2017; Garynov, 2010; Svet, 2017) (Figure 12, Figure 13).

Ural (Figure 14) became one of the "market"[57] leaders between 1955 and 1964 as, on average, every second or third middle grade computer in the country was an Ural, alongside other models such as the *Minsk, Setun, Kiev, Dnepr, Razdan*, and a dozen more. According to Smolevitskaya (2019), several Urals-1 were sold beyond the socialist bloc to Turkey, Egypt, Norway and the UK. Bashir Iskandarovich Rameev (or *Rameyev)* and his team built a prototype Ural-1 in 1955 with a small group of electrical engineers and mathematicians in Penza, a city in Russian heartland. Rameev worked with a small group of highly trained electrical engineers and mathematicians, whom he frequently sent for knowledge exchange to other computer construction bureaus. Rameev envisioned that the next generation of Urals, Urals-11, 12, 13, 14 and 15, would be the core of a standardised, compatible and mass-market series of middle grade computers, sufficiently obsolescence-proof and of the same quality as "the most common foreign machines" (Rameev, 1963).

The formation of the Ural configuration in the 1950s and 1960s can be visualised in Figure 15 where much work on linking new materials, competences and meanings is done by the Penza team.

[57] Even though there was no free market, products were still bought and sold in the USSR. The purchasing process of computers (as well as of most other goods) consisted of the buying enterprise (research institute, state agency, etc.) filing an application to the State Planning Commission (Gosplan). Gosplan would then negotiate with the enterprises how much of certain products they could produce to contribute to the plan. These amounts were in turn linked to estimates submitted by the enterprises themselves, and were often fraudulently inflated by them (Hanson, 2003; Peters, 2016). At the end of the year, the central Gosplan collected all such requests for all kinds of products, and matched them with the planned production for next year within the limits of the five-year plan (*pâtiletka*). The product would then be sold to the applicant for a price set by the Gosplan. This system was supposed to operationalise Marx's "socially necessary labour time" (Marx, 1992) to represent price (or rather exchange value). The orders took months and years to fulfil (Rameev, 1979; Hanson, 2003). Malinovsky attributes this quote to Isaac Bruk, one of the prominent computer designers: "Our overall government system, which the party created, could react rapidly to the party, but the party lacked the ability to react to the government" (Malinovsky, 2010).

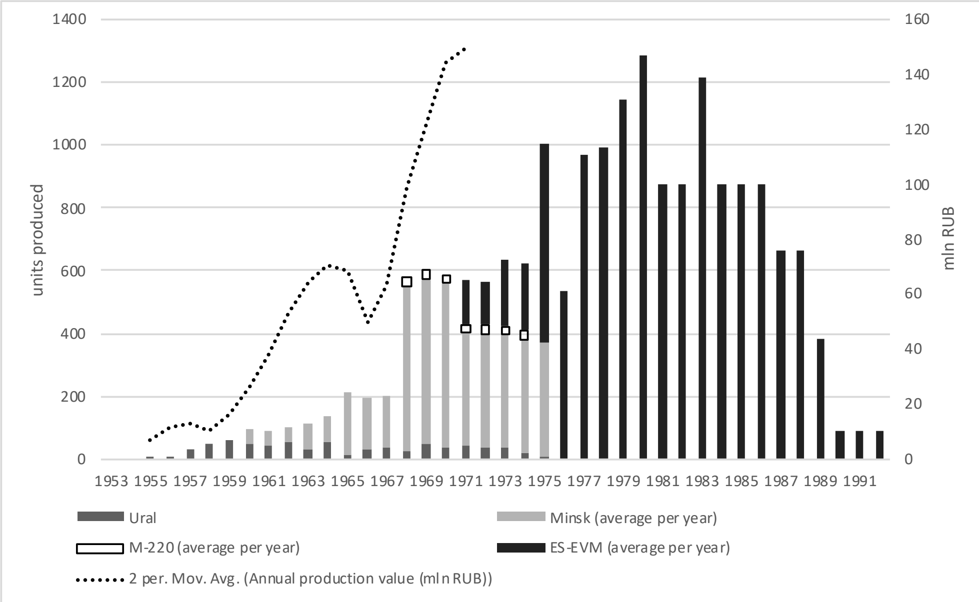


Figure 12. Production of prominent middle grade computers in the USSR (annual production data not available beyond 1970). Sources: own calculation based on Smirnov (2005, 2014)*, Badrutdinova et al.* (2014)*, Ershov & Shura-Bura* (1976)*, Fajnberg (2019) and CIA* (1971)*. For a coloured version of this image please refer to the digital version of this paper.*

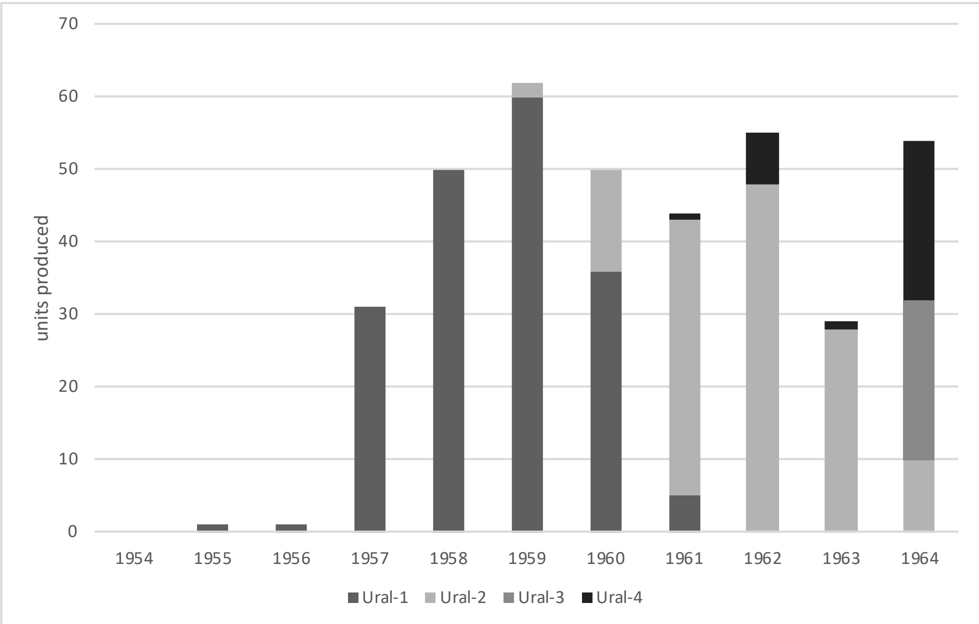


Figure 13. Ural *series production between 1954 and 1964. Based on data from Smirnov (2014). For a coloured version of this image please refer to the digital version of this paper.*

Figure 14. Ural-14. Source: archives of the Moscow Polytechnic Museum. Reprinted with permission.

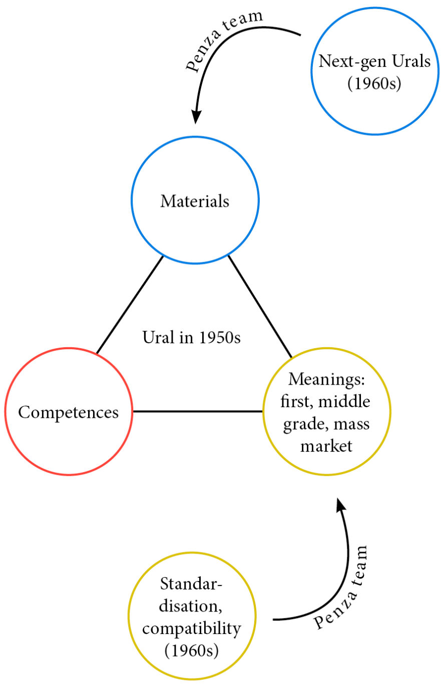


Figure 15. Visualisation of dynamics in the Ural configuration during the 1950s and 1960s. For a coloured version of this image please refer to the digital version of this paper.

6.3.2. **Party decree and unravelling of the configuration (1965-1968)**

In this section we cover the beginning of troubles for the Soviet computer industry in 1965 which led to a 1967 Party decree to prioritise a new computer project to the detriment of existing ones like the Ural.

Between 1965 and 1968 a growing number of computers (Figure 12) was being installed in "computation centres" (data centres) in response to increasing demand for computing in large organisations. The efforts of a relatively small cohort of qualified programming specialists[58], who would design the software, were stretched[59] (Przhijalkovskiy, n.d.-b; CIA, 1965). The best professionals were being scooped up by the military (Gerovitch, 2004), whose decision-making was effectively detached from the state and Party leadership (Hanson, 2003). As a result, software libraries were small and, typically, no basic software was supplied with the machines (CIA, 1966; Gerovitch, 2004).

There were also issues with the poor quality of computer hardware. The Soviet economy was characterised by distorted efficiency incentives for enterprises, especially those producing consumer goods, and very weak product innovation incentives[60] (Hanson, 2003). New products were introduced only largely due to special interest by high-profile decision-makers or the military (Allen, 2001; Hanson, 2003; Gerasimova & Chuikina, 2009). As a result, when in 1965 the next-gen Urals (11, 14 and 16) started manufacture (Figure 16), Rameev and his team had to downgrade the initial designs from magnetic disks to antiquated punch cards and 'punch tapes' (Rameev, 1966; Hodakov, 2010; Malinovsky, 2010).

Next to domestic hurdles, there were also external ones. Despite the intensification of machinery imports in early 1960s (Hanson, 2003), imports of complex technology, such as computer equipment, were low due to a Western embargo of advanced technology to the USSR since 1949. In that year the US facilitated the set-up of the Coordinating Committee for Multilateral Export Controls, also known as CoCom, a non-binding treaty between the Western states against socialist states to limit technology transfer to them (CoCom, 1959; US Office of Technology Assessment, 1979; Cain, 2005; Leslie, 2019). In 1970, the CIA reported that "[d]evelopment of semiconductor production in the USSR was almost certainly retarded by COCOM embargo of both vital raw materials and technology. [...] [I]nadequate production of ICs [integrated

[58] At the end of the 1960s the USSR had 1,500 programmers compared to 50,000 in the US (Przhijalkovskiy, n.d.-b).

[59] A similar problem of "software crisis" took place in the West as well at around year 1970 (Tatarchenko, 2017).

[60] This was due to, first, the principle of "use it or lose it" in budget allocation, and, second, measuring economic results by produced volumes (e.g. weight), not sales (Hanson, 2003).

circuits] is a major reason for the lag" (CIA, 1970).

Faced with these issues, in 1967 the Party decreed[61] to reorganise the R&D of Soviet computing and tasked the Ministry of Radio Industry to develop a series of computers to address the issues in the industry (Przhijalkovskiy, n.d.-b; Smirnov, 2005). This was the beginning of what would be labelled *ES ÈVM*, the Single System of Computing Machines. Although Rameev's 1963 strategy for a single compatible series was by then published, the authorities did not follow it and decided that the new ES series should be based on a foreign internationally acclaimed machine (Przhijalkovskiy, n.d.-b), the highly successful IBM-360, by licensing its manufacture[62].

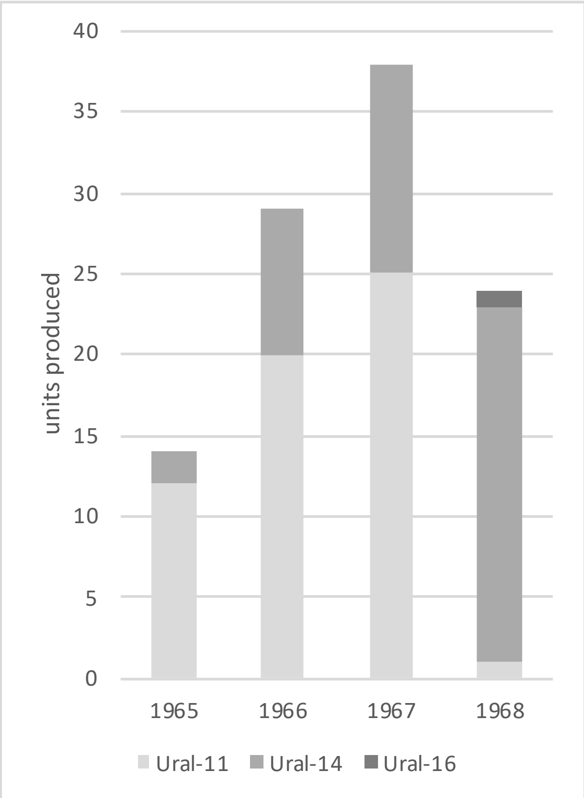


Figure 16. Ural *series production between 1965 and 1968. Based on data from Smirnov (2014). For a coloured version of this image please refer to the digital version of this paper.*

61 Decree by the Communist Party of the Soviet Union Central Committee and Council of Ministers of the USSR No. 1180/420 from December 30, 1967 "On the continuing progress in development and production of computers".

62 To this day, computer scientists and computer historians in Russia and other former Soviet countries argue about this decision, as evidenced by the presentations and discussions at annual SORUCOM conferences in Moscow. Some cite it as the most sensible thing to have done at the time, others call it disastrous and unethical and something that deeply hurt the Soviet computer industry (cf. Abramov, 2017).

As soon as the ES was announced in 1967, it quickly began pooling resources. Reportedly, more than 300,000 specialists and 100 organisations were pooled to work on ES ÈVM (Targowski, 2016), leaving other computers further down the supply priority for the already limited equipment and qualified specialists. In 1968 Rameev himself left the Penza institute, having been offered a position in Moscow as deputy lead designer in the newly founded Electronic Computing Technology Research Center (NICEVT) (Smirnov, 2005), one of the research centres working on the ES ÈVM series[63] (Przhijalkovskiy, n.d.-a). This was a big change for the Penza team (Smirnov, 2005) since he had been the main creative force behind the Ural.

To sum up what we learned so far: first, by the late 1960s Ural established itself as one of the most popular middle grade computers. Second, the ES ÈVM was launched to address the issue of incompatibility that, among other issues, plagued the Soviet computer industry. Third, there were few incentives for manufacturers to innovate, e.g. use lighter or cheaper materials. As result, the quality of components, ease of use and international competitiveness suffered. With the same effect, finally, an embargo of advanced electronic equipment to the Soviet Union by the Western countries (CoCom) was handicapping component reliability and processes innovation[64]. These contextual developments destabilised the Ural configuration: they forced the design of Ural to be downgraded to inferior materials (punch cards and tapes), while superior ones (i.e. magnetic disks) were pooled by ES ÈVM and the military, as well as the specialised labour, including Rameev himself. These dynamics are illustrated in Figure 17 with straight lines between the sub-configurations indicating linkage (continuous line) and destabilisation (dotted line), and arrows indicating the types of changes in the relevant sub-configurations and key actors, if identifiable, in these changes.

6.3.3. **Continuing unravelling (1969-1975)**

In this section we present a final unravelling in the Ural configuration.

In early 1970s, although the manufacture of ES ÈVM steadily grew, Ural (Figure 18) was still a legitimate computer. For example, in 1975 Ural-11 and 14 (Figure 14) were used by the centre of space flight control, along with the much larger BÈSM-6, to process data during the Apollo-Soyuz flight (Halikov, 1985; Smirnov, 2014). In the following four years, Urals were used for interplanetary probe flights (Halikov, 1985).

63 From NICEVT Rameev was, supposedly, intending to integrate the design of ES ÈVM with domestic expertise (Kazakova, 2013), such as that of his Penza team.

64 Although, Leslie (2019) dismisses the impacts of CoCom on Soviet computing.

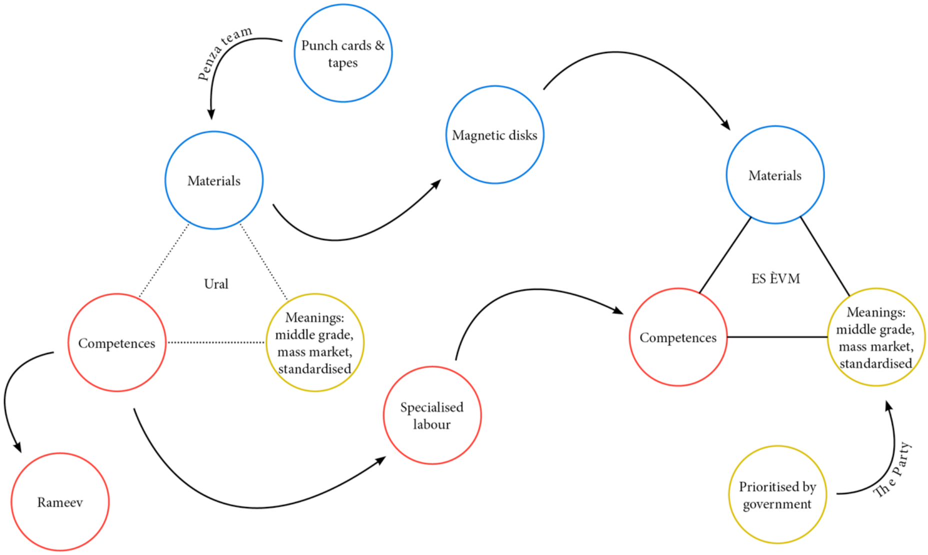


Figure 17. Visualisation of dynamics in the Ural *and* ES ÈVM *configurations between 1965 and 1968. For a coloured version of this image please refer to the digital version of this paper.*

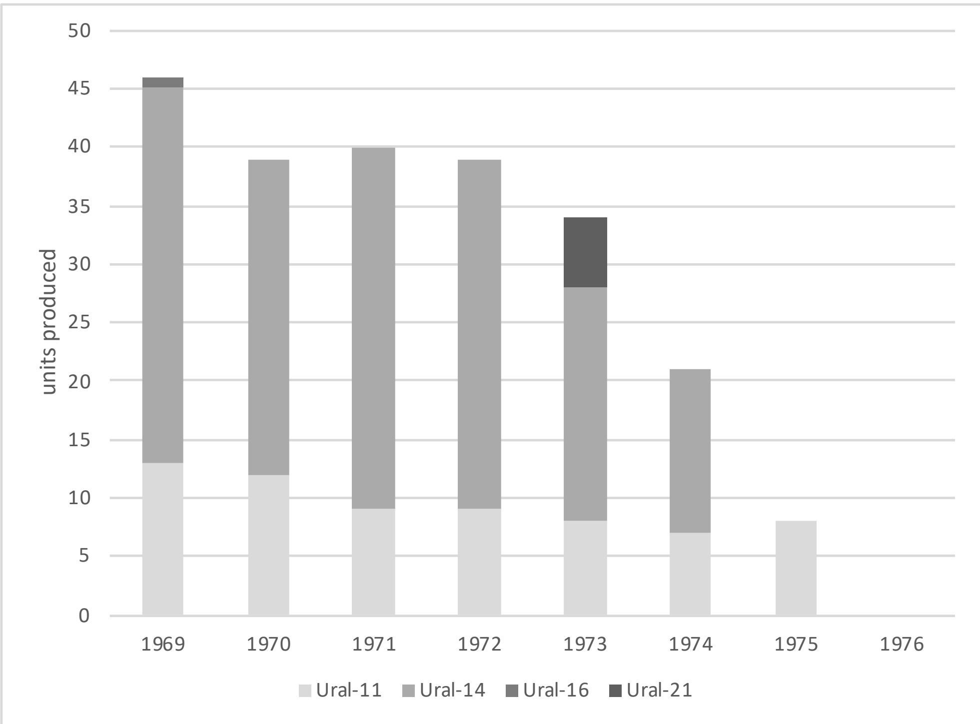


Figure 18. Ural *series production between 1969 and 1976. Based on data from Smirnov (2014). For a coloured version of this image please refer to the digital version of this paper.*

In early 1970s shortages of component supply for the entire industry continued[65] (Allen, 2001; Hanson, 2003; Harrison, 2017). One of the results of this technological lag was a handicapped capacity to implement the domestic computer design in full[66]. The available qualified maintenance staff, software and quality hardware were spread so thin across the growing number of users, that the average use time of computers halved compared to previous years (Gosplan RSFSR, 1974). Productivity issues, that have been accumulating since 1965, and the growing shortage of programmers were causing delays with delivering the first Urals-16: in 1971 buyers withdrew, which further stalled manufacture (Smirnov, 2005).

At the same time, the Penza team was also developing the next Urals: 21 and 25 (*Specifications…*, 1971; Smirnov, 2005). The latter one was supposed to be compatible with ES ÈVM and able to use its hardware components (which were expected to be abundant (Smirnov, 2014)) and the Ural software (which was at the time the most widespread in the USSR (Research Society, 1973; Smirnov, 2014)). Thus, the Ural-25 was planned as a Ural-ES ÈVM hybrid, compromising some of its identity.

In early 1970s, NICEVT proposed a new ES ÈVM model of similar specifications to Ural-25. The Ministry of Radio Industry, which was curating the computer industry, apparently, saw this as duplication of work because in 1972 it assembled an interdepartmental temporary scientific commission to consult which one of the two projects to include in the ES ÈVM project. It is insightful to learn what arguments the proponents and opponents of the Ural brought forth. Rameev's notes (Rameev, n.d.-b, n.d.-a), who was on that commission, reveal that the Ural-25 was called by some stakeholders "promising", "a step forward" and "a start of a new generation" full of market potential; and "too specialised" and "slow" by others. Particularly, the Academy of Sciences and some of the Ministry of Defence departments praised Urals and said they would never substitute them for ES ÈVM machines. The opponents of Ural, such as the representatives of the railroad industry, the State Committee for Science and Technology (*GKNT*)[67] and representatives of the Ministry of Defence (different than the ones mentioned above) said that they would prefer to use the upcoming non-Ural ES ÈVMs in the future to "decrease the diversity of computers" in their offices. Anatoly Dorodnitsyn, head of the data centre at the Academy of Sciences, also

65 The CIA assessed exactly what was lacking, and this is corroborated by Malinovsky (2010) and Smirnov (2005): testing equipment, displays, memory, high-speed data transmission equipment (CIA, 1973), and automated manufacture techniques (CIA, 1971).

66 In 1971 the CIA was reporting that "[t]he logical design of Soviet computers is rather good. In most cases, however, full advantage of the capabilities […] cannot be taken, because of insufficient internal memory and inadequate peripheral equipment" (CIA, 1971).

67 GKNT was a branch government unit subordinated to the USSR Council of Ministers and responsible for science and technology. A sort of 'super-ministry' of science and technology (Hanson, 2003).

doubted that Penza would supply the new machine in time because he had noticed a systematic slippage of deadlines by the Penza team ("the question is: can the Penza team deliver on time?" he asked).

In the end, the report of the temporary commission attempted to reconcile the opposing views (Rameev, 1972). The commission recommended the ministry to support the development of Ural-25 as part of the ES ÈVM series. Although we found no later documented decisions regarding Ural-25, its development was never finished, it was not included in the 1972 ES ÈVM production line and its financing stopped (Smirnov, 2005; Bezâev, 2018). Thus, the movement for a single series of standardised mass market computers which Rameev had started with his next-gen Ural strategy finally slipped away from him. That movement turned into ES ÈVM that found no place for Ural.

To sum up this section: a simple explanation to the phase-out of Ural, that it was phased out because it was technologically inferior to ES ÈVM, does not hold. Ural 14 and 16 were in use and production till at least 1975. Although few Urals-25 saw action, this newest model was debated on par with an ES ÈVM model in 1972, as an equal alternative. The processes of unravelling during this period can be visualised as in Figure 19 and the role of key stakeholders in the history of Ural can be summarised as in Table 6. First, the identity of Ural was destabilised by the team hybridising it, followed by production delays due to poor hardware and software quality, which, in turn, made some stakeholders doubt the Penza team's credibility. Ultimately, the clients withdrew the funding from the Ural project (Figure 19). As meanings, competences and materials encountered problems, the connections weakened and finally disappeared, and the configuration unravelled.

Stakeholders	**Decline-relevant roles in configuration dynamics**
The party	*Disrupted continuous reproduction* of meanings by officially prioritising ES ÈVM thus forcing resources to be rerouted there
Penza team of developers	*Disrupted continuous reproduction* of meanings by undermining credibility with hybridisation (and due to delivery issues); of competences when lead designer Rameev left; and of materials by replacing magnetic disks with older technology
Industrial users	*Disrupted continuous reproduction* of materials by withdrawing funding

Table 6. Roles of Ural stakeholders in the Ural phase-out.

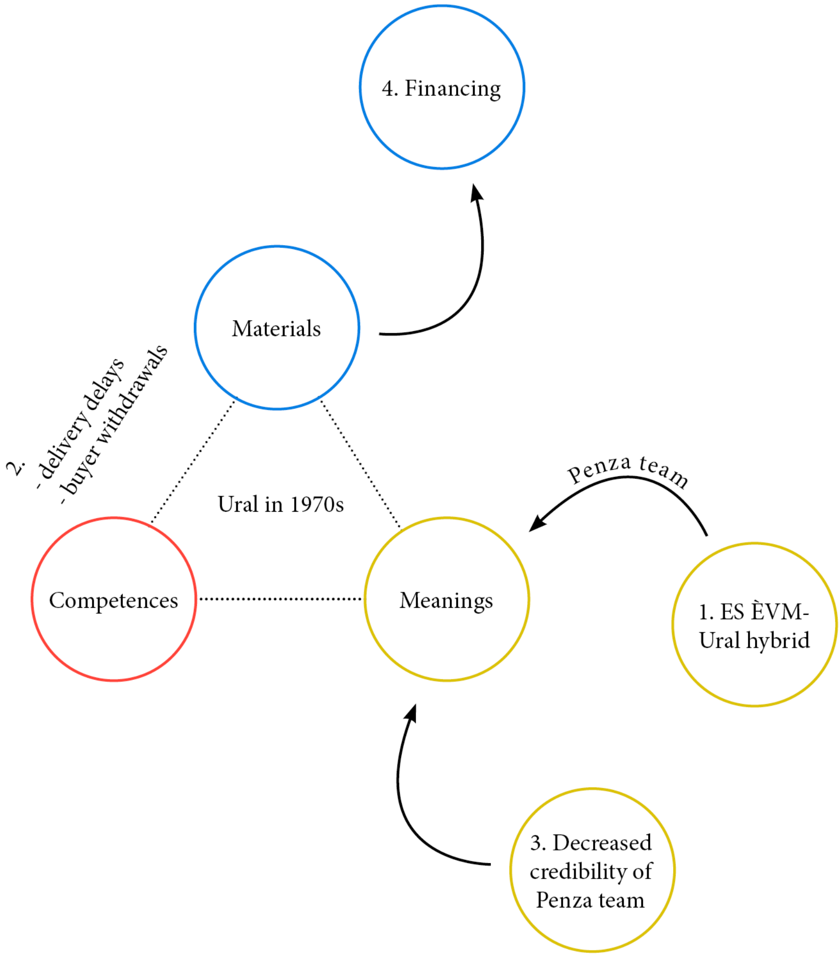


Figure 19. Visualisation of dynamics in the Ural configuration after the Party decree to prioritise ES ÈVM. *For a coloured version of this image please refer to the digital version of this paper.*

6.3.4. Cessation of manufacture and use (1976-1990)

In this section we turn to the fate of the unravelled configuration, or rather the stranded elements.

Rameev resigned from the position of deputy lead designer of ES ÈVM in 1969 upon his disagreement with the IBM decision, and his career afterwards was unremarkable to the fate of Ural or computing. In Penza, the former Ural crew of more than a thousand people (engineers, electricians, mathematicians, programmers, etc.) was trying to find their place in ES ÈVM. The factory workers, who had previously assembled Urals, went on to manufacture the ES ÈVM components. After the Ural-25 failure, the work of designers switched to the design of specialised tools for the military and space industry (Bezâev, 2018). In 1973, the team tried to develop a multiprocessor system U-1051 for air traffic control compatible with ES, but it never launched into production. More projects did not lead to anything (Smirnov, 2005). From 1975 onwards, the Ural team increasingly disintegrated and fragmented, working on smaller projects, such as spare parts for existing Urals, other brands, and, increasingly, ES ÈVMs (Smirnov, 2005). In 1982, the Penza institute was restructured and tasked to conduct R&D of air traffic control systems (Rubin, n.d.), which was another expertise of the institute. At the time of writing in 2020, most of the Penza team members had passed away.

No more Urals were produced after the 1970s (Figure 12), although some were still used in the space industry well into the 1980s (Halikov, 1985). We found no hard data, but considering the fast rate of replacement of older computers with ES ÈVMs, it may be safe to assume a steady decline of the use of Urals already by the end of the 1970s. Few Urals were preserved as they contained large amounts of metals (about one tonne of aluminium, 260 kg of copper, 150 kg of brass, 40 kg of bronze, 25 kg of zinc, 4 kg of nickel and 125 kg of other non-ferrous metals (Penza Council…, 1960)) and occupied a lot of room, both of which invited their decommissioning and sale, especially in times of late Soviet and post-Soviet economic hardship. Freeing up precious room from obsolescent machines was always a pressing concern (Motor Transport…, 1965). At one point in the 1960s, a surge in disposals of the older, vacuum tube Urals took place as soon as newer Urals were launched. This occurred quite frequently with other computer models as well, as evidenced by a government decree that specifically instructed organisations not to destroy or sell computers without permission (Gosplan SSSR…, 1968).

The surviving Urals were claimed by museums, such as the Moscow Polytechnic Museum which still exhibits a Ural-1 (Figure 20).

Figure 20. Ural-1 in temporary storage of the Moscow Polytechnic Museum in 2019. Photo by author. For a coloured version of this image please refer to the digital version of this paper.

6.4. Discussion and conclusions

We have analysed the decline of a Soviet/Russian computer Ural to empirically study a case of decline, particularly one in a non-Western context. The analysis was aimed to help fill an empirical and conceptual knowledge gap on decline and gain more insight into its patterns, and to do so while attempting to integrate the Soviet/Russian computer industry experiences.

We first discuss limits to generality of this case. We identified three contextual factors key for the decline of Ural. All of them had to do with drawing away the most skilled workforce (during its post-war shortage) and the most high quality parts from the development and diffusion of Ural: (i) general structural issues of the heavily planned economy with its slow innovation, which was at odds with the fast-paced rationale of the computer industry and could not compete in the rate of innovation with the capitalist system of incentives[68]; (ii) competing R&D projects, prioritised by the government at the expense of Ural (namely, ES ÈVM and the secretive military projects); and (iii) a broad foreign trade embargo which was barring the country from latest international advances in computing and other advanced electronic technology.

Clearly, the first one of these, the heavily planned economy, was an idiosyncratic feature of the Soviet politico-economic system. New products, such as new kitchen appliances or new types of computer devices, were introduced rarely and largely only due to special interest by high-profile decision-makers or the military. As a result, Ural's development and production was plagued by low productivity of manufacture and low reliability of components. Thus, any lessons drawn from this case regarding issues of economic incentives and the innovation system are very limited for contemporary neoliberal economies. The two remaining contextual factors, however, are observed also today in the Global North: the crowding out of R&D projects (e.g. R. Cowan & Foray, 1995; Hartley, 2006; Popp & Newell, 2012) and foreign trade embargoes, e.g. the oil embargoes of the 1970s (e.g. Graf, 2012). Our case confirms that both can play a large role in preventing further production and/or use of a given technology.

In terms of how exactly such prevention unfolds, we have shown the decline of Ural as the unravelling of a socio-technical configuration of meanings, forms of competences, and materiality, and driven by policy. First, material resources and expertise were withdrawn from Ural (and many other projects, like the Minsk). This was not a directed anti-Ural policy, rather a consequence of governmental prioritisation in an environment of a general shortage of these material resources and skills. Due to shortage of good quality hardware, Ural designers had to downgrade their initial designs from magnetic disks to inferior punch cards and 'punch tapes'; and due to a shortage of specialised labour (e.g. programmers, engineers), hundreds of thousands of specialists moved on to ES ÈVM, including the lead designer of Ural. Second, as a result, Ural's legitimacy decreased and never recovered due to manufacturing problems and the attempts of the Penza team to hybridise the Ural to fit into the new regime. Ural-related competences then further dispersed both when they were failed to be preserved in a closely-knit team and as the professionals retired. The unravelling intensified by the materiality of Urals: they were bulky, inconvenient apparatus full of precious parts, inviting to scrap and sell them. Because economic productivity of enterprises was measured in tonnes, not sales, there was little incentive for com-

68 To be fair, in addition to these two drawbacks, Hanson (2003) names full employment and unprecedented job security as beneficial features of this system; Ericson (1990) mentions clear goal-setting, directionality of resources and a clear management hierarchy; and Harrison (2002) points out consistent GDP growth over most of the Soviet history.

puter-building plants to miniaturise computers or components (at least for civilian application). Holding the configuration together requires work, and the conducted maintenance work was not enough in the case of Ural. Without the continuity of the configuration, users replaced Urals with ES ÈVMs. Thus, even though Ural was, in many ways, a first mover in cheap mass-market middle grade computers, it ultimately failed and fell into obscurity.

For one unfamiliar with (Soviet) computer history it may appear that the Ural computer was simply outcompeted by more advanced technology. We have been trying to show that the reality was more complex. Conceptually, we aimed to demonstrate that technology decline is not a straightforward process of substitution by a superior technology. In this study we focused on the decline of the Ural because it started as one of the symbols of Soviet computing. But many other, less emblematic Soviet computers met a similar fate, like the Minsk. It would be curious to follow their unravelling as well in future studies.

Certain limitations of this paper need to be acknowledged. The first one has to do with the inevitable framing of data in our sources. We have dealt with this challenge by including in the analysis only the data corroborated with one or more separate sources. This was not always possible, so some gathered data was excluded from the paper. Additionally, and linked to the previous limitation, despite our best efforts, large gaps in our data remain, particularly on the experiences of the users of Ural. Future studies would be needed to shed more light on this and other issues.

Another limitation of the present study is its relatively narrow historical account regarding the Ural and the Soviet computer industry, as we omitted a lot. This was a deliberate choice discussed in section 6.2, as we followed an analytical chronology approach which geared this study to a focused narrative, rather than comprehensive historical account.

Lastly, one of the aims of this paper was to open up the largely uncharted territory of Soviet computer history and help re-legitimise the experiences of people who lived, worked, exchanged knowledge, dreamt, and produced physical and cultural legacies within an alternative politico-economic system. It is tempting to treat technological differences between the USA and the USSR as symbols of general inferiority of Soviet science and technology (e.g. Castells, 1998), and, perhaps, of the post-Stalin Soviet way of life in general. We believe, like Kotkin, that it is helpful if the history of the USSR, including its computing history, is "recognized as an integral part of the course of European history" (Kotkin, 2002). It would thus be productive to engage with the rich untapped material, as authors in Russian and Soviet studies have been doing, and further contribute to integrating the Soviet experience in transnational history of technology.

Intermission III: gains thus far

I will now for the last time interrupt the empirically heavy narrative with an intermediate stocktaking. I formulate empirical and practical insights from the study of Ural's decline, also building up on the two prior cases:

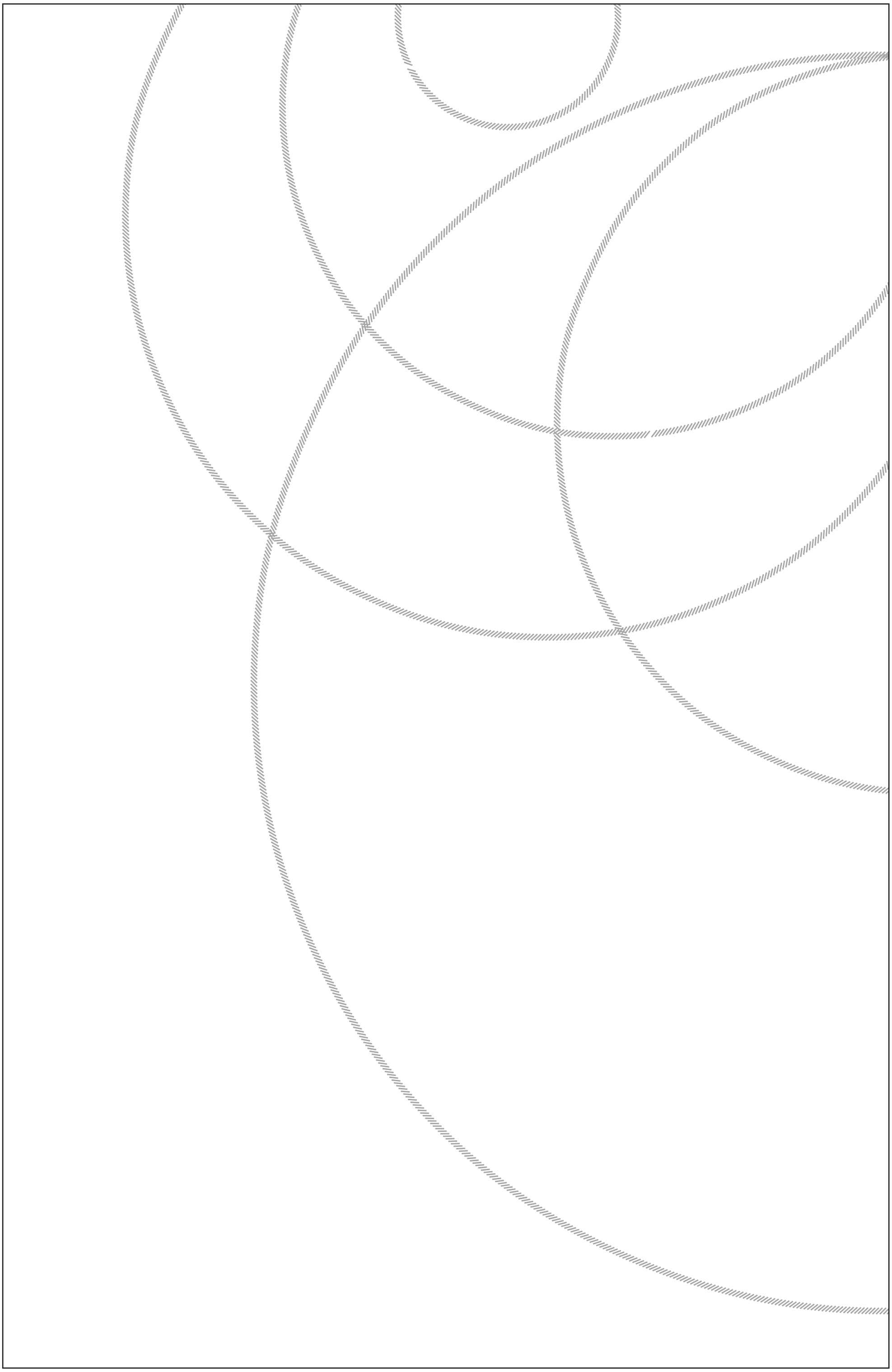
- the absence of free market relations in the Ural case seems to have hastened the phase-out, as technology developers had little to no vested financial interest or market power to continue supporting the technology; and
- unravelling may be spurred by making it prohibitively harder to use or recreate the declined technology: e.g. via withdrawal of subsidies, funding, introduce taxes and international agreements/embargoes (to leverage other regions, as seen with ENMOD, EU-wide light bulb sales ban, and the CoCom embargo). In cases of knowledge-intensive projects such as the Ural or cloud seeding, too many large-scale and competing projects (e.g. supported by government) can harm each other's efficacy because of the finiteness of resources such as money, specialists, and time. Such large-scale projects will also likely crowd out smaller or less prioritised by the government competing projects (e.g. the prioritised ES ÉVM compared to the less prioritised Ural).

Conceptually, by now I have formulated several key findings from the three cases, covered in the previous Intermissions. First, decline can be characterised by a decrease in intensity of performance of the configuration, i.e. a decrease in the continuity of its use and/or manufacture and linkages between the strands of the configuration. The technology does not always have to decline completely, and it may remain used and/or produced in small pockets or niches, away from the mainstream (e.g the Polaroid 2.0, film camera or the incandescent light bulb today). Second, the decrease in intensity seems to correlate with how strong or dynamically stable the three strands are, meaning that configurations demonstrate certain resilience. Third, three basic pathways seem possible: contraction, seen at some point in all cases, but which is most drastic in the Ural case; re-emergence, seen by the end of the observation of the cloud seeding case; and continuation of a niche status, seen by the end of the observation of the light bulb case.

By now, three conceptual observations seem apparent:

- the dynamics of intensity of performance may be traced geographically (in a given area such as a city or nation) and temporally (within a certain timeframe);
- a state of advanced technological decline may be conceptualised as a state of absence, or extreme unravelling, of one or more strands, because without even one, performance, or reproduction, of the same technology is not possible. This means much work will be needed to re-establish the related materials, meanings or forms of competences;
- unravelling in meanings, not in materials or competences, tends to catalyse unravelling of the configuration. This is in line with literature exploring the importance of expectations in the future of technologies (Van Lente & Rip, 1998; Borup et al., 2006; Van Lente et al., 2013) and indicates that the three strands may not be equally important. This finding could be a consequence of my case selection (where meanings played a more important role) and so warrants more scrutiny. I return to it in the following chapter where I analyse more cases from literature.

I now turn to attempting to synthesise the empirical work done so far, integrating the discussion points of the three intermissions.



Chapter 7. **Synthesis: towards an unravelling approach**[69]

I started this thesis with an observation, supported widely in the literature, of a lack of attention to a complex process of technological decline at the time when such knowledge is pressing: i.e. the climate and other crises and the growing in number decline policies. In this chapter I collect all the threads of the work that I have conducted to characterise, understand and intervene in technological decline as a phenomenon, i.e. my research questions. Below I first compare my cases, complementing them with additional ones from the literature. I then synthesise the findings into an approach that builds up on the conceptual framework already presented (Chapter 3). The unravelling approach represents technology as a socio-material configuration constituted by three 'strands' (materials, meanings and forms of competences) that can unravel due to internal and external stresses. I conclude this chapter with a discussion of political and governance interventions for decline.

7.1. **Comparing cases**

I will use my three historical cases to analyse the dynamics of technological decline. To remind, the first case is a geoengineering technology of cloud seeding. Cloud seeding projects started in the USA (as well as the USSR and the UK) right after World War II. As huge amounts of government and state funding were spent in various projects, the technology came under fire after it was used in Vietnam, alongside other disastrous use of chemicals there. When this was revealed in the press, the negative narratives on cloud seeding ('dangerous technology', 'unethical', etc.) clashed with the reinforcing ones ('new weapon', 'forest fire relief', 'water supply control for agriculture', etc.). This clash intensified the discussion on what cloud seeding actually is for, peace or war, with the former winning. A key event for closing the controversy was the signing of an international treaty to stop using cloud seeding for military purposes (the 1977 ENMOD treaty). Cloud seeding funding quickly dropped thereafter. Many federal-funded projects were shut down, but a lot of private and state cloud seeding endeavours continued. There cloud seeding was seen as a fire relief and water supply tool. Much cloud seeding skill and knowledge preserved in those small-scale and often intermittent projects. In effect, the socio-technical configuration of 'cloud seeding'

[69] This chapter is based on my submitted manuscript to the edited volume "Technologies in Decline" (Koretsky et al., forthcoming). Minor adjustments were made in this chapter to format figure and table references.

did not disappear, it just contracted. To grow it, actors would have had to revive and strengthen it. This is exactly what happened in the 1990s as new actors connected a new hyped-up meaning of 'geoengineering as solution to global warming' to the pre-existing configuration. As a result, by 2010, the seeded area in the US was at least twice as large as during previous peak years.

So, the key events in the history of cloud seeding's incomplete unravelling were (a) the formulation of a critical narrative by the press and its quick accentuation in the Congress and by civil society, who were already agitated by the pacifist and environmentalist movements, (b) the governance decisions to withdraw funding and sign the ENMOD treaty, and (c) the reinvigoration of academic and political debates (e.g. it was routinely brought up in the Congress) on global warming, and cloud seeding as a possible response. Inversely, from a counterfactual perspective, if no publication about the use of cloud seeding appeared in the press, it would not or would much later be picked up by Congress. The timing for the actual discussions was opportune as they coincided with existing environmental and pacifist societal critique. Without (or with a later) awareness in the press and Congress, cloud seeding would go unnoticed and would likely continue to be funded by the government. No international treaty would be signed or even proposed, or it would much later. As a result, the decline of cloud seeding would not even happen or it would be less noticeable.

The case of cloud seeding's incomplete and reversed unravelling differs from a more successful unravelling of the incandescent light bulb (ILB) in Europe. The ILB was specifically targeted in the mid 2000s by a coalition of stakeholders which included the industry, the EU and environmentalist groups. Other relevant social groups, the end users at homes and factory floor workers, were not, or only belatedly, consulted. It turned out that the latter two were the ones who bore a high cost for the phase-out, ranging from health changes caused by the replacement lamps, to layoffs, retraining and jobs switches of the workers. Although in some countries labour unions seemed to have cushioned the hit for workers, the numbers of job cuts were still two to three times larger than anticipated by the European Commission.

Similar to the cloud seeding case, the unravelling of the ILB started with an attack of a group of actors on the stabilised meanings of the ILB. The view of the ILB as a provider of pleasingly warm, 'natural' light was challenged by a critical narrative of energy inefficiency, resonant with a powerful larger discourse of climate change (since a large part of emissions comes from energy). Within five years, similar to the cloud seeding case, unravelling in competences and materials followed: massive layoffs, drop of patenting activity, and drop in sales and installation capacity. What is dissimilar to the re-emerged cloud seeding is that the ILB remains in use and production in small pockets of enthusiasts in a downscaled and ever-shrinking state.

To sum up the ILB case, the key events in its history were (a) the formation of a negative narrative by a powerful social group, (b) their lobbying for anti-ILB (i.e. phase-out) policy, (c) the imitation of the ILB by the LED, and (d) the withdrawal of the ILB to small pockets of production and use. Inversely, had the key social group not formulated a negative narrative of the ILB, the European Commission would not have to draft the ban, or at least would do it later. As a consequence, without the sales ban, the ILB would remain on the shelves for much longer.

A final case I have studied is the Russian/Soviet original computer series Ural. Ural was one of the most popular computers used in industrial design, medicine, meteorology and banking in the Soviet Union in the 1960s, until it was all but gone by the 1980s. One of the key events in the unravelling of Ural was Bashir Rameev leaving his post as the lead designer. This happened during a notable ministerial rerouting of resources, or at least neglect of ensuring enough resources to the development of Ural, thanks to a competing computer series ES ÈVM. ES ÈVM emerged and was supported by the government and a strong narrative of progress. As a result of such rerouting or neglect, materials and competences destabilised. Namely, due to shortage of good quality hardware, Ural designers had to downgrade their initial designs from magnetic disks to inferior punch cards and 'punch tapes'; and due to a shortage of specialised labour (e.g. programmers, engineers), hundreds of thousands of specialists moved on to ES ÈVM, including the lead designer of Ural. All of this weakened the Ural configuration and caused delays of supplies to buyers, propelling the Ural into an unravelling trajectory. Subsequently, Ural-related competences slowly dispersed as team members moved on or retired. Without the continuity of the configuration, users rather quickly replaced Urals with ES ÈVMs. The only legacy it had left is the very idea of a Soviet mass computer, adopted by the ES ÈVM.

Thus, summing up, the key events in the case of the Ural were: (a) lead designer leaving the group, (b) the state officially prioritising ES ÈVM over other computer projects, (c) a lack of resources which forced designers and manufacturers to use outdated parts in Ural, (d) hybridisation of the Ural by the design team, thus undermining Ural's identity and credibility, and (e) withdrawal of the last funder from the Ural line. Had Rameev remained the leader of the design team, judging from his documented leadership qualities and commitment to the Ural, he would probably manage to secure resources for continual development and production of Ural. If so, it would remain to be popular and could eventually be integrated into the ES ÈVM, which would have still existed because of the structural problems in the industry. As a consequence, the Ural may have survived until the collapse of the USSR.

Turning to case comparison, it is curious to observe that the competing configuration in the ILB and Ural cases (the LED and the ES ÉVM, respectively) was absent in the cloud seeding case. In the ILB and Ural cases the competing configurations played slightly different roles. For both the ILB and LED continuity was key: their strands transformed, acquiring and rejecting certain meanings ('nostalgic lamp', 'rough-service lamp' vs 'energy inefficient lamp'), competences (e.g. where to buy the banned lamps) and materials to stabilize the configuration. The competing LED was deliberately made to look like ILB in shape and colour output, and the controversy over the ILB did not end until the substitute LED technology had met all the demands of the critics (safety, full light spectrum, ease of use, familiar appearance, affordability). The processes were analogous in the case of Ural, where the Ural tried to imitate the new ES ÉVM, which actually undermined its own credibility as an ES ÉVM competitor. Thus, transformations and exchange of elements of the strands (such as the imitation of the supposedly backwards ILB and the hybridisation of the Ural) can occur and contribute to the speed of the unravelling.

Cloud seeding and the ILB followed similar pathways up to a point when cloud seeding started growing in geography and regularity of use (although it is yet unclear if this growth will continue). I concluded that cloud seeding was on a pathway of re-emergence, the ILB—on a pathway of decline (at least, as of 2019-2020) that involves technological substitution, and the Ural—even further on a pathway of decline. The phase-out of the ILB is, in principle, reversible as long as all elements (the bulb envelope, wires, the knowledge of their construction and use, the need for lighting, etc.) are available. Such availability was there in the case of cloud seeding, and was not in the case of the Ural.

Before I further analyse these cases by comparing and contrasting, I would like to bring some more cases from literature into the discussion.

Additional cases

To bring more variety of cases of decline and to characterise them from the perspective of unravelling, it is productive to revisit some of the cases found in the literature exploring decline and adjacent phenomena. I selected, based on the visibility and comparability of the three strands of materials, meanings and competences, four cases of decline from literature covered in Chapter 2.

First, I discuss the Polaroid instant camera (Minniti, 2016), a popular artefact from the end of the 20th century. The advent of digital photography created a strong alternative configuration with meanings, materials and forms of competences that challenged the previously widespread Polaroid. However, instead of declining, Polaroid users changed the negative, critical meaning of 'obsolete' to a reinforcing one of a subculture. Minniti writes that "[p]reviously dispersed users connected with each other and emerged as a relevant social group with the power of attracting a new producer of instant films, redefining along this process their collective identity as “polaroiders”. […] [T]he use of Polaroid technology acquired a new oppositional meaning, grounded on the definition of a new form of authenticity” (Minniti, 2016, p. 40). Similarly to the light bulb, the Polaroid configuration survived as a downscaled and altered version, “Polaroid 2.0”.

Another case is the US nuclear weapons field testing (MacKenzie & Spinardi, 1995; Sims & Henke, 2012; Bourne, 2016). In the 1990s, the US did not test nuclear weapons anymore which created a legitimacy problem for the nuclear weapon expert community and threatened the continuous existence of nuclear weapons, at least in combat readiness. Competences began to unravel. Luckily for the expert community, they have managed to link up other materials (computer systems, instruments, and experimental facilities), competences (computer modelling and simulation) and meanings (the importance of modelling and simulations in nuclear deterrence) to the configuration. Benjamin Sims and Christopher Henke write: “the weapons laboratories were able to articulate, and gain acceptance for, a post-Cold War narrative that continued to position their expertise as a central element of nuclear deterrence” (Sims & Henke, 2012, p. 342). This strengthened the competence strand, and then the entire configuration.

One more case of technological decline to compare is ink, an example from Shove and colleagues (2012). According to them, a hundred years ago the technology of producing writing ink used to be common knowledge for white collar workers and parents of school children. By the time ball pens, a competing configuration, saw wide use, this knowledge was increasingly found only in encyclopaedias or textbooks. They would instruct to “take twelve pounds of bruised galls, five pounds of gum, five pounds of green sulphate of iron, and twelve gallons of rain-water”, “[b]oil the galls”, “draw off the clear liquor”, “[a]dd to it the gum”, dissolve the sulphate and “mix the whole” (Shove et al., 2012, p. 60, quoting “Enquire Within Upon Everything: The great Victorian standby”). As writing with ink shifted from the sphere of the commonplace to that of an unusual tool, the competences required to produce and use ink sunk to obscurity. Shove and colleagues point out that while it is possible to reproduce the procedure, certain tacit knowledge is not preserved in this guide, for instance, how exactly one should draw off the clear liquor, and will need to be generated anew.

Lastly, I would like to bring up the UK coal-fired power’s (incomplete) decline. As Turnheim and Geels (2012, 2013) show, the unravelling of coal power was a very long process and it started with the contestation of coal and emergence of a critical narrative of “pollutant” in the 1920s. The meanings did not unravel until new energy technologies emerged, such as nuclear, oil and gas power. The pressure further intensified with new anti-coal laws such as the 1956 Clean Air Act and the 1965 White Paper on Fuel Policy which decreased the role of coal in the energy mix. Coal was started to be seen as “outdated” and “old-fashioned”. The increasing unravelling in meanings was joined by an unravelling in the materials and competences in the form of shrinking markets and massive layoffs of miners. By the 1980s and 1990s coal power downscaled massively from most sectors of the economy to just electricity generation.

The four cases of technological decline show that it is possible to view the processes of decline as unravelling of configurations, which allows further comparison.

Key observations

The cases studied in this thesis and the four additional cases differ in the outcome of unravelling, with some declining, others returning, and yet others stuck in-between, contracted into niche uses and production. How does the framework from Chapter 3 help to distinguish how and why? As a next step I will discuss five apparent aspects in which the cases differ.

First, the cases feature different, what seems to be, *types* of technologies, involving different knowledge, materials, economic sectors and types of actors. Cloud seeding is very different to use than the light bulb: you need an airplane up in the sky, guided by a ground-based meteorologist, to disperse chemicals for reasons of fire hazard mitigation, watering crops or clearing the sky for the Olympics. Whereas the light bulb is a relatively simple technology in terms of usage: a hand pushes the switch, the wire lights up and provides lighting. In innovation studies, different typologies (e.g. Tushman & Rosenkopf, 1992; Taylor & Taylor, 2012) classify technologies based on technical complexity and level of analysis (i.e. technology reflecting a paradigm vs. technology generations that follow out of this paradigm). Taking the STS perspective, the difference between technologies is not in kind or type, but in complexity of co-existing entities that make up a technology. Perhaps, then, one aspect in which technologies (and their resilience) differ is the variety of co-existing entities within the strands at a given moment.

To clarify: it appears that a high variety of co-existing meanings (i.e. interpretive flexibility), at a given moment, could indicate, perhaps counterintuitively, high resilience of the meanings strand, at a given moment. Similarly, Van Lente and colleagues (2013) suggest that technologies with more interpretive flexibility at a given moment are more resilient to unravelling of the configuration[70] (at least to one that starts

[70] “The more specific an envisioned application is, the more difficult it becomes to reorient expectations after disappointment. Emerging technologies that are the generic basis for applications across a variety of fields, therefore, are likely to display more diffuse hype patterns with less profound consequenc-

with meanings). The cloud seeding and the ILB cases seem to confirm this, as these technologies with a relatively high variety of co-existing meanings[71] did not decline.

Next, variety in competences may mean variety in skills, knowledge and forms of labour, which also seems to reinforce the resilience of the configuration. For example, in both nuclear weapons field testing and cloud seeding cases, those competences that unravelled away from the configuration were replaced by alternative competences: building and physically testing bombs and seeding compounds were replaced by computer modelling and simulations of nuclear explosion and in meteorology, thus not letting the configuration unravel too much.

Finally, the role of variety in co-existing materials is more ambiguous as it might mean either interdependence of various material entities (e.g. a mechanism) or their variety without interdependence (e.g. availability of analogues). In the first case, it follows that the variety does not increase resilience, rather the opposite: in a complex system more things can go wrong, as the so called Murphy's law goes. This is supported by the Ural case. Here, Ural's complexity as an artefact did not prevent its decline, in fact it intensified it as actors hastened to free up precious space from the old bulky machine, full of expensive parts (the removal and sale on the black market of even one of which could greatly reduce the efficacy of the machine). In the second case, that of variety of analogous materials, complexity may indeed increase resilience as one material may be replaced by another. It thus appears that, for the most part, resilience of a configuration depends on variety: the greater the variety (and so, embeddedness, interconnectedness) within a strand, the more resilient, embedded the strand and, hence, the configuration will be. Low resilience of a strand would then imply that there is no or very low such variety.

A second observation is that technological decline is a phenomenon in time *and* space. In all of the discussed cases, the geographical and temporal intensity of linkages changed during unravelling (Figure 21). Configurations which are performed rarely and/or nowhere (relative to before) are the declined ones. This usefully specifies the phenomenon of decline further as radical decrease of intensity of performance of the technology over time and space.

es of disappointment (Borup et al., 2006). A suggested reason for this is that emerging technologies with generic applications can be linked to a more diverse set of expectations associated with different paths of social embedding" (Van Lente et al., 2013, p. 1617).

[71] Including "cloud seeding as forest fire relief", "cloud seeding as agricultural water supply tool", "cloud seeding as a weapon", etc.; and "ILB is cheap", "ILB puts out natural light", "ILB is part of the culture".

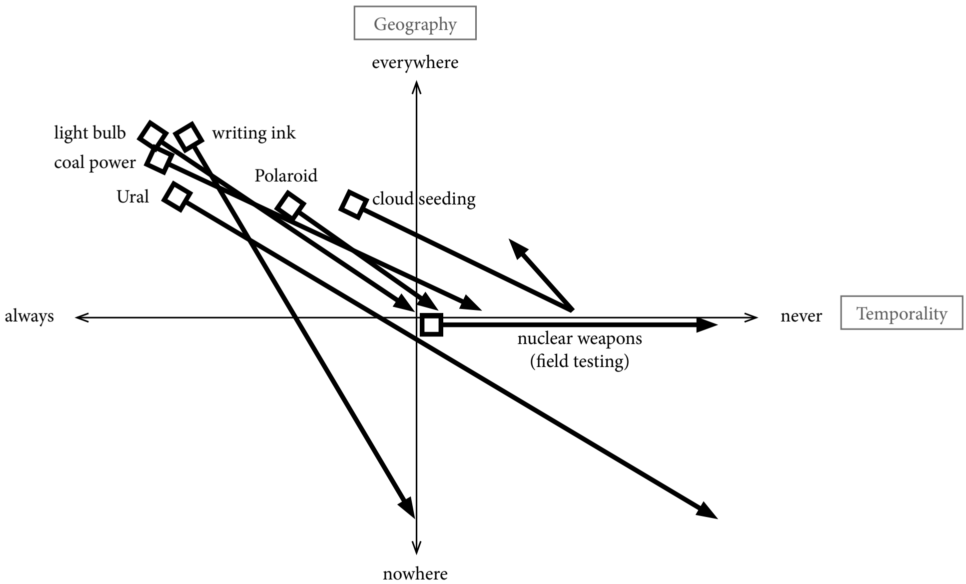


Figure 21. Sketching a relationship between relative geographic and temporal intensity performance of configuration, with a state of decline in the bottom right quadrant.

A third observation is concerned with the type and conditions of change in the socio-technical configuration. It appears that there are two types of change. First, there is reinforcing or at least non-disruptive change, which can involve incremental innovation, emergence of alternative uses and meanings of the given technology, the development of new competences, etc. Such reinforcing change supports the variety of entities within strands, as just discussed. Then, there is also disruptive change, which displaces co-existing entities via e.g. new materials, counter-meanings and/or shocks in forms of new competences that shake up the given strand. Disruptive change can lead to loss of resilience of a strand, its unravelling and, potentially, the unravelling of the whole configuration. For example, new chemical substances for cloud seeding did not lower the resilience of the material strand, nor did the co-existence of different meanings of cloud seeding: e.g. fire control tool and irrigation tool. In fact, the latter reinforced the strand as it meant that cloud seeding was used in multiple applications and locations. Unravelling for cloud seeding started with a shock that introduced a powerful counter-meaning ("hazardous and ethically dubious technology") that challenged the other meanings.

A fourth observation relates to the starting point of technological decline. In my three case studies unravelling in meanings, not in materials or forms of competences, tended to catalyse unravelling of the configuration. This could be because in my cases intentional processes of decline (e.g. state driven), rather than emergent (e.g. market driven), are more prominent. Additional empirical research will be needed to draw stronger conclusions, but the leading role of unravelling meanings could indicate that the three strands may not be equally important in *catalysing* a typical purposeful decline. Of course, catalysing is only part of the unravelling processes, as I have shown in the cases.

A fifth observation, however, confirms an earlier STS and transition studies finding that there is no strict dichotomy between emergent and coordinated decline, however obvious it might seem. Indeed, in some cases it seems that technologies are “just” gone, i.e. turn obsolete and succumb to the forces of innovation, such as the film photo cameras (generally) losing the competition to digital photo cameras. But technologies may also decline forcibly, purposefully, as a result of public or industrial policy, even if its use value is still high. There are clear examples where different fields of application in different contexts in a literal sense *declined* the usefulness of the DDT, nuclear plants and Teflon pans. The dichotomy between emergent (unintentional) and coordinated (purposeful) decline seems obvious.

However, there are also signs that such strict dichotomy is misleading. Instances of mixtures of the two are well-known. On the one hand, some outcompeted technologies were planned to be outcompeted. Consider anti-competitive practices, planned obsolescence (where a company’s older product is made to be outcompeted by a newer one), and, more generally, the historic role of the state in creating and supporting free markets (“laissez-faire was planned” (Polanyi, 1944)). From this perspective, a fully emergent quality of decline can be seriously questioned. On the other hand, top-down decline is usually first triggered by some sort of emergent destabilisation in the system. Geels and colleagues (Geels et al., 2019) observe that decline can unfold through an external shock, technical advances or shifted demand that lead to gradual regulatory tightening or a rapid phase-out decision. Thus, it appears that instead of an ‘emergent—coordinated’ dichotomy it may be more accurate to speak of a much messier interaction between emergent and coordinated processes. This idea is already present in the term ‘governance’ which, in contrast to the word ‘govern*ment*’ (Rhodes, 1997), is aimed to reconcile coordination at the systems level with an emergent character of the system, arising from the interaction between multiple societal groups (EEA, 2017).

In seemingly clear-cut cases of either emergent or purposeful decline (e.g. computers replacing typewriters or the DDT ban, new drugs replacing older versions or the phase-out of ozone-depleting aerosols) the key may lie in methodology: perceptions of emergence or purposefulness depend on the part of the historical event chain one looks at (Pettigrew, 1990). For example, in the case of British coal power (Turnheim & Geels, 2012, 2013), one could study coordinated decline within a period starting in the year 1975 when the Margaret Thatcher government closed down the coal mines; or one could study emergent decline within a period starting in the year 1925 and see falling competitiveness of British coal and public protests against it. Similarly, in all three cases covered in prior chapters, emergent dynamics led up to a phase-out decision. From this perspective, attempting to identify some essential emergent or purposeful character of decline becomes meaningless, and it is more meaningful to speak of a messy interaction of emergent or coordinated processes. From the STS perspective, the scale of analysis itself tends to skew the conclusions: emergence, autonomy and technological determinism[72] are more (albeit deceivingly) apparent if larger timeframes are considered (Misa, 1988; also Wyatt, 2008).

Similar to causes, processes of decline may also be said to have more of the emergent or more of the coordinated processes, while, in fact, both types are always present. Depending on cases where either emergent or coordinated processes matter more, one may observe differences between actors' actions. With emergent decline a firm may try increasingly desperate strategies to preserve the status quo (Turnheim, 2012), and with coordinated decline a firm may have time to prepare, or it even supports the decline, so the phase-out of the technology in question can go on faster and relatively orderly (Stegmaier, Joly, et al., 2021; Stegmaier, Visser, et al., 2021). It was not among the aims of the present book to compare emergent and purposeful decline processes. It is, however, a fruitful topic for future research, for instance, to discuss solutions that could avoid the (political) gap between proponents of strictly market and strictly regulatory solutions.

Based on these observations, I am now in a position to formulate a generic representation of technological decline and to present an approach for studying future cases of decline.

7.2. An unravelling approach of technological decline

As discussed in Chapter 2, a theorisation of the dynamics of technological decline will need to: have empirical grounding of detailed granularity, appreciate the complexity and messiness of the socio-material dynamics of decline, and be middle range. I take socio-technical configuration as the main ontological entity to start outlining a theory of the dynamics of technological decline. Describing the dynamics of the configuration amounts to tracing the dynamics of the three strands, as presented in the cases above. In the following I will first give a theoretical account of the unravelling within

[72] Technological determinism is a reductionist theory according to which a technology, and mostly technology, determines the development of social structure and cultural values.

the three strands, and then turn to the dynamics between the strands.

Unravelling in materials

Unravelling in materials may start as the resilience of this strand falls. The material strand may unravel due to changes in materialities: changes in physical availability, technical and design characteristics, material degradation, loss of funding, etc.

The survival of the material strand depends on the extent to which its 'obduracy' is or is not maintained. The obduracy of technology (Hommels, 2005a) refers to its inflexibility and the result of materialised past decisions. As a kind of materialised path dependence, obduracy can be observed in urban spaces and energy infrastructure, for example. Obduracy of the built environment is "hardly conceivable to deconstruct [...]; once a city's downtown area, including all its buildings, roads, and distribution networks, is there, it displays obduracy and offers resistance to change" (Hommels, 2005b, p. 329). Obduracy inherits from prior debates on agency of smaller mundane artefacts, such as seat belts or doors (Latour, 1992). In both small and large-scale objects, obduracy both stands in the way of the new and preserves the potentiality of the old to be revived. My findings suggest that resilience in materials may depend on the high variety in substitutable materials[73], such as analogous types of tools and artefacts, materiel, funding, etc. Or, in other words, resilience in materials depends on repairability (Sims & Henke, 2012; M. L. Cohn, 2016; Russell & Vinsel, 2018).

The unravelling in materials may cause unravelling in forms of competences, as in the case of shutting down the ILB production facilities that forced the workforce to transfer, seek new jobs, or retire. Another example is the Walkman, related competences of which (such as knowing how to manually rewind a cassette) were replaced by the CD player-related competences. Meanings may be affected by the unravelling in materials as well. Regarding materials as physical objects, tools and artefacts, Sims (2009) uses the term 'slippage': a mismatch between the expectations of how technology should be performing with perceptions of how it is actually performing. As a result of slippage, either degradation ("a technology is perceived to have aged or otherwise changed in such a way that it no longer performs as intended, even though functional requirements have not changed significantly" (Sims, 2009, p. 2)) or obsolescence ("a perception that demands or engineering standards have changed such that certain interests are no longer being met, even though the technology itself may still be performing to its original specifications" (Sims, 2009, p. 2), as in the case of the last Urals in the late 1970s, now perceived as years behind the new technical

[73] There is, however, uncertainty about what happens when this variety is embodied in a mechanism of dependent parts. High variety in materials would decrease resilience here since failure in one part would mean failure of whole (as discussed in section 7.1).

advances) occurs. Maintenance work is required to counteract slippage (Hommels, 2005a; Howe et al., 2016).

What, then, becomes of the actual artefacts as a result of unravelling? My cases show that they get dismantled (Ural) or used in small niches (the ILB and cloud seeding). Shove *et al.* (2012) note that they disappear with little (what Shove and Pantzar (2005b) call 'fossilisation') or no trace, become dormant (i.e. not gone, but also not performed), or connect to other configurations. Insights from sociological studies of debris (e.g. Edensor, 2005; Qviström, 2012; Stoler, 2013a; Schopf & Foster, 2014) are useful to expand on the fates of materials. In particular, Ann Stoler notes that fossilisation can be more than inert. It can both "hold and spread [...] toxicities and become poisonous debris" (Stoler, 2013b, p. 13) and their locations can become cherished or dreaded history.

Unravelling in meanings

Unravelling in meanings may start as the resilience of this strand falls. Unravelling in meanings may be seen on a societal level as delegitimation, and on a more individual level as the inverse of Merete Lie and Knut Sørensen's 'domestication' (Lie & Sørensen, 1996; Sørensen, 2006).

Unravelling in meanings may also be caused by presence of strong competing negative meanings. This can be seen, for example, in the clash of positive and negative interpretations of cloud seeding right after the revelations of the seedings in Vietnam. According to the European Environment Agency, "[m]edia campaigns, public debates, (scientific) publications and reports can advance particular frames, discourses and metaphors that erode the cultural legitimacy of technologies or practices" (Geels et al., 2019). Those are what Roberts calls "negative storylines" (J. Roberts, 2017).

Delegitimation could also take place without advocacy against a technology. Take, for instance, the change of what a Polaroid should mean—a hip and innovative or an old-fashioned and strange way to photograph. Or take the change of a painting should mean. In case of painting, a change from imitation of real world to its interpretation (i.e. the Modern Art movement) took place during the advent of photography at the end of the 19th century. Photography took over the role of imitating the real world, and so the meaning and purpose of painting was reimagined. This reimagining "led to decades of vitality in the world of painting, as artists were both inspired by photographic images and pushed beyond realism" (Hertzmann, 2018, p. 6). Such transformation may be conceptualised as the inverse of what Les Levidow and Paul Upham describe as 'anchoring' (Levidow & Upham, 2017), as the loss of recognition of the given technology and the resulting decline of related communication and coordination activities across social groups. The end result of unravelled meanings is a discredited, marginalised and/or forgotten technology.

Van Lente and colleagues (2013) suggest a possible antidote to unravelling in meanings: to have a higher number of positive storylines than negative. They propose that "technologies that are the generic basis for applications across a variety of fields [...] are likely to display more diffuse hype patterns with less profound consequences of disappointment" (Van Lente et al., 2013, p. 1617). In other words, as discussed in section 7.1, interpretive flexibility of technology, without outright critique of the technology as a whole, guards against unravelling in meanings.

Unravelled meanings may affect materials, forcing resources to be rerouted away from the Ural, light bulb manufacture and cloud seeding projects, or as seen with the decommissioning of nuclear reactors in Germany, Italy and other places. Forms of competences may also unravel due to an unravelling in meanings: e.g. broad awareness of health risks of cigarettes leading to a decline in smoking.

Unravelling in forms of competences

Unravelling in forms of competences may be caused by problems within the strand, when variety or just the availability in forms of competences (i.e. resilience) is low. For instance, the literature on Kondratiev waves describes shortages of workers as carriers of competences as reasons for decline of firms (Köhler, 2012). Such unravelling can be seen in closure of ILB manufacture facilities and the slow decline of the Ural team of designers. It follows that unravelling can also come about via more direct actions such as retirement of the labour force, 'brain drain' (from a given geographic region), unavailability/inaccessibility of codified knowledge (i.e. stored in literature or archives), and other ways that stop the performance of competences. Unravelled competences become (forgotten) secrets. This affects materials via degradation due to lack of repair and maintenance, and meanings via reframing of demands, standards and perceptions of performance (Borup et al., 2006; Van Lente et al., 2013).

William Michener and colleagues (1997) propose a model that could be useful for the study of unravelling of competences. He studies degradation of methodological instructions in scientific organisations: from the fullest amount of content shortly prior to and at the time of publication of the instructions, to losses of specificity with repeated revisions, to accidental loss of data, to losses due to retirement and career changes, to, finally, losses of remaining records due to death of persons who created the information. Such unravelling may be called 'collective forgetting' (Shove et al., 2012) or 'unlearning', the process of discarding knowledge (Becker, 2005). In the Ural and the ILB cases most of the competences were forgotten as workers retired or moved on and codified knowledge became more cryptic, whereas in cloud seeding much competences travelled to the adjacent field of meteorology.

The case of unlearning in nuclear power in post-Soviet context is also informative. After the collapse of the Soviet system, many kinds of specialists in Eastern Europe could not find work anymore and moved to more economically stable places. This had negative repercussions for the often high-tech industries that they had left, such as nuclear power. Roland Sturm (1993) documents the unlearning of nuclear energy operations on a societal scale that led to neglect and degradation in materials (increased frequency of service interruptions, mainly due to equipment failure). Sturm concludes that the reason was indeed the loss of competences: "The departure of […] operators, for example, left the […] station without enough skilled personnel to operate all its reactors" and "[t]he lack of domestic experience and comprehensive manufacturing capabilities in Eastern Europe – each country specialized in specific aspects – have exacerbated difficulties in obtaining spare parts and maintaining plants" (Sturm, 1993, p. 188).

Dynamics and pathways of unravelling of the configuration

As seen above, unravelling in the strands may lead to unravelling of the configuration. Unravelling occurs *within* and *between* the strands, which do not unravel in isolation from each other. Unravelling is also typically damaging to the relevant actors who have a stake in the technology. Shove and colleagues (2012) refer to the configuration as a 'circuit' to emphasise the entanglement and sequential character of changes within and the fact that the circuit breaks (i.e. continual performance stops) if even one of the three strands disappears. In my case studies I observed that such circuit breaks tend to start with the meanings.

One of the key insights of STS is that holding the configuration together requires work (Law, 1987; Latour, 2005). In fact, the stability of socio-technical configuration is an impressive and rare achievement of actors in the configuration (Latour, 2005). Bourne suggests that configurations "consist of trajectories that seem to want to pull apart or decay" (Bourne, 2016, p. 18). Invention, innovation, investment, routine maintenance, continual manufacture and/or use are needed to delay that pulling apart because they help maintain variety in the strands. As seen in some cases, decline is stimulated by coming in contact with competing configurations that put pressure on the strands of the focal configuration. Such was the case of the light bulb and the LED, the Polaroid and the digital camera, the Ural and the ES ÈVM, the writing ink and the ball pen, coal-based power and oil-based power, and probably many more, perhaps most, technologies.

As the cases demonstrate, decline is not a binary switch, but a spectrum between continual performance (i.e. use and/or production) and a lack thereof. In section 7.1 I visualised decline as a radical decrease of intensity of performance across time and space, where unravelling is a vector, or directionality, of technology towards decline. I can now be more specific and demarcate two types of decline indicated by the degree of performance intensity: weak and strong. Weak decline indicates a state where technology is simply not used anymore, while all of the strands remain intact. For instance, to manually prepare writing ink codified knowledge is noted in books, the necessary materials can be found, and the meanings of "ink" persist. Or in the UK cycling may be said to be in weak decline because at least one meaning of the bicycle persists (transport or exercise), the competences to make and ride bicycles have not disappeared, and bicycles and the lanes are still around, albeit the latter may be buried under layers of new asphalt. Strong decline indicates the completeness of unravelling within and, hence, between the strands (Figure 22), and is thus discontinuous decline. The difference between weak and strong decline amounts to how likely the technology is to return.

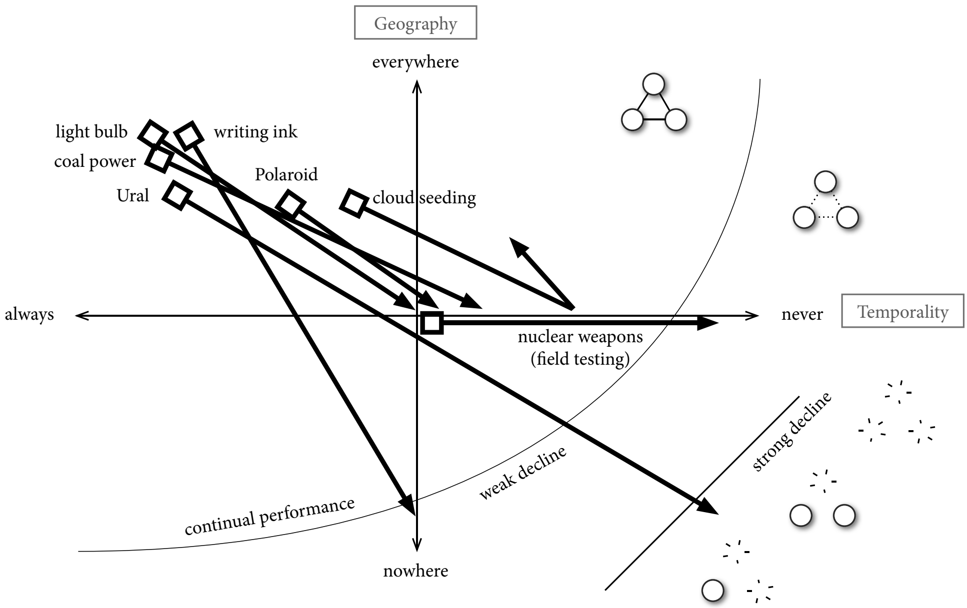


Figure 22. Sketching decline as a relationship between relative geographic and temporal intensity of performance of configuration and types of unravelling.

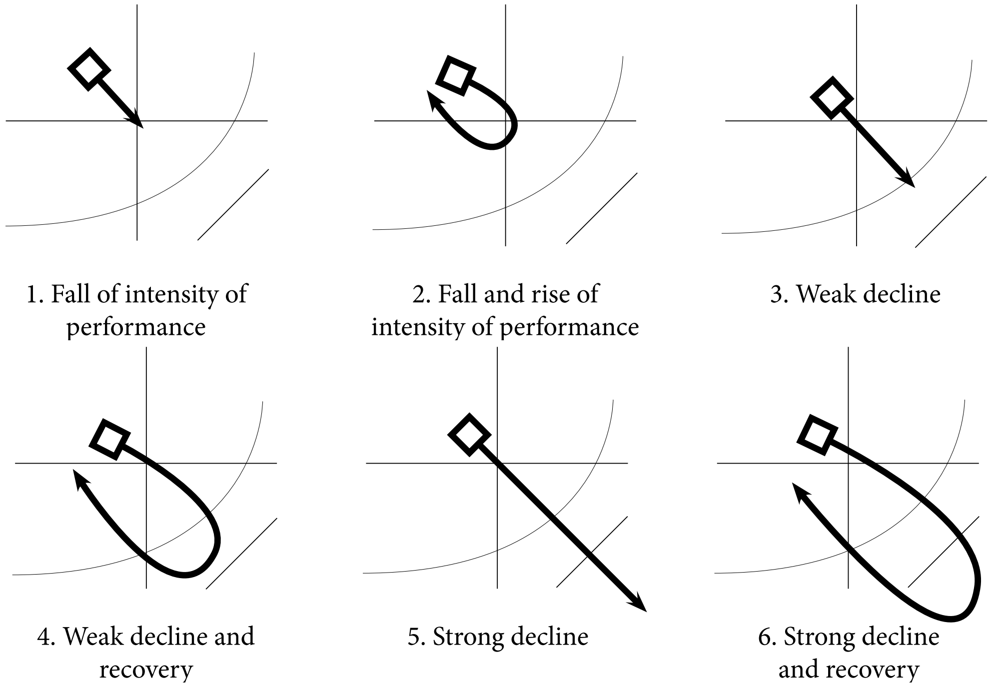


Figure 23. Five ideal-type pathways of unravelling overlaid on the axes of geography-temporality.

Figure 22 is a rough sketch for illustrative purposes, and "everywhere", "nowhere", "always" and "never" should be interpreted not as quantifiable states, but as general indicators of high or low geographic or temporal performance *in a given geographic and temporal context*. In this sense, weak and strong decline, in a given geographic and temporal context, are ideal-types rather than empirical evaluations. Other dimensions, such as the scale of industry and the policy environment, matter, of course; they are not foregrounded in the figure, but are indicated by the different states of the configuration (the three circles).

As a next step, the distinction between weak and strong decline allows me to portray unravelling as part of certain (ideal-type) pathways of socio-technical development (Figure 23). Note that in the figure the axes are geography and temporality, and the exact shape of the arrow may vary.

1. Fall of intensity of performance.

The technology is used and/or manufactured less than before, its trajectory is aimed downward. Such is the case of the incandescent light bulb (e.g. in the EU), coal-fired power plants (e.g. the UK), and the Polaroid (e.g. in the EU).

2. Fall and rise of intensity of performance.

Here the configuration remains in the 'continual performance' area of Figure 22 and no decline takes place. Many configurations, such as the majority of cases I discussed so far, end up in this state of reduced performance, fluctuating between higher and lower performance intensity (in a given geographic and temporal context, such as Europe between 1950 and 1990). One example is cloud seeding which has been seeing a comeback, as I showed in Chapter 4.

3. Weak decline.

A configuration which continues in the direction of decreased performance intensity ends up in a state of 'weak' decline in a given geographic and temporal context. Here, the technology is performed so rarely and in such a geographically dispersed way that the associations between the strands are barely there at all. The networks of producers, users and/or maintainers are significantly shrunk. One could say such technologies are on 'standby', although not gone yet. Most technologies, 'declined' in colloquial use of the word, can be placed in the category of 'weak' decline, such as nuclear weapon field testing, manually prepared writing ink, cloning, or the British bicycle lanes buried under layers of new asphalt.

4. Weak decline and recovery.

A weakly declined technology may become continuously performed again in a given geographic and temporal context. Such re-emergence could manifest in a reintroduction of technology, as in the case of vinyl records.

5. Strong decline.

When a configuration is performed with less and less intensity (relative to before), this means that one or more of the strands are unravelling. A loss of one or more would lead to a break in the 'circuit'. This is a case of a discontinuous, or 'strong' decline where work will be needed to create or re-create the missing component(s) of the former configuration.

Strong decline is more of a hypothetical category because it is hardly possible to ascertain, especially in a large geographic and temporal context, whether materials, meanings or forms of competence are truly gone and will need to be recreated (manufactured, invented, constructed, theorised, learned, etc.). But one may, perhaps, characterise a technology on its way to strong decline when it is found only in museums, e.g. the Ural computer, the linotype machine, kamikaze aircraft, stone arrowheads, medieval and antique construction technologies and other traditional crafts[74]. Strong decline occurs when associations are impossible because slippage, de-anchoring and/or unlearning are too profound (e.g. all materials are destroyed, carriers of competences or knowledge are gone, specific parts of the technology are banned from use or manufacture). After a strong decline, all that remains are dissociated materials, meaning and competences 'debris' in the form of "fossilised" (Shove & Pantzar, 2005b) rust, hints and secrets.

6. Strong decline and recovery.

Even after a strong decline, a technology could make a U-turn and re-emerge. From the perspective of the actors involved in the re-creation of materials, meanings and/or forms of competences, this pathway will probably look like the process of invention. Re-emergence in this case occurs when work has been done to (re)construct the strands and reconnect, "re-ravel" them. A weak decline is easier to recover from as to reintroduce a strand (back) to the configuration is less costly.

All three cases I have explored in detail in this book have passed through the decrease of intensity of performance. The decrease has stopped in the case of the light bulb because the ILB has found its niche in industrial applications and horticulture, as well as among people with preferences for the ILB. The light bulb can be categorised as a pathway 1 exemplar. The intensity of performance has actually reversed for cloud seeding, so it is a pathway 2 exemplar. The Ural's status could be categorised as weak decline because it is not used nor produced as prominently as before. However, the Ural has been delegitimised and for a long time forgotten, and the associated competences are gone with the people who retired and can hardly be found in books. The only intact Ural can be found in a museum and its (cultural) legacy has been largely forgotten. Thus, Ural may be better categorised as pathway 5 exemplar, or, bearing in mind the difficulties of ascertaining strong decline, at least on its way to one.

74 I thank Tatiana Koretskaya for some of these suggestions.

7.3. **Governance implications**

In this section I will focus on the governance implications of the empirical and conceptual explorations of the thesis (so, the third research question). I will start with the general lessons from transition studies and continue with the implications of my case studies.

The field of sustainability transition studies is explicitly oriented to investigate issues of transitions towards socio-economic systems that are in line with sustainability goals, such as decarbonisation. Such goals are pressing due to the observed insufficiency of current sustainability transition efforts (e.g. Delina & Diesendorf, 2013; Rogge & Johnstone, 2017; Schlaile et al., 2017; C. Roberts et al., 2018). Typically, such goals require a mix of different types of policies, attention to contexts, and engagement with a broad range of stakeholders to “nurture social acceptance, stimulate learning-by-using, forge supportive industry coalitions in favor of [transition] and compensate potential losers” (Markard, Geels, et al., 2020, p. 5). Accelerated sustainability transitions require more interventionist policies than before and a shift from “a neo-liberal policy paradigm and hands-off policy style towards […] a stronger role for policymakers in shaping markets, stimulating innovation, launching larger missions, building infrastructure, and regulating businesses” (Markard, Geels, et al., 2020, pp. 4–5).

Sustainability transitions research has established several ground rules for policy-making such as:

- policy needs to address systemic changes in current structures for both consumption and production (Kivimaa & Kern, 2016);
- a mix of policy instruments is needed (Kivimaa & Kern, 2016; Markard, Geels, et al., 2020) because (i) narrowly scoped policies do not often work and systemic changes are needed, (ii) policy-makers are dependent on firms and the wider public for legitimacy, consent, knowledge, and resources, and (iii) policy-makers are themselves part of the socio-technical system that is intended to be changed;
- four styles of policy mixes are possible depending on the style of public-private relations, which are liberal market economies (e.g. the US, the UK), coordinated market economies (e.g. the Netherlands, Germany), state-influenced market economies (e.g. France, Japan), and state capitalism (e.g. China, Russia, the Middle East) (EEA, 2017). The style influences the kinds of instruments are preferred, ranging from totally market-based (e.g. subsidies, taxes) to steering instruments (e.g. formal rules, regulations, laws) (EEA, 2017);

- transitions always involve resistance from powerful coalitions of actors with vested interests (Geels, 2014; C. Roberts et al., 2018; Stegmaier, Joly, et al., 2021);
- the envisioned processes of change need to be just on the grounds of the principles of, among other, affordability, transparency and accountability, intra- and inter-generational equity, responsibility (Sovacool et al., 2017).

Kivimaa and Kern (2016) list the following governance processes for deliberate decline of socio-technical systems:

- control policies: gradual phasing-out of sale of the system in question, introducing trade barriers and international phase-out agreements (even just as a symbolic move);
- significant changes in regime rules: structural reforms in legislation or significant new overarching laws;
- reduced support: withdrawal of discursive backing and of state R&D funding (although not necessarily regional and private funding);
- changes and shifts in social networks.

The results of these processes typically lead to de-legitimation, weakening commitment of key actors to continue supporting the socio-technical system, market decline as a result of either demand shifts or control policies, and resource demobilization (Bento et al., forthcoming).

The existing literature addresses the general spectrum of phase-out and decline policies such as (phased) tightening of regulations and bans, removal of subsidies, introducing incentives which make the targeted technology less or more attractive, and reactive and active support policies (Geels et al., 2019). More reactive policies entail financial compensations (e.g. redundancy payments, early retirement benefits) and other safety nets for workers, compensations to firms and communities for losses, state subsidies of company liabilities. More active policies entail retraining and other labour adjustment programmes, financial assistance to relocate, wage subsidies, assistance to finding new jobs, redevelopment programmes for the affected regions (e.g. investment in infrastructure), stakeholder consultations, subsidies or tax incentives, assistance to firms with upgrading technologies and practices and reorienting towards new technologies and markets.

The findings of the present work can offer practical usefulness for public or industrial policy. In terms of the proposed unravelling approach, this implies that for a deliberate decline of an established technology, governance actors may need to support the unravelling processes in meanings, materials and forms of competences. The unravelling may be pursued via awareness raising, resource management, regulation and monitoring, leaving room for those with interest to continue working in a niche (in which case technology impacts could perhaps be better controlled). For this, though, governance actors would need to carefully map the given technology as a configuration of meanings, competences and objects and infrastructure, and carefully examine how entangled and diverse these are. My findings in this thesis suggest that when the 'strands' are unique to the given technology, it might be safe to support a contraction of one of these unique ones, aiming for the less diverse strand. The weakened strands may be more susceptible to substitution with more desirable (sustainable) ones, thus, avoiding the need to phase-out the technology. In fact, technological decline policy does not have to mean nor should it necessarily aim for absolute eradication. The downside is a potentially easier re-emergence.

Inversely, a technology in decline whose revival is desirable (e.g. crafts or bicycle lanes) should be supported in all three strands, or at least the weakest ones, in an attempt to increase the geography of its use and/or production. Much investment may be needed to restore or recreate a strongly unravelled technology.

That being said, policy-makers should not be overly ambitious about the scale of the system they are aiming to phase out, or at least be conscious of the differences between systems on the one hand and commodities on the other. For example, a specific model of a smartphone (i.e. commodity) is easier to phase out (even though it, being a commodity, will likely be quickly replaced) than the smartphone as a communication technology.

In drawing the governance implications below, I offer a particular interpretation of findings of the empirical cases studied in this thesis. Most of them align with the above broad principles and insights from prior studies, but some are more specific and will have limited applicability to certain contexts and styles of governance, as they may require a lot of adaptation work. The specific insights are the following:

1. It is helpful to view a given technology, as just discussed, as constituted of three interlinked strands: materials, meanings and forms of competences. My findings show that strands with less variety than in prior periods are less resilient to intervention and so should be targeted. The findings show that the unravelling of even one strand is enough for the decline to start.

2. As seen in the cloud seeding case, strong, independent investigative media, as well as a receptive and active parliament, may be key for delegitimising a technology.

3. As seen in the ILB case, these may be equally important:

    a. a coalition of government(s), industry and (environmental) NGOs in favour of phase-out;

    b. strong labour unions that can cushion the damage of technology's phase-out for workers, but not too strong to stop or reverse the phase-out;

    c. supporting and/or promoting alternative existing or nascent desirable (e.g. more sustainable, ethically acceptable or less harmful to health) solutions or technologies that fulfil the same need as the phased-out technology. This could be done via offering subsidies, tax incentives, direct funding of R&D and (re) training, public relations efforts, and compensations to actors who stand to lose from technology's decline;

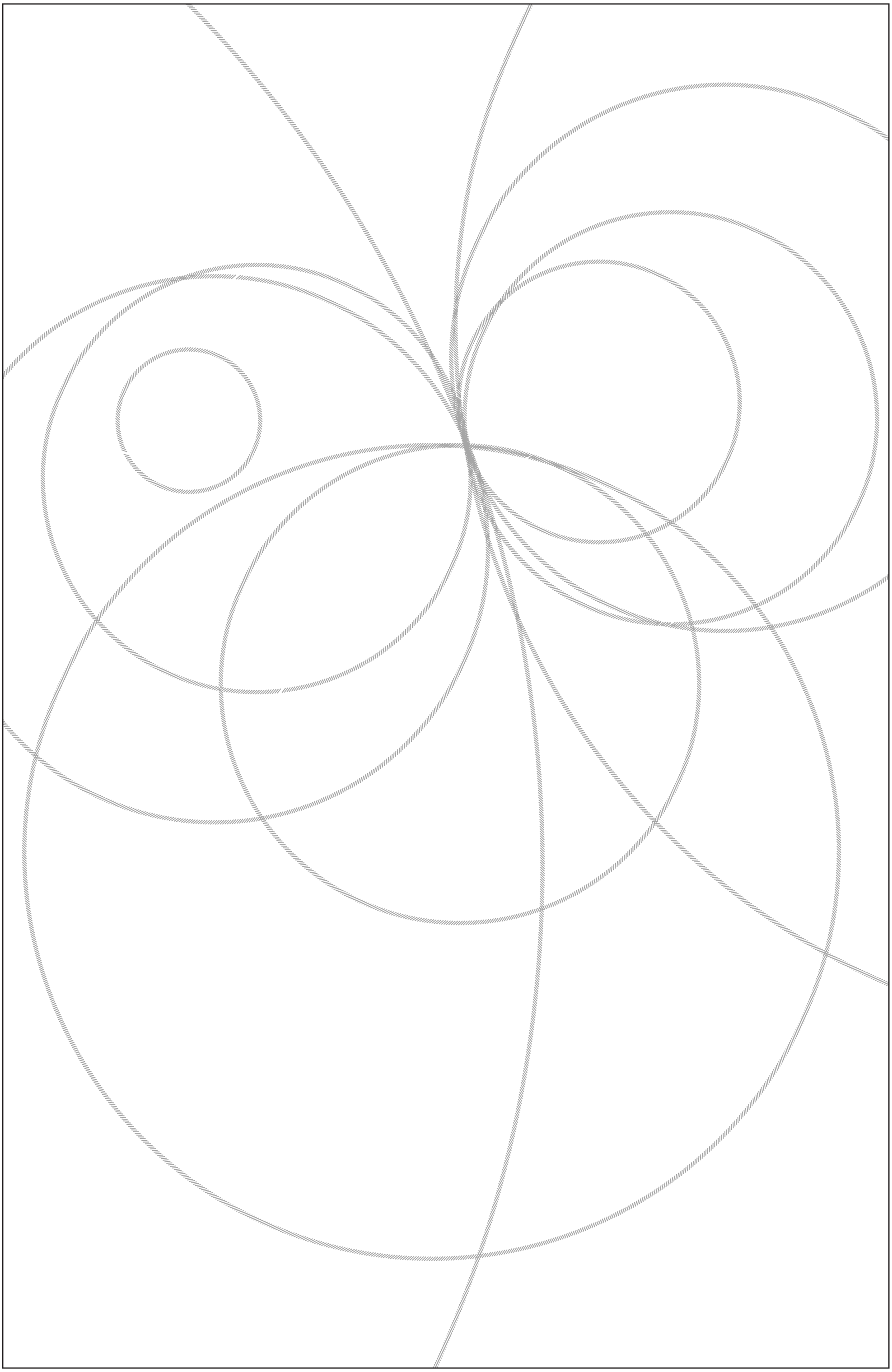
    d. an insight which goes against the rationale of transparency and accountability of governance has to be mentioned because of its efficacy in situations where public resistance is not expected: ignoring or dismissing public concerns (the so called "decide-announce-defend" (DAD) policy).

4. As seen in the Ural case, the absence of free market relations may hasten the phase-out, as technology developers had no personal financial incentive to keep supporting it.

5. As seen in all three cases,

    a. trade instruments and international agreements may be used to leverage other countries' decline of the given technology;

    b. a more just decline is one in which the formerly useful knowledge and skills are mobilised in other fields and technologies (albeit at the expense of irreversibility of the decline).



Chapter 8. **Conclusion**

8.1. **Summary and implications**

In this final chapter I collect all the threads of the work that I've conducted in the preceding chapters towards answering my research questions: how to characterise, understand and intervene in the processes of technological decline? I started with reviewing the literature (Chapter 2) and with formulating a conceptual framework based on STS and sustainability transitions literature, which helped me to analyse my three empirical cases. I found that most studies suffer from an emergence bias, i.e. a tendency to focus conceptually and empirically on the beginning of technologies' life cycle. This leaves the later stages largely underconceptualised. My conceptual starting point, drawn from the literature, was to view technology as a socio-technical configuration of entangled socio-material 'strands' (materials, meanings and forms of competences). Their dissociation, or unravelling, is the mechanism behind decline. Decline, I found, is not irreversible and the strands can be reconnected by actors, and this can lead to re-emergence. The dynamics of unravelling depend on the resilience of the configuration and its variety of socio-material entities.

With each case I gained additional insights on how to characterise decline and how to adjust and further develop the framework. Based on the framework, I proposed an approach in Chapter 7 to study future cases of decline and represent the constituting processes. The unravelling approach identifies processes within each strand and offers six ideal typical pathways. The proposed approach will need further fleshing out and adjustment, but already holds, I suggest, five benefits for the field of STS and sustainability transitions.

First, in alignment with the symmetry principle, I propose with the unravelling approach to focus more explicitly on a given technology's 'end of life' to counteract the prevalence of studies on emergent technology. Second, I propose that a pragmatic analytical distinction between social and material processes within decline are useful to show their entangled dynamics (cf. H. Klein & Kleinman, 2002; Geels, 2007a). Third, I propose to focus more on high empirical granularity of analysis and on generation of rich case descriptions that are used towards middle-range theorisation (cf. Frickel & Moore, 2006; Wyatt & Balmer, 2007). Fourth, I propose to focus more on the analysis of processes outside of market and industry dynamics, since labs, public places, parliaments, newsrooms, kitchens and other sites are equally important (cf. Polanyi, 1944; Hughes, 1994; Latour, 2007; Soete, 2011; Upham et al., 2015). And fifth, I propose to focus more research (including historical) on the analysis of issues related to acute societal and policy relevance, such as the climate crisis.

The larger scope of the present work is linked, but not limited to the climate crisis. As I noted in Chapter 1, there is an urgency to navigate this crisis in both mitigation (phasing out unsustainable technologies) and adaptation (phasing out or transforming infrastructures that are no longer fit for a globally warmer world and one with a higher sea level); a need to ensure, if at all possible, long-lasting abandonment of phased-out technologies (such as chemical weapons); a need for care and prevention of decline that is actually unwanted for ethical, environmental or other reasons (e.g. traditional crafts, traditional farming, cycling). But the study of decline of established systems could be equally useful for dealing with ethical questions, for instance, responsibility in deliberate decline, nuclear weapons field testing, mass production, surveillance, and more (Escobar, 2015). Further research could investigate the connection of decline and phase-out with (post-)colonialism, imperialism and other forms of exploitation, both to study the caused decline and the ways to cause decline of these forms.

Since the presented unravelling approach stems from STS and transitions literature, it draws, just like this literature, from ecology, complex systems theory, resilience research, ecosystem services, adaptive governance, institutional theory and more (Loorbach et al., 2017; Geels, 2020a). There is room for more connections and adjustments from those literatures for empirical work, theorisation and design of policy recommendations.

The current research may also be linked to literature beyond STS and transition studies, such as sociology of loss (Elliott, 2018) and sociology of retreat (Koslov, 2016). In the former, the interest is on who becomes “stranded or displaced, how, and with what effects; how loss can be designed by social actors and institutions; and the contradictions that may arise” (Elliott, 2018, p. 307). In the latter, the complexity and ambivalence of retreat from “particular places but also from particular ways of life that are […] proving unsustainable” (Koslov, 2016, p. 381) is studied. According to Liz Koslov, without “taking retreat seriously as a concept, strategy, and existing practice, meaningful conversation and action around climate change adaptation will continue to prove illusory” (Koslov, 2016, p. 362). Future STS and transitions research could ask (more) questions raised in this literature.

Politically, a legitimate question may be asked: why should anyone support such a radical solution as (deliberate) technological decline, instead of transforming, changing a given technology into something more acceptable (e.g. elimination of toxic material, restriction of application fields). I argue that, indeed, not every technology needs to be fully phased-out, but my findings point to the danger that a transformed undesirable technology will re-emerge in the future, as the case of cloud seeding shows. Sustainability transitions need acceleration exactly because transforming, nudging and offering alternative technologies via the market and more innovation is proving insufficient (see Chapter 1). As shown in Chapters 1 and 2, more radical, disruptive measures are becoming necessary as the climate crises worsens, biodiversities collapse and socio-economic tensions worsen. Phasing out does not mean that the need which the technology in question is fulfilling will be gone. Instead, room would be made for alternative, hopefully, more sustainable solutions.

Developing this argument further, it seems pressing for a sustainable future that designers, investors, end users, policy-makers and other stakeholders of a given technology question what this technology helps to achieve and for whom. Do we really need what a given technology offers or, at least, could we not substitute the technology with something that fulfils this need better? Katinka Waelbers and Tsjalling Swierstra (2014) in their study on how new technologies relate to the 'good life', propose two specific questions for governance actors of new technologies, but they seem equally useful to ask regarding existing technologies:

1) How does the technology mediate our relations (a) to the parties that are affected by our actions, (b) to the consequences of our actions, and (c) to the beliefs and practices that constitute our conceptions of the good life;

2) How does the technology mediate our beliefs about (a) how the world is, (b) how we can act in that world, and (c) how we should act in that world?

Suggestions to appoint spokespersons for future generations (UN Secretary-General, 2013; Balch, 2019) and for nature itself (Stone, 1972, 2010) might help with answering these questions, as well as with strengthening grounds for legal action, which has been on the rise (Viglione, 2020; Schiermeier, 2021).

Typically, policy-makers' focus of nurturing novelties overshadows a focus on initiatives and ongoing decline of technologies. Such overshadowing might be fuelled by a utilitarian logic of rational progression towards more efficiency. The assumption is that superior technology substitutes the inferior one and the latter then proceeds to fade away, or, as Lindqvist hyperbolised: "all bicycles [were] thrown in the ditch and all horses shot when the first Model T rolled off the assembly line" (Lindqvist, 1994). However, there has been a rise in deliberate decline policies since the late 2010s (Green, 2018). Perhaps, actors start recognising that, according to Heyen and colleagues, a "regulated phase-out can offer legal as well as planning certainty for business, workers, consumers and infrastructure planning" (Heyen et al., 2017, p.

327). In terms of the unravelling approach, this implies that for a deliberate decline of an established technology, governance actors may need to support the unravelling processes in materials, meanings and forms of competences.

8.2. **Limitations and outlook**

A few closing words on the limitations of this thesis. First, the conceptual choices. The separation of technology into three 'strands' can be questioned, as well as the ontological status of these strands. Specifically, my finding regarding the prominent role of meanings in nearly all presented cases could imply that the separation was invalid in the first place. I would challenge such possible critique by reminding that a distinction between the three strands is analytical; they were never supposed to be exclusive and non-overlapping. Of course technology and society are deeply implicated, but the separation is no more than an analytical attempt to navigate the complexities in *what causes* unravelling and in *how* it *proceeds*. Similarly, the somewhat uncompromising collating of different things into the three strands can be questioned. Indeed, this is a radical simplification inherited from literature on the dynamics of social practice theory (see Chapter 3). I tried to alleviate this by clearly operationalising in Chapter 3 what these strands constitute of and maintaining internal consistency between cases by strictly adhering to this operationalisation. Additional research could no doubt improve the proposed approach on both accounts.

Second, the role of actors, structures, infrastructures, levels, knowledge paradigms and ideologies could have been studied more systematically in this work. Future research could go beyond the implicitly flat ontology of the present work and analyse how the different levels of aggregation matter in processes of decline. It could also be productive to study local situations from the unravelling perspective (e.g. city or regional bans).

Third, the proposed approach is limited in its ability to prescribe how to trace the 'same' technology. A technology changes with time, thus how to know when change stops and unravelling begins? In addressing this limitation, I have followed the rationale in transition studies where the responsibility to define the object of analysis and keep it in focus lies with the analyst (Geels, 2011; Stirling, 2019). As discussed in each empirical chapter's methodology section, I have identified the beginning of unravelling as a decrease in output of production and/or use of the given technology, an approach that I further specified in Chapter 7.

Fourth, this work is also limited in its meta-theoretical comparison with other approaches and frameworks. Although a comparison of this book's findings with findings from other literature would have been beneficial for the field, it was beyond the scope of present explorative work and could be taken up by future research.

Fifth, transition studies stem from a systems perspective. By definition, commodities, or end products, are not resilient to decline, not obdurate; to phase out a commodity is fruitless because it can be, by definition, replaced. This is why destabilisation and phase-out of *systems* is needed. While I do study configurations in this work, I did not focus on what is typically understood as systems in transitions literature, i.e. configurations that provide societal functions such as mobility, food or energy. The proposed approach would benefit from exploration of such cases, but decline of configurations smaller than systems is (also) an occurring phenomenon worth studying, as elaborated in Chapter 1.

Although I have not studied these larger socio-technical systems, the unravelling perspective might be applicable to study them too. It is then the responsibility of the analyst to delimit the unit of analysis and maintain it throughout the study. Gregory Unruh (2002) writes that discontinuity on a sub-system level (e.g. internal combustion engine and fuel cells) can look like continuity on a system level (transportation). This line of thought may be continued by observing that higher levels of aggregation (e.g. transportation) have more inertia and thus are significantly less susceptible to decline. As mentioned in the preceding chapter, a specific model of a smartphone is easier to phase out (even though it, being a commodity, will probably be quickly replaced) than the smartphone as a communication technology.

Lastly, although I was motivated to understand decline as a problem of sustainability and decarbonisation within the larger challenge of the climate crisis, most of the discussed cases, except the light bulb, coal power, and, perhaps, cloud seeding, only indirectly relate to sustainability. This, however, should not disqualify the observed patterns, and, if anything, expands the programme of understanding and engaging with decline into issues beyond sustainability and decarbonisation. It is a task of future research to study more cases of decline of various technologies for the sake of sustainability and beyond.

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Impact paragraph addendum

What is the main objective of the research described in the thesis and what are the most important results and conclusions?

The main objective of the research is to explore how to characterise, understand and intervene in the processes of technological decline. Existing studies tend to focus conceptually and empirically on the beginning of technologies' life cycle. This leaves the later stages largely underconceptualised. The larger scope of the present work is linked, but not limited to, the climate crisis. There is an urgency to navigate this crisis in both mitigation (phasing out unsustainable technologies) and adaptation (phasing out or transforming infrastructures that are no longer fit for a globally warmer world and one with a higher sea level). But there is also a need to ensure, if at all possible, long-lasting abandonment of phased-out technologies (such as chemical weapons), and for care and prevention of decline that is actually unwanted for ethical, environmental or other reasons (e.g. traditional crafts, traditional farming, cycling).

In the dissertation decline is explored as "unravelling", or dissociation, of entangled socio-material aspects that constitute a technology: materials, meanings and forms of competences. They "unravel" as competences become less used, materials are harder to come by, and the meanings turn outdated. Six ideal-type pathways for the outcome of unravelling are formulated, some of which result in decline, while others in its reversal.

What is the (potential) contribution of the results from this research to science, and, if applicable, to social sectors and social challenges?

The scientific contribution of the present work lies in the proposed unravelling approach which may help study future cases of decline, and in the proposition for STS and transitions studies to counteract the prevalence of studies on new and emergent technologies and focus more on technologies' 'end of life'. I also propose that STS scholars should not shy away from middle range theorisation in favour of exclusively exploring the messiness of case studies.

The presented research can offer practical usefulness for public or industrial policy. For a deliberate decline of an established technology, governance actors may need to support the unravelling processes in meanings, materials and forms of competences. The unravelling may be pursued via awareness raising, resource management, regulation and monitoring, leaving room for those with interest to continue working in a niche (in which case technology impacts could perhaps be better controlled). For this, though, governance actors would need to carefully map the given technology as a configuration of meanings, competences and objects and infrastructure, and carefully examine how entangled and diverse these are. My findings in this thesis suggest that when the 'strands' are unique to the given technology, it might be safe to support a contraction of one of these unique ones, aiming for the less diverse strand. The weakened strands may be more susceptible to substitution with more desirable (sustainable) ones, thus, avoiding the need to phase-out the technology. In fact, technological decline policy does not have to mean nor should it necessarily aim for absolute eradication. The downside is a potentially easier re-emergence.

Inversely, a technology in decline whose revival is desirable (e.g. crafts or bicycle lanes) should be supported in all three strands, or at least the weakest ones, in an attempt to increase the geography of its use and/or production. Much investment may be needed for that.

To whom are the research results interesting and/or relevant and why?

This research may be of relevance to scholars, policy-makers working on issues of sustainability, technology ethics and industry policy in general, and anyone else curious of thinking about why some technologies remain abandoned and do not return (such as an old computer line from the 1960s), while others do (such as cloud seeding for geoengineering or the vinyl record); how to prevent or slow down the decline of desirable technologies (desirable for ethical, environmental or other reasons, e.g. traditional crafts, traditional farming, cycling); and of the dynamics of decline of technologies in general. Expertise in these topics is growing in importance as we progress deeper into the climate crisis.

In what way can these target groups be involved in and informed about the research results, so that the knowledge gained can be used in the future?

During the four years leading up to this book, I have spoken about the present research (for lengths between several minutes to half an hour) to more than a dozen different audiences ranging from the Dutch national STS graduate school WTMC to international scientific conferences to a TEDx event. I have also published two academic papers included in the present book in open access in highly-ranked journals, and two more are on their way. This book itself is a way to communicate my research, as is the press release that followed it. Lastly, I always got back to my informants to share the results of the work that they have contributed to.

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[75] Ivan Koretskiy

About the author

Zahar Koretsky (Corețchii) is a Russian-Moldovan born in Tiraspol, Moldova. In his first career, Zahar worked as a written press business reporter after obtaining his Bachelor degree in Journalism and Mass Communication. Looking to expand his horizons, he applied for and won a scholarship for a joint Master programme in ESST (European studies in Society, Science and Technology) at Maastricht University and the University of Oslo. During his Master studies Zahar spent a semester at the TIK centre in Oslo, where he wrote his thesis on innovation management in firms, studying the Norwegian telecom Telenor. He later spent several months as an intern at the Rathenau Institute in the Hague where he learned about Technology Assessment.

After his studies, always passionate about sustainability and climate, Zahar became a research assistant at Radboud University where he conducted research on the EU's R&D efforts in mitigating climate change. For this work he attended the 2015 Paris climate conference COP21, where he presented his work-in-progress.

In 2017 Zahar embarked on his PhD track at Maastricht University, which resulted in his dissertation titled *Unravelling: The Dynamics of Technological Decline*. In the four years of his PhD trajectory, Zahar published three academic articles and several op-eds in *Medium*, organized a conference panel (on how technologies 'die'), earned the University Teaching Qualification, as well as the Dutch national graduate school WTMC diploma, gave numerous talks about his research at conferences, relevant research groups across Europe and a TEDx event, gave a newspaper interview, became an active member of the STS and sustainability transitions community, grew his Twitter presence, and learned Dutch to a good level. In his appraisals, Zahar is noted for his work independence, ambitiousness, orientation on result, broadness of research interests, and dedication.

As of the year 2022, Zahar continues the work started in his dissertation at the Interdisciplinary Laboratory for Science, Innovation and Society (LISIS) at the French Research Institute for Agriculture, Food and Environment (INRAE) and Gustave Eiffel University in Paris in collaboration with Bruno Turnheim.