IRREVERSIBLE NUCLEAR DISARMAMENT

Researching the Decline of Large Socio-Technical Systems using Science and Technology Studies Tools

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York IND Working Paper#6

March 2024

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March 2024

University of York, UK

Introduction

This is report is the outcome of a workshop on the application of Science and Technology Studies (STS) methodologies to the study of irreversibility and nuclear disarmament. It is part of a project on 'Irreversible Nuclear Disarmament' funded by the UK Foreign, Commonwealth and Development Office (FCDO). The first stage of the project in 2022-23 resulted in a report on what 'irreversibility' might mean in practice, with irreversibility understood not as a fixed end state, but as a spectrum on which a state can more or less easily reverse a disarmament process, depending on how deep and broad that process has been. The report drew on Science and Technology Studies to conceptualise irreversibility as the 'unmaking' of a nuclear weapons complex understood as a large socio-technical system and the STS scholarship on technology phase-out, tacit knowledge, and the destabilisation and discontinuation of socio-technical systems. The next phase of the project sought to develop a richer understanding of how scholars have developed and applied theories of innovation, governance, phase-out and system change from STS and actor-network theory in order to inform a detailed study of what 'unmaking' a nuclear weapons complex would entail.

The report has four parts comprising a workshop report and three deeper dives into specific approaches:

Part One: A report of the workshop on Science and Technology Studies research and studying irreversibility in nuclear disarmament.

Part Two: Exploring stability and system development in a disrupted Large Technical System: the case of railway privatisation in the UK (Kat Lovell)

Part Three: A methodology for researching technological decline from a socio-material perspective (Zahar Koretsky)

Part Four: The practical application of systems mapping (Nick Ritchie)

Part One: How can Science and Technology Studies (STS) help us research irreversibility in nuclear disarmament? A workshop report

The workshop of which this report is an outcome brought together nuclear policy experts who have engaged with STS together with STS scholars from other fields in order to unpack how STS theories and methodologies have been applied to the study of change, transition and breakdown in large socio-technical systems, and how STS theories and methodologies can be applied to the study of nuclear complexes and their 'unmaking'. Participants included experts that have applied STS theories and methodologies to the study of military and civil nuclear complexes as well as non-nuclear areas, notably transport systems and energy systems and the phase out of specific technologies.

Three themes emerged from the discussion around which this report is organised:

1. Methodologies for studying continuity and change in large technical systems (LTS).
2. Explanatory concepts for thinking about and studying continuity and change in such systems.
3. How the concepts and methodologies apply to, and inform, the notion of irreversibility in relation to nuclear disarmament.

Methodologies for studying irreversible discontinuation of LTS

An important outcome of the workshop discussion was a general consensus that there is no single ready-made STS methodology that can be applied to the study of the discontinuation and decline of LTS. Participants reported that they have had to combine an eclectic range of STS perspectives, for example a multi-level perspective, a lacking governance perspective, governance and action perspective, a policy negotiation perspective, and the three streams model. Researchers have combined these approaches in different ways to focus on different levels of analysis, for example micro-level changes, at an organisational level, the processes of policy negotiation, and governance systems in order to unpack technical, historical, cultural, and governance properties and dimensions. The reason for this eclecticism is because STS researchers tend to study very complex, messy phenomena.

Participants characterised the study of change in large socio-technical systems as a creative process that involves inventing methodologies and concepts through the research process and drawing on a range of theoretical tools under the umbrella of STS to develop new descriptions, typologies and explanatory frameworks. This tends to involve a continuous tracing of things as they develop through processes of renewal and decline in order to understand how things got to be as they are - how they became "configurations that work"[1] - and how they could have been otherwise. Such social-material configurations take a form that fulfils a function that can become embedded, legitimate, durable and open to constant development and reproduction. STS scholars generally seek to understand what such configurations are, the basis upon which they were produced and are reproduced, the extent to which they are understood to 'work' by whom and for what purpose, and processes of resistance and change. This involves the explanatory power and inertia of materials *and* ideas and culture and therefore taking seriously how, where and why the social/ideational and technical/material intersect and are reproduced in order for the system to work.

A number of participants drew on the multi-level perspective (MLP) developed by Frank Geels in the 1990s to analyse transitions in large socio-technical systems with a focus on technological regimes, alternative spaces (or niches) and the 'socio-technological landscape' within which technological regimes are situated. These are conceptualised as 'nested' insofar as niches are nested within regimes that are nested within landscapes. This approach incorporates broader processes of change within the historical context in which technologies emerge, become embedded and then decline. Geels and others argue that a multi-level perspective is necessary because change in large socio-technical systems is complex and multi-causal.[2] STS scholars have also drawn on transition studies and institutional theory to examine how large socio-technical configurations become institutionalised, how they are stabilised and destabilised, and how they erode and sometimes go extinct. This highlights the importance of looking at multiple dimensions of change in order to understand transition, evolution and decline, for example policy, socio-technical, and economic dimensions.

Understanding the demise of an LTS is a relatively new research area that asks how processes innovation and embedding of a socio-technological system after processes of destabilisation and decline. This work suggests that a process of 'de-institutionalisation' will *not* be the reverse of institutionalisation. Moreover, it is clear that there is much work to do to understand what actually happens between invention and uninvention, innovation and exnovation and the timelines of these life cycles. Other researchers have explored repeating historical sequences of reproducing and managing core components of an LTS through case studies and archival research.

All of these approaches are underpinned by different theories of change, for example the theory of change through niches and how in transitions research there is a tendency to view change as something that happens when a niche reaches a particular point of maturity and represents an alternative that cascades through a system. This might be

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[1] Rip, A. & Kemp, R. (1998). Technological Change. In S. Rayner, E.L. Malone (Eds.) *Human Choice and Climate Change: An International Assessment*. Batelle Press, 327–399.
[2] Geels, F. (2005). *Technological Transitions and System Innovations: A Co-Evolutionary and Socio-Technical Analysis*. Edward Elgar: Cheltenham.

caused by a combination of technology, history and cultural dynamics that creates conditions of possibility for change processes to unfold and take root. Here, researchers have examined the UK nuclear industrial base as a LTS encompassing civil and military nuclear complexes and the relationships between them. They have done so through process tracing, case studies, snowballing and opportunism. The latter acknowledges the importance of contingency and taking advantage of opportunities when information emerges from the cloak of secrecy that covers many areas of the UK nuclear enterprise. This has involved studying industry-scale materialities, supply chains, skills flows, recruitment pathways, tacit knowledge, the social construction of rationales for multi-billion dollar flows of revenues, and the political asymmetries at the scale of the entire formation. Tracing money flows can be particularly useful to understand conditions of possibility for change in LTS.

Other scholars highlight a methodological focus on the functions of an LTS in relation to processes of change. For example, the core function of an LTS might be the production of energy. This core function will continue, but the particular configurations that produce that function can change, for example from fossil fuels to renewables. STS scholars have therefore looked at empirical indicators of the decline of a particular substance or a particular technology *within* a LTS rather than change in the underlying *function* of a socio-technical system. For example, every element of a socio-technical system could change but the core function could remain. Moreover, significant change *of* a LTS can happen *through* accumulated small changes *within* the LTS. Functions can also be the output of many discrete but interconnected systems rather than one large socio-technical system, which opens up methodological questions about how we define and study LTS, their functions and interlinkages and where and why we draw empirical and conceptual boundaries around an LTS. Based on this, instead of unmaking a single socio-technical system, we might think instead of phasing out certain capabilities of one or more LTS by severing links between sub-systems within an LTS and/or links between 'separate' large socio-technical systems.

Concepts

The openness and inventiveness of STS methodologies has generated a wide range of concepts to examine continuity and change in LTS.

Power, agency and structure

Workshop participants explored the different ways in which STS research privileges agency and structure and highlighted a tendency for STS to over-emphasise notions of agency (for example the agency of governance actors, system builders, stakeholder coalitions, policymakers and so on) at the expense of structures (material, institutional ideational and so on). If discontinuation and irreversible change are *systemic* phenomena, and systems are condensed out of more *distributed structures*, then an agency-centred approach will be less useful in studying processes of change. This can necessitate critical reflection on what counts as 'the system', 'the network', 'the regime' and so on that captures what is being studied. Here, the emphasis is on comprehending and interrogating deeper and more expansive configurations that sustain a stabilised and therefore make possible a 'constellation' of practices. For nuclear weapons complexes, the means being attentive to what it is that stabilises nuclear infrastructures and what it is that nuclear infrastructures condense out of, for example wider systems and structures of colonial modernity, patriarchy, militarism and capitalism.

A helpful distinction was also drawn from scholarship on sustainability transitions, transformative governance and transformative change between first-order causes and second-order drivers of change in relation to agency and structure. For example, on biodiversity loss the first-order causes are destruction of biodiversity on the ground whilst second-order causes are the conditions of possibility for the destruction, for example certain values, consumerism, coloniality and so on.

This means paying attention to power and privilege, something that some participants argued STS approaches often overlooked. Understanding asymmetries of power in producing and reproducing LTS and the framing of what it means for a configuration to 'work' is important. The question of where power sits in socio-technological systems and drivers of and processes of change is, arguably, central to the study of LTS formation, momentum, reproduction and decline. Power and power relations are understood here in multidimensional ways and surfaced through the study of actors and coalitions, resources, rules of the game, policy discourses and so on. STS cases studies highlight the discursive power of different actors competing to fix a particular concept in specific ways, for example 'preservation' (of nature vs. of the economy in the case of resistances to the coal industry in Germany by environmentalists).

STS scholars have also looked at the role of forming, mobilising, and resourcing transnational advocacy networks to drive change processes, for example mobilising environmental and health NGOs against well-financed industry lobbyists in the EU process to ban the incandescent light bulb. Understanding the formation of networks, information flows, knowledge production and political advocacy can be an intrinsic part of STS case study, and activists involved in change processes can be crucial sources of knowledge.

For some, this includes study of the power of ideology, for example in terms of an ideological commitment of the UK state to retain a civil and military nuclear complex, but also the ways in which an ideology of privatisation has unintentionally destabilised the civil nuclear complex because of the vast levels of investment required and the challenges of cementing a sustainable funding model. This highlighted the importance of studying change in LTS through destabilisation generated by unintended consequences.

Tacit knowledge

Tacit knowledge[3] is an important component of LTS and how we think about the possibility of continuity and change, particularly the role of tacit knowledge and expertise in sustaining an LTS or aiding its decline. Participants noted that expertise and the population of people that has the ability to sustain these kinds of large technological systems is an issue that cuts across the study of large socio-technical systems.

A study of tacit knowledge and the UK nuclear weapons complex shows that claims were made by nuclear weaponeers about how much knowledge was required to sustain a nuclear weapons capability and the material capabilities, resources and staffing levels needed to embody that knowledge. This was a cyclical process in the UK in which concerns about the fragility of the nuclear weapons complex repeatedly surfaced with the ebb and flow of nuclear weapon design and production. The argument was that the nuclear weapons research establishment at the Atomic Weapons Establishment at Aldermaston would not be able to develop the next generation of nuclear weapons if required to do so, or even maintain the current stockpile without a minimum level of staffing, capabilities and resources. However, these claims could not be subjected to external validation because the wider UK government lacked the expertise and tacit knowledge to interrogate questions of how much knowledge was needed for particular weapons research projects. This is because the expertise to do so resided almost exclusively within the institution itself. Agreeing an appropriate level of resources and people was consequently a contested process within the UK in which expertise and tacit knowledge played a significant role in shaping the parameters of debate.

From this experience, we can infer that knowledge management practices in a transition from a nuclear-armed to a nuclear-disarmed state will be guided by the weapons production complex and the requirements to sustain categories of explicit and tacit knowledge over the course of this process (which could be many years or even decades) and that these requirements and resources will be contested within the state and without, with contestation circumscribed by limited levels of knowledge outside the weapons production complex, especially tacit knowledge.

The challenge of *capturing* tacit knowledge was also discussed. For example, the US Lawrence Livermore National Laboratory (LLNL) tried to overcome the problem of vanishing knowledge when parts of the workforce retired by recording retirees talking about their work on the basis that this would capture more information than just a written report. This is, in part, because written reports were often moved around and there was no single archive to keep track of them. The success of these techniques to preserve knowledge, which would otherwise have to be reinvented, was mixed. This is

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[3] This is the type of knowledge that is not explicated but acquired through experience and the practical craft of 'doing' rather than 'explicit knowledge' acquired through documents, technical manuals or instruction. Collins, H. (2010). *Tacit and Explicit Knowledge*. University of Chicago Press: Chicago.

evidenced in challenges faced by US national nuclear laboratories with re-manufacturing weapons components when original specifications cannot be located. A major challenge has been sustaining old computer systems given the difficulties of starting anew with modern hardware and software.

It was noted that shortages of critical expertise in the UK nuclear weapons programme, especially the artisan and specialised crafts needed to build and maintain weapons and infrastructure, was as much a problem as material shortages and imposed major and potentially existential delays to the UK Chevaline warhead programme in the 1970s. The challenges of sustaining both civil and military nuclear expertise in the UK through cycles of investment and construction emphasises how fragile a nuclear weapons complex can be.

The discussion delved further into the theme of knowledge production and methodology, in particular the challenge of secrecy and manipulation in studying nuclear LTS. Peter Gallison's essay on the vast storehouse of secret knowledge was referenced in relation to military-industrial complexes and the politics of access to such knowledge in order to *do* STS analysis and incentives to self-censor in order to gain access.[4]

Life cycles of mature LTS

Participants highlighted the importance of Thomas Hughes' work on studying more mature LTS in relatively stable situations. He provides useful concepts for thinking about socio-technical systems, such as momentum, systems building and reverse salients.

Momentum refers to the ways in which an LTS becomes embedded and resistant to change through path dependencies and 'lock-in'. Momentum can increase and decrease through the actions of different actors in different places through exogenous shocks like war, social and regulatory movements, and technological change. Sovacool, Lovell and Ting's cycle of LTS that builds on Hughes' was referenced: this involves phases of 1) invention and development; 2) expansion and adaptation; 3) system growth; 4) momentum and path dependence; 5) technological style; 6) reconfiguration; 7) contestation; and 8) stagnation and decline.[5] This raises questions about whether empirical case studies of contestation, stagnation and decline can reveal patterns of practical reversibility and irreversibility.

Path dependencies were identified in studies of nuclear complexes, but also in transport complexes, for example in studies of rail privatisation in the UK. These were identified

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[4] Gallison, P. (2004). Removing Knowledge. *Critical Enquiry*, 31, 229-243.
[5] Sovacool, B. K., Lovell, K., & Ting, M. B. (2018). Reconfiguration, Contestation, and Decline: Conceptualizing Mature Large Technical Systems. *Science, Technology, & Human Values*, 43(6), 1066-1097.

as interdependencies of technologies and practices and the processes involved in running the railways that become deeply embedded and entangled thereby increasing the difficulty of introducing new governance systems. Other participants noted that path dependency can quickly embed a significant *change* rather than embeddedness, for example path dependency took root very quickly in the nuclear disarmament process in South Africa in the early 1990s.

The concept of 'system builders' refers to the core actors (individuals, organisations, etc.) that design and use an LTS. LTS can change as system builders adapt to changing circumstances and new system builders emerge. Participants drew on Hughes' influential book *Networks of Power* (1983) in which he explores the role of 'system builders' and theorises the concept of technological systems within a socio-historical context. He traces the development of electricity networks as socio-technological *systems* in the US and Europe and how this unfolded through (and required) a coalition of entrepreneurs, politicians, and engineers that created "not just technical infrastructure like power lines but also the capital, political support, market demand, and values that help enable and perpetuate that system".[6]

Hughes says little about little about the decline of LTS and here workshop participants referenced Frank Geels' and other work (e.g. Summerton[7]) that explores how the momentum of a LTS can be overcome and how systems can change and decline. Reasons can range from underlying problems within the system (what Hughes called 'reverse salients'), to 'negative externalities' like unwanted and unforeseen environmental impacts, and changing external conditions, such as new innovations, markets, war, cultural values or political ideologies.

The challenge with mature LTS is that there are often multiple system builders engaged in a range of complementary and contradictory system building processes. Participants highlighted a shift from thinking in terms of 'system builders' and towards 'system building' set out in Eric van der Vleuten's work on deep transitions, for example through developing new technologies or switching to different but already existing technologies to fill the space of a discontinued or declining technology.

Reverse salients are those components of a system that are out of equilibrium and impeding the intended function or performance of the system. These are often identified by system builders. Studying the reproduction, stagnation and decline of mature LTS can be aided by a focus on reverse salients rather than a complex network of system builders and users. **Kat Lovell explores this further in her contribution below.**

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[6] Pritchard, S. B. (2012). An Envirotechnical Disaster: Nature, Technology, and Politics at Fukushima. *Environmental History*, 17(2), 219–243
[7] Summerton, J. (ed). (1994). *Changing Large Technical Systems*. Boulder, CO: Westview Press.

Participants noted that when there are too many system builders to trace, we can instead trace *innovation activity* by studying reverse salients and how different actors engage with them. This is particularly important when a system's goal shifts, for example from non-renewable to renewable energy production. It was also noted that change processes in mature LTS can introduce reverse salients into a system that go unrecognised in ways that can lead to serious problems such as accidents. For example, UK rail privatisation and reorganisation processes disrupted connections between different elements within the system. Some key relationships stopped working and enabled the serious railway accidents that happened in the 1990s and 2000s.

Bounding a nuclear LTS

Participants engaged with the question of how we conceptualise an LTS in terms of boundaries. Some participants understood the boundaries of an LTS through the ways in which the actors working in the system used and interpreted boundaries and that part of the *process* of system building is necessarily about establishing boundaries. We can then ask questions about how and why a system's core actors define boundaries in particular ways and how this connects to understandings of what forms of change are possible and not possible.

In nuclear LTS, it was argued that irreversibility in nuclear disarmament is likely to be far more achievable for the integrated nuclear complex in its entirety, i.e., civil and military together as a whole, rather than for its parts. In particular, it was argued that the continuation of a civil nuclear complex keeps 'nuclear' on the agenda and 'keeps the system warm' and stable through cycles of investment.

The question of the scale of a nuclear LTS was also raised in terms of a nuclear arsenal as a nationally bounded system, a focus on dismantling a single (national) nuclear complex, what is inside and outside the boundary and how porous it is. The Nuclear Non-Proliferation Treaty (NPT) has cemented an artificial divide between civil and military nuclear complexes, but a number of STS studies have highlighted the synergies between these complexes in different countries. We can also consider the spillover effects of discontinuation into other systems, geographies and politics.

The boundaries of an LTS also raises the question of supply chains, what gets included and excluded, and what happens to domestic and international supply chains in terms of how they might be sustained or collapse in the event of a disarmament process or another type of technology phase out.

Others have drawn boundaries *within* the nuclear weapons complex around a 'production estate' encompassing the development and the production of nuclear weapons and the 'operational estate' encompassing the wider political-military structures and activities into which nuclear weapons are embedded and their use is enabled.

However, the politics of the differentiation between civil and military nuclear complexes complicates the argument that the irreversibility of a nuclear disarmament process will be maximised by unmaking a state's full nuclear complex. Many NPT states parties stress their right to peaceful uses of nuclear technology under the terms of the treaty and are opposed to further constraints on development of nuclear technologies for peaceful and developmental purposes.

Technology substitution and social value

Participants discussed the role of technology substitution in the process of LTS decline and discontinuation, specifically whether irreversible phase out of a technology requires a technological substitute. This connects to the idea of sustaining the function of a LTS whilst shifting the technological basis of its provision, for example the provision of security (as the function) in a different form (not nuclear weapons).

Others noted that change is less about technology substitutions and more about changes in the *meaning* of a technology, for example the change in meanings that make sense of biological weapons, which can be driven by different processes such as cost. The social value of technologies is what is at stake here, and we can differentiate between a technology that is phased out or goes out of use completely and has little no social value, and technologies that are phased out by being banned or outlawed (such as chemical and biological weapons) but has to be constantly worked at to make it so because the social value of a prohibited technology can remain.

Others drew a similar distinction between the irreversibility of the 'ending' of a technology and the end of the *relevance* of the thing to be terminated. A useful distinction was drawn between a) the ends of irreversibilities (and 'irreversibilisation' of endings) and b) the end of relevance. The example of Sweden's nuclear programme was raised as an example where there was a large socio-technical system that enabled the development of a nuclear weapons programme but also a set of changes that led Sweden to roll the programme back to the point where it is now very difficult (inconceivable?) to imagine it reversing that decision.

STS and the concept of irreversibility in nuclear disarmament

Two ways of thinking about irreversibility emerged from the workshop. One is irreversibility as a deliberate policy and a shift in the goal of a system to begin its own unmaking as a deliberate process. The second is irreversibility as a more organic de facto practical condition resulting from the coming apart of a system without necessarily involving a consistent top-down deliberate policy pushing the system in that direction.

The role of imagining irreversibility was also noted as an important part of the process of realising it. Participants discussed the role of imagined futures of LTS in terms of how future imaginings constrain choices or enable choices or enable processes relating to the direction or decline of large technical systems: how the future is imagined plays its own part in whatever happens to that system and how it's shaped in the future and direction it moves in. Participants also argued that in addition to considering how future imaginaries shape what we think is possible, we also have to consider how the past is constantly being revised and constantly being reconceptualised in terms of what led us here and how stories are told and retold. The concept of 'multi-stability' is useful in this regard: this is the idea that technologies can mean multiple things to different people in actuality without there having to be an interpretive battle about who gets to decide a single 'truth' such that compering meanings coexist and are often in tension.

Strong decline

We can also imagine a taxonomy of 'unmaking' an LTS that draws on the ways in which different disciplines approach and understand a similar phenomenon, For example, In economics, there is product discontinuity, company restructuring, and industrial contraction. In civil engineering there is decommissioning and dismantling. In policy studies there is policy phase out. In political science there is regime change. In geology there is the erosion of formations. This taxonomy could be investigated further.

STS, innovation studies and transition studies literature tend to examine unmaking and decline as a process of the weakening and breaking of connections between one or more elements of a system or configuration, and how this can then weaken the remaining connections. This can cause the system to shrink during the process of unmaking and diminish the *role* of the system in the surrounding environment. Elements of an LTS are divided into categories of materials, meanings and competencies that have to be aligned for the system to work and for its technology(ies) to be produced and used. Decline results from the lack of alignment between materials, meanings and competencies, as **Zahar Koretsky discusses in his contribution below.**

A weak and reversible form of decline can occur when these three elements of a system, or configuration, are dissociated and not linked together by stakeholders into a coherent form and might become part of *other* configurations. Recovery from this weak state of decline is possible if core elements are re-linked again, for example in the case of the resurgence of vinyl records and record players. Strong decline occurs when one of the three main categories of elements (materials, meanings or competencies) has gone. For example, a competence can disappear when the people who used and understood a technology have retired, materials can be destroyed and forgotten, and meanings can change substantially over time. Recovery from this kind of strong decline becomes labour-intensive and costly and practically the same as re-inventing something.

Decline can therefore start with unmaking one of these elements. This could be the result of deliberate processes through the mobilisation of an un-making coalition between states, industry, NGOs and so on who are advocating against a technology in order to undermine either competencies or meanings, to discursively attack a technology or undermine the system producing the materials. They might do this by supporting alternatives that promise to fill the same need in another way, perhaps using subsidies, tax incentives, direct funding of R&D, retraining people, compensating actors who stand to lose from un-making, and so on.

The reversibility of deep discontinuation

However, it was noted that institutional theory discusses 'institutional remnants' - those aspects or components of an institution or LTS that are left over when a system has to all intents and purposes ended, been replaced or taken on a completely different form. Under the right conditions these remnants can come together again and be reactivated or recapitalised in ways that are unexpected and sudden.

The process of political decision making and its role in the purposeful phase out of a technology was discussed in relation to the difficulties of 'final' and unequivocal decisions to discontinue a technology and unmake an LTS in ways that make it practically irreversible. It was noted that the only aspect of an LTS that might be truly irreversible is the *exact constellation* of a system of relations as it was before ceasing to function *in that particular way*. The stop-start phase out of nuclear energy production in Germany and Italy were raised as cases in point, for example in Italy the last nuclear energy production plant was closed in 1990, but now the new government is discussing re-entering nuclear energy generation again.

In addition, explicit knowledge will remain in classified documents in archives, in museums and textbooks and so on. 'Technological oblivion', as one participant described it, is therefore not an easy thing, even when engineers are gone or have died out or companies have folded, the knowledge is not simply 'gone'. It's still somewhere, even if only written or taught in abstract theoretical terms or in museums: it still 'exists'.

Irreversibility as a condition to be sustained was also highlighted. In the case of the prohibitions on chemical and biological weapons, these are *not* once and for all and forever. Rather, irreversibility has to be worked at: there are treaty review conferences, NGO and diplomatic activities within the chemical weapons regime, the operation of international organisations like the Organisation for the Prohibition of Chemical Weapons (OPCW) and its inspection regime, and so on. Irreversibility in this sense is a condition that has to be (re)produced over time until the social value of the technology is defunct. For example, this sort of activity does not take place around siege weapons, which leads to a different understanding of irreversibility as a more complete 'ending' because nobody's interested in the technology any longer (which connects to the discussion of 'endings' and social value above).

Gabrielle Hecht's concept of 'nuclearity'[8] was used by a number of participants to argue that nuclear disarmament will never be absolutely irreversible. Nuclearity refers to the quality of being 'nuclear' - the degree to which a state or something else is collectively understood to be in some sense 'nuclear'. This is subject to discursive framing that can render things 'nuclear' and 'non-nuclear' and therefore exceptional and banal. In the context of the South African nuclear weapons programme, there is a clear sense in which it ended, but at the same time it never *completely* ended, not least because the civilian use of nuclear technologies continued and successive governments remained determined to retain the highly-enriched uranium produced by the weapons programme, which remains secured somewhere in the Pelindaba nuclear complex. Instead, its *nuclearity* was reframed and renegotiated.

These concepts encourage us to think about and research not just about how technologies can decline, lose social value or be substituted, but also why certain technologies persist and don't go away. Here, John Stone's work in 'The Point of the Bayonet' that examines why such a useless piece of technology still persists to today was referenced.[9]

In addition, aspects of an LTS continue through aftercare of things that remain, for example nuclear waste. This shows us that uninvention/exnovation is not a simple *reversal* of invention/innovation. Instead, discontinuation of certain social techniques, systems or technologies can require new or modified institutional arrangements, financial arrangements and governance systems.

Summary

In sum, there is no single methodology for an 'STS' approach to studying the decline of a nuclear weapons complex as a large socio-technical system and the practical irreversibility of decline. Instead, researchers have developed and deployed a variety of concepts and approaches guided by their engagements with the complexity of the systems they are studying and the questions they are asking of them.

However, we can summarise some of the key concepts that can guide research STS research on nuclear weapons complexes, 'unmaking' and irreversibility as follows:

1. The 'de-institutionalisation' of an LTS as something different to institutionalisation and asking questions about what happens between these processes.
2. A multi-level perspective that explores multiple dimensions of change in order to understand the life-cycles of LTS (invention, expansion, momentum, reconfiguration, contestation, decline).

[8] Hecht, G. (2014). *Being Nuclear: Africans and the Global Uranium Trade*. MIT Press: Massachusetts.
[9] Stone, J. (2012). The Point of the Bayonet. *Technology and Culture*, 53(4), 885–908.

3. Focussing on the functions an LTS performs or fulfils and how an LTS can decline through the performance of the function by other LTS by shifting the socio-technological basis of its provision.
4. The agency of system builders that design and use an LTS and the wider social system necessary for its perpetuation, and the distinction between 'system builders' as agents and 'system building' as a process.
5. Researching reverse salients within a system and negative externalities as drivers of stagnation and decline.
6. An analytical distinction between first-order causes and second-order drivers of change in LTS.
7. Understanding how the boundaries of an LTS are drawn, what gets included and excluded, and examining the wider set of LTS within which the particular LTS of interest is embedded and stabilised, or condensed out of.
8. Critically examining asymmetries of power involved in producing and reproducing LTS and the framing of what it means for it to 'work' (for who, by whom, and to what ends?).
9. The formation and erosion of explicit and tacit knowledge and knowledge management practices as an LTS declines.
10. Investigating the social value of technologies and differentiating between a technology that is phased out or goes out of use completely and has little or no social value, and technologies that are phased out by being banned or outlawed but retain social value in some contexts.
11. Similarly, a distinction between the material 'ending' of a technology and the ideational 'ending' of the relevance of the technology to be terminated.
12. A distinction between irreversibility as a deliberate policy and irreversibility as an organic *de facto* practical condition resulting from the coming apart of a system.
13. How shared imaginings of the future of an LTS shapes choices about its direction, including the possibility and desirability of its decline.
14. The distinctions between 'strong' and 'weak' decline and linkages between the core materials, competencies, meanings and institutions that constitute an LTS.

This shows that there is a rich toolbox of concepts and cases that we can apply to the intellectual and practical challenge of understanding nuclear disarmament processes and the basis upon which we can imagine them to be to all intents and purposes irreversible and actively plan for that outcome.

Part two: Exploring stability and system development in a disrupted Large Technical System: the case of railway privatisation in the UK

Dr Kat Lovell

Introduction

Changing the practices and actors of system development, privatisation and restructuring of UK railway represents the reconfiguration of a mature and stable socio-technical system. The launch of the privatisation (and reorganisation) of British Rail, the public organisation that operated and oversaw engineering of the railway network, followed the general election in 1992. By the end of 1997 the core functions of British Rail had been divided into a network of supply and operation firms in a newly privatised railway system. The restructuring of this reconfigured mature system presents a setting where tensions and complexities play out between stability and disruption in the continued development of an embedded socio-technical system. This essay reflects upon a study and methodology developed, using Large Technical Systems (LTS) theory, to study these events. LTS theory uses a socio-technical perspective to understand changing systems that is well-suited to application in large infrastructure networks like a railway system and the LTS concept of reverse salients is used to trace innovation activities, underpinning analysis of system development.

Large Technical Systems theory

As part of a wave of thinkers considering the social construction of technologies, Thomas Hughes was a historian of technology focusing on the development of engineered complex systems, such as electric light systems. Hughes conducted detailed historical studies of the development of these systems, investigating the processes through which they developed. He identifies these systems as being *'both socially constructed and society shaping'*.[10] Hughes's detailed account of the first 50 years of the development of electric lighting, drew on a range of sources and included careful examination of Thomas Edison's design notebooks, was used to develop our understanding of socio-technical systems. The resulting LTS theory considers how such systems come to be developed, co-ordinated and pass through different phases of development.[11]

In studying the activities of key developers connected to what would become complex engineered systems, Thomas Hughes highlights the system qualities being developed

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[10] Hughes, T. P. (1987). The Evolution of Large Technological Systems. In W. E. Bijker, T. P. Hughes, & T. Pinch (Eds.). *The Social Construction of Technological Systems*. MIT Press: Massachusetts, 51.
[11] Ibid.

within these technologies. So the work of Thomas Edison on the development of electric light, extends far beyond work on the lightbulb (with which he is sometimes associated). Electricity generation, transmission and distribution for electric lighting were constructed together and contributions of human actors and processes (e.g. maintenance workers and procedures) developed alongside physical subsystems and components (e.g. cables or maintenance equipment). Key motivations within development activity for the system were the conditions and costs to be experienced by users. Hughes identifies such co-ordinating actors, like Edison, as *system builders*.[12] Hughes also notes that a system-building role changes at different stages in a LTS's continued development and adaptation to its environment and, in later work, there has been a shift to discussing system building as an activity in complex socio-technical systems.[13]

Hughes notes that LTS are developed towards a *'common systems goal'* that is a set of envisioned performance attributes for the system.[14] In the case of electric light much of this understanding came from the competing gas lighting.[15] For Edison (and his team) technology development and system design work focused on producing lighting using this electrical technology that was at least as effective and of a comparable cost as the existing gas lights. As key decisions are made, elements and co-ordination of a LTS become established, its characteristics and components become more stable and will require more effort to change or reconfigure. Hughes uses the idea that systems acquire 'momentum':

> *'Old systems like old people tend to become less adaptable, but systems do not simply grow frail and fade away. Large systems with high momentum tend to exert a soft determinism on other systems, groups, and individuals in society.'*[16]

Hughes notes that the creation and existence of LTS go through a series of recognisable phases (though order and transitions through these can vary): invention, development, innovation, transfer, growth, competition, consolidation and decline. With their continued development, elements of LTS become more stable and system momentum and style build up with movement through these phases.[17] This lifecycle understanding has been extended in different ways by Bolton and Foxon[18] and Sovacool

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[12] Hughes, T. P. (1979). The Electrification of America: The System Builders. *Technology and Culture*, 124-161; Hughes, T. P. (1983). *Networks of Power: Electrification in Western Society, 1880-1930*. The Johns Hopkins University Press: Baltimore.
[13] Van der Vleuten, E. (2019). Radical change and deep transitions: Lessons from Europe's infrastructure transition 1815–2015. *Environmental Innovation and Societal Transitions*, 32, 22-32.
[14] Hughes, (1987). The Evolution of Large Technological Systems, 51
[15] Hughes (1979). The Electrification of America; Hughes (1983). Networks of Power.
[16] Hughes (1987). The Evolution of Large Technological Systems, 48
[17] Ibid., 48
[18] Bolton, R. & Foxon, T. J. (2015). Infrastructure Transformation as a Socio-Technical Process—Implications for the Governance of Energy Distribution Networks in the UK. *Technological Forecasting and Social Change*, 90, 538-550.

et al.[19] both building on Summerton's discussion of systems reconfiguration, to consider the later phases for LTS.[20] This complements work in transitions for socio-technical systems, considering disruption[21] and decline.[22]

Reverse Salients

Connecting key concepts described above and considering how change happens in socio-technical systems, Hughes identifies a model for system development applying across different types of system-builder and system phases: reverse salient correction. A reverse salient[23] or bottleneck[24] refers to part of the system that, if its performance were improved, could improve system performance. System-builders are focused on performance at a system-level, rather than components or subsystems in their own right, and so attention for fixing or improving a system's design or operation focuses on elements, connections or assemblies that are holding back, or present opportunities for, system performance.

Hughes uses the imagery of a line of system performance (like a battle front) where interconnected elements contribute to system performance and where sometimes parts of the system exceed (become a salient) or fall behind (become a reverse salient) in relation to the line of performance relative to the system goal:

> *'The reverse salient will not be seen, however, unless inventors, engineers, and others view the technology as a goal-seeking system'*[25]

System actors will be aware of reverse salients for a system's performance, they are conceived as facts of performance relative to a common understanding of the system's goal.[26] However, in order to address performance at a reverse salient, actors need to frame the problem to direct and mobilise development activity. This 'critical problem definition' is created by system actors and it can be shaped according to perspectives

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[19] Sovacool, B. K., Lovell, K. & Ting, M. B. (2018). Reconfiguration, Contestation, and Decline: Conceptualizing Mature Large Technical Systems. *Science, Technology, & Human Values*, 43(6), 1066-1097.
[20] Summerton, J. (1994). Introductory Essay – The Systems Approach to Technological Change. In: Summerton, J. (Ed.). *Changing Large Technical Systems*. Westview Press: Boulder, 1-21.
[21] Kivimaa, P., Laakso, S., Lonkila, A. & Kaljonen, M. (2021). Moving Beyond Disruptive Innovation: A Review of Disruption in Sustainability Transitions. *Environmental Innovation and Societal Transitions*, 38, 110-126.
[22] Koretsky, Z., Stegmaier, P., Turnheim, B. & van Lente, H., (2023). Technologies in Decline: Socio-Technical Approaches to Discontinuation and Destabilisation. Taylor & Francis.
[23] Hughes (1983). Networks of Power; Hughes (1987). The Evolution of Large Technological Systems.
[24] Rosenberg, N. (1969). The Direction of Technological Change: Inducement Mechanisms and Focusing Devices. *Economic Development and Cultural Change*, 18(1): 1-24.
[25] Hughes (1983). *Networks of Power*, 80.
[26] Hughes (1983). *Networks of Power*, 22.

and interests of these actors and is a space of agency (and contention) within system development.[27]

Reverse salient correction as the mechanism for system development is present (throughout systems, phases of development and the activities of different system builders) wherever system-building is working towards a 'system goal'. There may be changes in the actors and knowledge bases involved, variations in the selection, speed and styles of reverse salient correction (and critical problem definition). There may even be changes and differences over priorities in system performance. But the common structure of system development around selecting and addressing reverse salients, offers a lens to view and analyse change and changing processes of change, across socio-technical systems. This was used as the basis for a method developed and applied for the study of the UK railway system, across different industry structures around privatisation.

Studying stability and disruption: Reconfiguration of the UK railway

In the complex, long-established socio-technical system of the UK railway, the understanding of system-building, developed from the study of the creation and development of networked systems, still resonates. Understanding the mid-1990s privatisation and re-organisation of the sector, and its continued development, needs a systems perspective. However, it does not fit with Hughes's phases of system development.[28] Steps taken to introduce competition into the sector were initiated and shaped by actors (for the most part) from outside the railway system – indicating that this was not a case of the continued development of the system towards existing performance goals as seen by system actors. However, following privatisation, much of the system's identity, its key performance objectives and its physical components and technologies were unchanged; and many system actors stayed within the system. So, although the organisations, institutions and co-ordination processes for the operation and development of the system were changed over a relatively short period of time (~5 years), there was also a substantial level of continuity in the system itself. This positions this privatisation as a reconfiguration of the system,[29] where there is reduction in system momentum and increased uncertainty over mechanisms and direction of continued development but not a new system. The study was conducted over 15 years after the initiation of the privatisation process. Although, at the time of the study the industry governance was continuing to shift and change, it was possible to use secondary sources to set up a timeline of privatisation stages. Using 'temporal bracketing',[30] three phases were defined (the core industry pre-privatisation,

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[27] Hughes (1987). The Evolution of Large Technological Systems.
[28] Hughes (1983). *Networks of Power*; Hughes (1987). The Evolution of Large Technological Systems.
[29] Summerton (1994) Introductory Essay; Sovacool (2018). Reconfiguration, Contestation, and Decline.
[30] Langley, A (1999). Strategies for Theorizing from Process Data. *Academy of Management Review*, 24(4), 691-710.

privatisation and newly privatised industry) reflecting important policy and organisational interventions in the sector. These phases represent different conditions for the system, relevant for its development, and they were treated as embedded cases within the case study. A sample (12 months) of data on system development activities was then generated for each of the three phases.

The generation of system development data, built on understanding of the reverse salient correction mechanism discussed above, drew on an industry specialised publication as data source. Modern Railways Magazine is a long-running publication, with reporting including management and policy issues alongside reports on engineering developments, targeted at industry actors and observers. Such industry specialist, contemporarily written accounts provide a record of communications by and for system actors, to whom both system performance priorities and reverse salients in system performance will be apparent.

Following preparatory work to bound the study and produce guidelines for data generation, relevant sections of the magazine were read and development activity recorded in a database where each entry represented innovation activity at a reverse salient. An entry could be initiated either by reports of problems to be addressed (representing a reverse salient) or by reports of innovation activities (e.g. reports on R&D projects or work to change system operation). Later reports on the same area activity were linked to the entry with additional information being added to the database. This approach captures understanding of problems and projects as they develop and so it has the potential to incorporate development activity that doesn't reach implementation, failed initiatives as well as successful ones and changes in understanding of reverse salient or in development priorities over time. The data samples included examples of competing initiatives, proposed projects that didn't come to fruition and examples of interactions between different development activities (e.g. a range of development activities across the existing network linked to the creation of the channel tunnel rail link).

In the empirical studies produced, these reverse salient correction data were analysed and used in conjunction with other data sources. Analysis of these data examined key actors initiating activities responding to system reverse salients (who set up projects and how?) and the motivations/priorities connected to the developments. Comparisons of development activity across the three samples showed changes in actors initiating developments and in the balance of performance priorities (with some areas of performance becoming more prevalent) following privatisation. For example, increased development activity for punctuality (and linked to delay penalties introduced in the new industry structure) was observed.[31] Examining these data as snapshots of system

[31] Lovell, K. & Nightingale, P. (2016). Business Models in Rail Infrastructure: Explaining Innovation. Proceedings of the Institution of Civil Engineers-Transport, 169(5), 262-271. Thomas Telford Ltd.

development activity overtime (and combined with interview and secondary data) they also highlighted areas where varied development activities continued over time and reverse salients proved difficult to address because of challenges co-ordinating actors and resources to respond.

Conclusions and reflections

The use of the reverse salient correction mechanism to structure empirical studies of mature and complex socio-technical systems offers opportunities to study system-building and to better understand shifts between stability and instability, with the potential to build a better embedded critical understanding of potential transformations of these systems. One strength of using tracing of reverse salient correction is that a study can consider developments from across large and complex systems, over long periods of time. It can also guide studies of change, where conventional starting points (such as an identifiable system builder) are not available. Future studies might extend these aspects further in using text analysis or natural language approaches.

However, tracing reverse salient correction activity also has limitations and careful development and adaptation is needed for its successful applications in different research studies. For example, care should be taken over potential quantitative analyses. Understanding of reverse salients and structures of responding development activities change over time. Both reverse salients and approaches to develop corrections, can be understood as factors of a time and setting.

The tracing of reverse salients can be conducted from a range of data sources and designs can be developed connecting data sources and research questions in different ways. Industry specialised press, used as a data source here, is not available or appropriate for all studies. Other sources of data for analysis of reverse salients could include non-specialist press, patent records, interacting with key actors (perhaps through workshops or key organisations where development is centralised), policy documentation or archives of industry reports.

Tracing system development activity through reverse salient in this way, can show changing patterns in areas such as the key actors, their motivations, and where within a system attention is being focused. It can also highlight points where reverse salients have become difficult to address; for example, where resources and knowledge are difficult to coordinate to respond. Further, applying this conceptual lens to different settings can be used to interrogate mechanisms for changing levels of irreversibility: how could alignment or disconnect between key actors and crucial reverse salients come about?

Part three: A methodology for researching technological decline from a socio-material perspective

Dr Zahar Koretsky[32]

Introduction

Propositions for multi-actor state-guided missions towards addressing societal challenges via phasing out coal power plants and coal mines, and other unsustainable technologies such as the internal combustion engine, have been gaining traction.[33] One of the pressing questions in the growing interdisciplinary literature on sustainability transitions, which draws insights and methods from economics, political science, sociology, history and other fields, is: under what conditions is phasing out of an established technology possible and irreversible? This is not a trivial question as deliberate phase-out is often entangled with the need to actively confront powerful actors and destabilise structures of power, as well as to care after the legacy of the declining technology, such as stranded assets (e.g. physical (infra)structures or sunk costs), emotions of attachment (e.g. leaving a beloved home), a change in material conditions of laid-off workers (in case of e.g. a closed coal mine), and unfulfilled needs of the former users. A further issue is that there is no guarantee that a phased out technology will stay phased out, or with what implications.

In the emergent literature on the topic there is a lively debate on these issues. Terms like decline, phase-out, destabilisation, discontinuation, exnovation and others are proposed, and they foreground various aspects of the problem.[34] In this report I will use the candidate umbrella term 'ending', proposed by a transitions scholar Lea Fünfschilling,[35] to refer to the family of these adjacent concepts, and I will use 'decline' as a specific type of ending, one that describes processes of decreasing production and/or use of a given technology to the point of its abandonment. I study decline from a socio-material perspective, common in the interdisciplinary social scientific field of science and technology studies (STS). The STS perspective that I adopt argues that technology embeds politics.[36] From the socio-material perspective, a given technology

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[32] This report is based on Koretsky, Z. (2022). Unravelling: The Dynamics of Technological Decline. Doctoral Thesis. Maastricht University.
[33] IPCC. (2022). Climate change 2022: Impacts, Adaptation and Vulnerability. IPCC Sixth Assessment Report. IPCC Geneva, Switzerland.
[34] Sovacool, B. K., Iskandarova, M., & Hall, J. (2023). Industrializing Theories: A Thematic Analysis of Conceptual Frameworks and Typologies for Industrial Sociotechnical Change in a Low-Carbon Future. *Energy Research and Social Science*. https://doi.org/10.1016/j.erss.2023.102954
[35] https://portal.research.lu.se/en/projects/endings-towards-a-theory-of-endings-in-innovation-studies
[36] By 'technology' I mean any class of human-created objects: from stone knife, to clothing, to radio, to a factory, to the energy grid. See Latour, B. (1991). Technology is Society Made Durable. *The Sociological*

is viewed as a configuration of co-constituting, co-creating material and social relations. By analytically untangling the relations, the analyst is able to describe linkages, their dynamics and patterns, and how alternatives are made less possible. In contrast to the related socio-technical perspective, taken up in sustainability transition studies, a socio-material perspective studies in detail the sociology of technology.

A conceptual framework for analysing decline from a socio-material perspective

I analytically separate the 'components' of a technology into three units of analysis:

1. Materials (e.g. objects, tools, hardware, physical infrastructure, production facilities, material resources)
2. Competences (e.g. tacit or codified knowledge on design, production or use)
3. Meanings (individual, e.g. interpretations, emotions; and collective, e.g. public discourses, institutions, rules, narratives).

Reproduction of the three components and their alignment (i.e. production and/or use of a technology) is key for continuity of the configuration. Without even one of the elements, the configuration collapses, unravels into separate strands, and decline begins. Reproduction is in turn enabled by the supporting structures of laws, norms, standards, institutions, lifestyles, knowledge, markets, competences, infrastructures and sunk investments, known in sustainability transitions studies as a 'regime'.[37]

The three components are not monolithic and are themselves networks of various entities, co-existing and competing. They are dynamically stable as long as there is alignment, and they can become unstable if there is too much internal contestation.[38]

Method

I applied this conceptual framework to three empirical cases:

1. The re-emergence of cloud seeding in the US.[39]
2. The declining incandescent light bulb in the EU.[40]

Review, 38(1), 103–131. https://doi.org/10.1111/j.1467-954x.1990.tb03350.x; Foucault, M. (1977). *Discipline and Punish: The Birth of Prison*. (A. Sheridan, Trans.). Pantheon Books.

[37] Geels, F. W. (2007). Transformations of Large Technical Systems: A Multilevel Analysis of the Dutch Highway System (1950-2000). *Science Technology and Human Values*, 32(2), 123–149. https://doi.org/10.1177/0162243906293883.

[38] Goulet, F. (2021). Characterizing Alignments in Socio-technical Transitions. Lessons from Agricultural Bio-inputs in Brazil. *Technology in Society*, 65(101580). https://doi.org/https://doi.org/10.1016/j.techsoc.2021.101580

[39] Koretsky, Z., & Van Lente, H. (2020). Technology Phase-out as Unravelling of Socio-technical Configurations: Cloud Seeding Case. *Environmental Innovation and Societal Transitions*, 37, 302–317. https://doi.org/10.1016/j.eist.2020.10.002.

[40] Koretsky, Z. (2021). Phasing out an Embedded Technology: Insights from Banning the Incandescent Light Bulb in Europe. *Energy Research and Social Science*, 82(102310). https://doi.org/10.1016/j.erss.2021.102310.

3. The declined *Ural* computer in Russia.[41]

Cases were selected using five criteria: (1) a measurable (e.g. decreased production) decline of technology in a given period of time compared to an earlier period, (2) intentionality of decline decisions[42] (e.g. phase-out policies, bans, treaties), (3) case variation (e.g. geography, decline outcomes), (4) data accessibility, and (5) personal curiosity in a case.

I used narrative analysis drawn from historical sociology to order empirical material into narratives from antecedent events (development of technology) to final events (measurable ending of a technology). Primary and secondary qualitative and quantitative data was collected based on: (a) any mentions of the related technology (i.e. "cloud seeding" and its alternative labels that I identified based on preliminary literature review; and (b) mentions of information, identified during close reading of the sources, related to:

1. Materials: design characteristics, location and number of production facilities, funding amounts and sources, production and use statistics.
2. Competencies: state of the art and its dynamics, necessary knowledge and skills and their dynamics, career changes of key persons.
3. Meanings: personal accounts of key events from key persons such as lead designer, (former) employee, or representative of government as a key user.

Texts were coded by year and unit of analysis forming a database and a timeline. This was a lengthy process which took around six months per case. It was then possible to analyse (done in several iterations) the patterns emergent from the reconstructed chronology notably: (1) key event chains that enabled alignment (e.g. new projects funded, appearance of more positive framings in press) or misalignment (e.g. a national sales ban) of the components; and (2) periods in the history of the technology, such as "development" and "decline".

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[41] Koretsky, Z., Zeiss, R., & Van Lente, H. (2022). Exploring the Dynamics of Technology Phase-outs Through the History of a Soviet Computer "Ural" (1955-1990). *Science, Technology & Human Values*. https://doi.org/https://doi.org/10.1177/01622439221130139.
[42] A traditional focus in sustainability transitions studies on emergent, 'natural' outcomes of transitions has been critiqued for downplaying the role of deliberate human action in change (see Feola, G. (2020). Capitalism in Sustainability Transitions Research: Time for a Critical Turn? *Environmental Innovation and Societal Transitions,* 35, 241–250. https://doi.org/10.1016/j.eist.2019.02.005 and Geels, F. W. (2011). The Multi-level Perspective on Sustainability Transitions: Responses to Seven Criticisms. *Environmental Innovation and Societal Transitions*, 1(1), 24–40. https://doi.org/10.1016/j.eist.2011.02.002. 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, G., Oosterveer, P., & Loeber, A. (2013). Sustainability Transitions in Food Consumption, Retail and Production. In G. Spaargaren, P. Oosterveer & A. Anne Loeber. *Food Practices in Transition: Changing Food Consumption, Retail and Production in the Age of Reflexive Modernity*. Routledge: New York, 9.

Cases

Cloud seeding

Cloud seeding are attempts to modify the chemistry of clouds in the atmosphere to stimulate or stop precipitation. This was done via chemical compounds (usually dry ice or silver iodide that created ice crystals out of air moisture) delivered by plane. Cloud seeding projects started in the USA (as well as the USSR and the UK) right after World War II. The key events in the history of cloud seeding's incomplete and reversed 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 1977 international anti-cloud-seeding treaty, and (c) the reinvigoration of academic and political debates on global warming, and cloud seeding as a possible response. By early 2000s, cloud seeding saw a reintroduction in both academic and political circles. By the beginning of 2010s, cloud seeding featured in US 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.

The incandescent light bulb

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 key events in the ILB's history were (a) the formation of a negative narrative by a powerful social group, (b) their lobbying for ILB phase-out, (c) the imitation of the ILB by the competing LED, and (d) the withdrawal of the ILB to small pockets of production and use. By 2024, the exempted ILBs can be bought as 'decorative lamps' and so called 'rough-service lamps'. However, on a wider scale there is a confident decline of the ILB.[43]

The Russian/Soviet original computer series Ural

The *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. The key events in the case of the *Ural* were: (a) lead designer leaving the group, (b) the government officially prioritising *ES ÈVM* over other computer projects, (c) a lack of resources which forced designers and manufacturers to use outdated parts in the *Ural*, (d) hybridisation of the *Ural* by the design team, thus undermining the *Ural's* identity and credibility, and (e) withdrawal of the last funder from the *Ural* line. No more *Urals* were produced after the 1970s, although some were still used in the Soviet space

[43] Zissis, G., Bertoldi, P., & Serrenho, T. (2021). Update on the Status of LED-Lighting World Market since 2018. Publications Office of the European Union. Luxembourg. https://doi.org/10.2760/759859.

industry well into the 1980s. Few *Urals* were preserved as they contained large amounts of metals and occupied a lot of precious room. The surviving *Urals* were claimed by museums.

Conclusions

The role of competing configuration

In the ILB and *Ural* cases the competing configurations (the LED and the *ES ÉVM*, respectively) played slightly different roles. The competing LED was deliberately made to look like the 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 the *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 substitution of the components contribute to the speed of the unravelling. That competing configurations did not play key roles in the cloud seeding case. Cloud seeding and the ILB followed similar pathways up to a point when cloud seeding started growing in the geography and regularity of use. 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 (with LED), and the *Ural*—even further on a pathway of decline. The unravelling of the ILB is, in principle, reversible in the future as long as all components (the bulb envelope, wires, the knowledge of their construction and use, the need for lighting, etc.) remain available. Such availability was also there in the case of cloud seeding, but was not in the case of the *Ural*.

Disruptive vs reinforcing/non-disruptive change

Two types of change in the socio-technical configuration were observed. First, reinforcing, or at least non-disruptive, change, which can involve incremental innovation, emergence of alternative uses and meanings of the given technology, etc. Such reinforcing change supports the variety of entities within components, making the misalignment of a component less likely. For example, the co-existence of different meanings of cloud seeding: e.g. fire control tool and irrigation tool, reinforced the meanings component (as it meant that cloud seeding was used in multiple applications and locations). Second, disruptive change, which disrupts the configuration via e.g. new materials, counter-meanings and/or shocks in forms of new competences that shake up a component. Disruptive change can lead to loss of resilience of a configuration's component, and, potentially, the unravelling of the whole configuration. Coming back to the cloud seeding examples, its unravelling started with a shock when a powerful counter-meaning ("hazardous and ethically dubious technology") challenged the other meanings.

The starting point of technological decline

In the three cases, 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 components 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.

Weak and strong decline

The three cases demonstrate that decline is not a binary switch, but a spectrum between continual performance (i.e. use and/or production) and a lack thereof revealing two types of decline: weak and strong. Weak decline indicates a state where technology is not used or produced anymore, while all of the configuration components remain intact, such as in the cases of cloud seeding before its re-emergence and the ILB today. Strong decline indicates the completeness of misalignment in components and unravelling between them, and is thus discontinuous decline. The difference between weak and strong decline amounts to how easy (e.g. cost-wise) it is for the technology to return. A strong decline, thus, describes irreversibility of decline, or at least its functional or "adequate irreversibility"[44], which implies a high *level* of irreversibility (without ensuring the unrealistic absolute and permanent irreversibility). When investigating irreversibility, one could look for direct indicators such as cost estimations for R&D, manufacture and/or training related to the technology in question (the costlier, the stronger the irreversibility), or for more indirect indicators such as those used in the cases: changes over long periods of time of design characteristics, location and number of production facilities, funding amounts and sources, production and use statistics, state of the art and its dynamics, necessary knowledge and skills and their dynamics, career changes of key persons, and personal accounts of key events from key persons that form institutions and public discourses. Such data help formulate a causally linked storyline needed to place the current state of the given technology in perspective with its history.

[44] Ritchie, N. (2023). Irreversibility and Nuclear Disarmament: Unmaking Nuclear Weapon Complexes. *Journal for Peace and Nuclear Disarmament*, 1–26.

Part four: The practical application of systems mapping

Nick Ritchie

Systems analysis and mapping systems provide a useful set of tools to studying large socio-technical systems and much has been written about them as analytical tools.[45] A system can be understood as an "interconnected set of elements that is coherently organised in a way that achieves something".[46] System maps comprise networks, nodes, and edges. Barbrook-Johnson and Penn define networks as boxes (the nodes) connected by lines (the edges) that can have arrows to indicate the direction of the connection.[47]

Systems mapping tools

Barbrook-Johnson and Penn unpack seven types of systems mapping process: rich pictures, theory of change diagrams, causal loop diagrams, participatory systems mapping, fuzzy cognitive mapping, Bayesian belief networks, and system dynamics. Theories of change diagrams, causal loop diagrams and participatory systems mapping are the most relevant to mapping nuclear weapons complexes for the purpose of understanding hypothetical disarmament processes and how irreversibility could be maximised.

Theories of change diagrams

ToC diagrams to map the connections and pathways between an intervention and its outcomes. They attempt to map causal logic to describe the impacts that might be created by an intervention.[48] ToC diagram tend to use the following categories to structure the diagram:

- "Inputs: the resources (broadly defined) used or required.
- Activities: the actions, events, and undertakings of the intervention.
- Outputs: the immediate tangible products of the intervention. These tend to be easy to define and identify, akin to something like deliverables from a project.
- Outcomes: the potential short and medium-term effects of an intervention. These might be more difficult to measure and will be less tangible than an output.

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[45] For example, Barbrook-Johnson, P. & Penn, A. (2022). *Systems Mapping: How to Build and Use Causal Models of Systems*. Palgrave Macmillan: Switzerland; Williams, B. & Hummelbrunner, R. (2010). *Systems Concepts in Action: A Practitioner's Toolkit*. Stanford University Press: Stanford; Meadows, D. (2009). *Thinking in Systems: A Primer*. Earthscan: Abingdon; Reynold, M. & Holwell. S. (eds.) (2020*). Systems Approaches to Making Change: A Practical Guide*. 2nd Edition. London: Open University and Springer.
[46] Meadows. *Thinking in systems*, 13.
[47] Barbrook-Johnson & Penn. *Systems Mapping*, 5.
[48] Ibid., 35.

- Impacts: the long-term effects of an intervention and/or the long- term changes it contributes to."[49]

The mapping process starts with setting out the specific elements of the intervention in terms of inputs and activities. Next, the intended long-term impacts of the intervention are mapped. Finally, the gaps between the intervention and its long-term goals are filled in. The steps and categories mapped should be as specific and realistic as possible. Foregrounding and capturing risks, assumptions, and obstacles to change can aid the process. A further step can involve exploring the interconnections and interactions between the different pathways in the map.[50]

Causal loop diagrams

A causal loop diagram asking 'how could irreversibility in nuclear disarmament be caused?' would formalise causal connections between nodes (understood as variables in the system that can go up or down over some scale) and positive or negative feedback loops between nodes. Causal loop diagrams start with a 'core system engine', which is a set of nodes that is the core of the system.[51] Data is collected to build a catalogue of variables and the causal connections between them. The set of variables and their causal connections is then used to develop the structure and content of the core system engine with a limit of around twenty nodes to stop the core becoming too unwieldy. Causal connection should be unambiguous. The model can be expanded once the validity of the core system engine has been tested with others.

Participatory systems maps

Participatory systems maps are also causal models of a system built through participatory workshops with a system's stakeholders. Here, the nodes in the map are called 'factors', with particular attention paid to factors such as outcomes or functions of the system, or interventions. PSM maps are often large with 50 or 100 nodes and many more that number of connections. This allows analysis to focus on sub-systems and creating sub-maps. This is done by drawing boundaries around a key factor two or three steps 'upstream' or 'downstream'. The first step, as with other models, is to draw a boundary around the full system. Then consider stakeholders in terms of who affects or is affected by the system. 'Focal factors' are then chosen, and these are usually the outcomes or 'functions' of the system. Once focal factors have been identified, general factors are then added. These are factors that influence or are influenced by the focal factors. The key criterion for a factor is that it makes a difference to how the system works. The map is built by drawing causal connections between the focal factors and then the general factors.

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[49] Ibid., 35.
[50] Ibid., 40.
[51] Barbrook-Johnson & Penn. *Systems Mapping*, 49.

Influence diagram

Williams draws a useful distinction between 'influence' and 'causal' systems diagrams. An influence diagram maps the relationships between factors right now. It is a way of building a snapshot rather than mapping causality (noting that influence relationships do not imply causality). The process involves first identifying the central issue, problem or focus, identifying major influences (which can be anything that influence a state of affairs), identifying secondary influences, and identifying the relationships between the influences and the importance of those relationships.[52]

Causal diagrams

A causal diagram maps relationships between factors with causal arrows. Factors here are variables and the relationships are direct 'if/then' variable-driven relationships with no or trivial intervening factor variables. Williams writes that "If you want to know what influences a situation at a particular moment in time then you use an Influence Diagram.... The core focus is on features, what may be operating on a particular behaviour. If you want to know how a situation changes over a period of time then you use Causal Diagrams...The core focus is about mechanisms, how things change".[53]

Viable System Models

Williams also discusses 'Viable System Models'. VSM is "a systems approach that identifies the minimum requirements that must be placed on collective human endeavours if they are to prove enduring and capable of development" and that "any human activity system is composed of mutually interlocking and nested Sub-Systems, which when in balance with each other and with the system's environment, together provide sufficient conditions for the viability of that system".[54] This could be useful in understanding the minimum requirements for a functioning nuclear weapons complex and how a disarmament process breaches those requirements.

The Centre for Examining Complexity Across the Nexus (CECAN) suggests the following steps in a mapping process[55]:

1. Specify the focal area, focal problem and set some initial boundaries for the system, for example physical boundaries or a policy domain.
2. Decide on the main focal factor(s): this is a variable that can increase or decrease within the system. The focal factor(s) are the building blocks of the process and frame the focus of a system map. For a causal loop diagram this is

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[52] Williams, B. (2021). *System Diagrams: A Practical Guide* <https://bobwilliams.gumroad.com/l/systemdiagrams>, 36-39.
[53] Ibid., 46.
[54] Williams. *Systems Diagrams*, 75.
[55] Penn, A. & Barbrook-Johnson, P. (no date). Participatory Systems Mapping: a practical guide. Centre for Examining Complexity Across the Nexus (CECAN) <https://www.cecan.ac.uk/wp-content/uploads/2020/09/PSM-Workshop-method.pdf>.

the 'core system engine'. For an influence diagram these are the major influences. For a theory of change diagram they are the intervention and intended outcomes.
3. Brainstorm and gather data on all the general factors (influences, activities, outcomes, impacts, outputs) that can impact the focal factor(s). These could be technical, social, economic, political, ecological etc. They can be quantifiable, e.g. prices, or qualitative such as social attitudes. Mapping stakeholders can be useful here
4. Consolidate and connect factors: show how the factors influence each other with the main focal factor(s) at the centre for an influence diagram, the causal connections between factors-as-variables for a causal loop diagram and steps between outcome and intervention for a theory of change diagram, or systems and sub-systems for a participatory systems map.
5. Check the connections: Look for any nodes with very few connections to check for bias and missing connections, check causal directions, check for obviously important factors that are missing, and examine factors with lots of connections coming in and out to check whether these really are really highly-connected.

We can work through this process by asking specific types of questions, Williams provides just such a list of such questions on 'understanding interrelationships', 'Acknowledging multiple perspectives', 'Reflecting on boundaries' and 'Applied to the process'. Key questions include:

- How do the various elements of the diagram interact?
- What are the major processes by which they interact?
- What are the interrelationships between resources identified in the diagram (i.e., people, money, things, knowledge, skills)?
- Which relationships in the diagram are known and certain and which elements are unknown or uncertain?
- How do boundary issues affect interrelationships?
- What conflicts, tensions, or agreements emerge from these multiple perspectives?
- What assumptions underpin or are expressed by the diagram?
- Who or what is advantaged or disadvantaged in the situation?
- Where is the locus of control in the system?
- Who or what has the ability to radically change the situation?[56]

Barbrook-Johnson and Penn suggest asking:
- Which factors are controllable by whom and to what degree?
- Which are vulnerable to particular changes?
- Which are obstacles to interventions?
- Which are 'owned' by different stakeholders?

[56] Williams. Systems Diagrams, 24-25.

- What are the potential influences on outcomes?
- What are potential unexpected impacts of external change, are there trade-offs between different stakeholders' interests
- Are there interactions between different interventions?[57]

We can then interact a systems diagram by analysing the map using the following steps:

1. Look at factors which are of high importance and focus on the factors one or two steps 'up' and 'down' from them.
2. Examine factors that represent any interventions or policies in the system, and the factors downstream from them.
3. Examine factors that have many incoming (highly influenced) or outgoing (highly influential) connections.
4. Look particularly at factors up or downstream from these highly connected factors.
5. Look at factors that have outgoing links only (drivers) and factors that have incoming links only (sinks).
6. Explore any factors with a high number of outgoing connections, but which have low controllability (i.e. a potential vulnerability)? Or any factors with many outgoing factors, that are controllable (i.e. a potential lever)?

They advise working backwards for a map focussed on policy outcomes: first map the intended outcomes and the general factors which impact or are impacted by them and *then* add policies at the end. Then you can use the map to explore possible changes in terms of how the map would need to be structured differently and new factors that would have to be added.

Obstacles to a desired change can be studied using **Force Field Analysis.** This approach asks four questions: 1) What forces help create a desired state?; 2) What needs to be done to help those helping forces help? 3) What forces are hindering the creation of a desired state? 4) What needs to be done to help those hindering forces hinder?[58]

Analysis can be aided by a **Keep, Chuck, Change, Create** approach to addressing problematic situations or achieving a desired outcome. This asks: What needs to be kept? What needs to be chucked? What needs to be changed? What needs to be created?[59]

Here is an example from Williams of stakeholders in rice production in the Sahel region with one item per box.[60]

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[57] Barbrook-Johnson & Penn. *Systems Mapping*, 62-72.
[58] Williams. *Systems Diagrams*, 26.
[59] Ibid., 26.
[60] Williams. *Systems Diagrams*, 22.

Involved in			
Stakeholder role	The role is affected by …	The role contributes to …	Interest, motivation, or stake
Village leader	Election process	Acquisition of resources	Authority
Farmer	Maintenance of irrigation	Village wealth	Village economy
Fertiliser seller	Fertiliser availability	Rice productivity	Profitability
Village Future			Village Future

This is an example of systems and sub-systems from the National Infrastructure Commission's report on 'System Mapping for UK Infrastructure Systems Decision Making':[61]

Infrastructure System	Infrastructure Subsystem	
Digital	Mobile Communications	
	Fixed-line communications	
	Broadband	
Energy	Electricity	Generation
		Transmission
		Distribution
	Gas	Storage
		Transmission
		Distribution
	Petroleum (e.g. oil)	Storage
		Transmission
Transport	Highways	Strategic Roads
		Local Authority Roads
	Rail	
Water	Storage (including abstraction)	
	Treatment	
	Distribution	
Wastewater	Collection	
	Treatment	

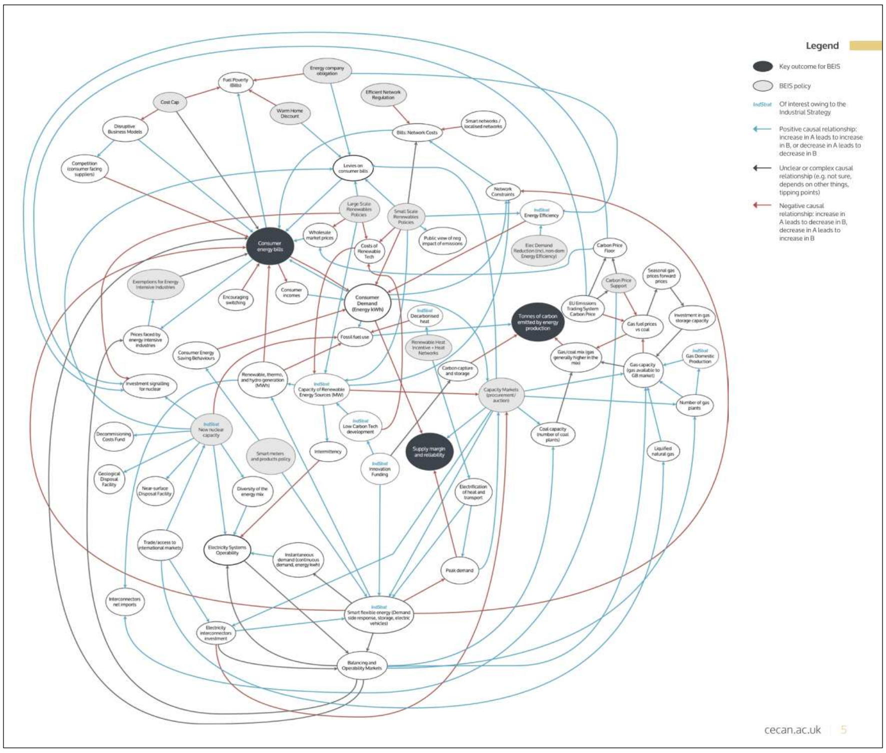
This is an example of mapping the main interdependencies between systems and sub-systems (or primary and secondary sectors):

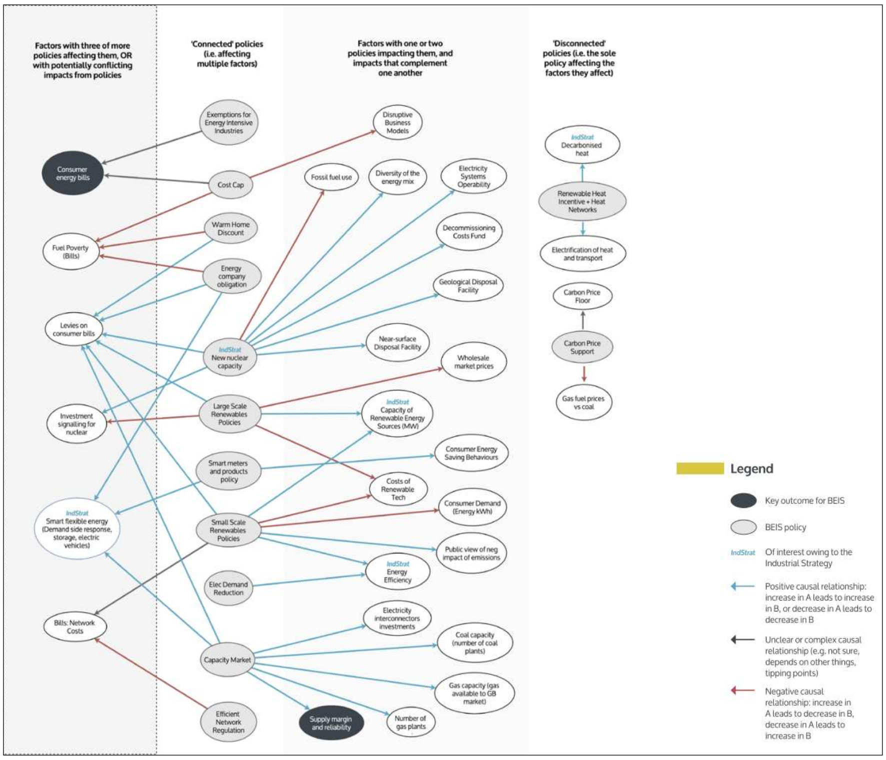
[61] National Infrastructure Commission (2020). 'System Mapping for UK Infrastructure Systems Decision Making' <https://nic.org.uk/app/uploads/Systems-mapping-for-UK-infrastructure-systems-decision-making.pdf>.

Primary Sector	Secondary Sector	Interdependencies Identifed											
Energy	Water/Wastewater	Shared data network for smart metering.	Water and energy companies can work together to increase household efficiency, in future energy use of a home will increasingly be from water use.	Energy is one of the top 3 operational costs for water companies.	Barrier to energy and water partnerships.	Price control differences across water and energy could mean resilience measures (i.e. Cost-bebnefit analysis) do not stack up on their own.	Resillience to specific hazards not same across sectors (e.g. drought).	Conflict between carbon net zero drive and need to pump water as a response to drought.	Petroleum refineries need clean water to operate.	Move to hydrogen economy for transport will result in high water demand.	Bioresources from waste water treatment provides methane bio-gas.	Water availablity can constrain ability to build and operate new generating plant.	Watersource heat pumps as renewable heating (in a domestic and commercial setting).
	Digital	Command and control of energy systems (i.e. operational technology). Decision support systems	Access to drivers / exchanges (comms) run on diesel generator back ups.	National grid has its own independent fibre network.	Facilitates contact with energy supplier.	High Integrity Telecommunications System (HITS)	Energy provides power to the Emergency Services Network (ESN).	Digital allows for workforce communication.	Telecoms is reliant upon electricity supply (throughout network).	Data Centres.	Security of communications (e.g. hack into smart meters)	Blackstart events	Comms are key in balancing energy system across entities.
	Transport	Energy required for railway control centres and signalling.	Renewable generation on railway feeding into grid e.g. Riding sunbeams (solar power on railways) which is identifying opportunites to install renewable generation	Specific transport services for energy sites (e.g. train service for Sellafield staff). If transport service stops sellafield impacted.	Energy required to get fuel out of ground to power transport.	Fuel needed to for transport modes and freight.	Technology required for safety critical functions depend on electricity.	Rail network electrification creates further demands on energy grid.	Energy required for the transport of nuclear material.	Energy required for space heating at rail depots.	Non-traction electricity.	Traction electricity, rail	Bi-directional at substations
Water	Energy		Using renewable energy to move water around in regional pipes.	Reduction in water would lead to a reduction in energy production.	Water pumping reliance on energy	Energy from waste (i.e. sludge) providing loss of mains protection (e.g. Thames Water generating 1/5th energy needs).	Demand side contracts Short term low frequency demand (scenario > source of resilience to energy sector)	Mutual reliance on natural water sources (e.g rivers).	Sludge as feedstock for power stations is creating a market.	Nuclear power station need for water.	Hydroelectric > water storage association with meterological conditions		
	Digital	Reliance on digital to provide emergency forecasts (e.g. EA Flood alerts) and emergency alerts.	Reservoir control systems.	Work force communications.	Digital required to keep customers informed during an incident. Leads to improved customer satisfaction.	Contact with supplier (day to day).	Digital offers transformative analytics to predict and forecast demand.	Digital provides command and control for water networks.	Emergency communications.	Facilitates implementation of smart meters.	Capex for better communications - ofwat priority		
	Transport	Water run-off from road and rail networks can impact water quality.	De-watering of tunnels, glasgow subway/ CTRL /Mersey tunnel	Water and drainage assets co-located with transport, impact of bursts etc.	Water treatment chemicals transported by road.								
Transport	Water/Wastewater	Bridges have water infrastructure services running across them.	Tankering chemical, water, supplies etc	Transport embankments are used for flood defence. Impact of flood run-off.	Dewatering for tunnels etc. that can impact on water environment (i.e. groundwater).	Transport enviroment fund to improve water quality.	Water is required to build transport infrastructure.	Pollution in run-off from road and rail infrastructure.	Cars end up in water courses > batteries from ev impacting polution	Current project by Environment Agency and Network Rail considering water quality issues.	Differing draiange standards across sectors. For example, Environment Agency want to slow down water, whereas Highways England/Network Rail standards want to speed up water.	Link between Sustainable Drainage Systems (SuDS) and wastewater management.	No septic tanks are allowed which has implications for railway stations being connected to the sewerage network.
	Energy	Banning or restricting diesel might impact Transport for London's emergency supply in greenwich LUL increases resilience opposite effect if taken out	Reliance on energy for smart motorway and signal control.	Smart charging locations impact demand	If there is an extensive power cut then people leave cities, impacting transport network.	During power outages and frequency disruptions, tolerance of electric trains is challenged.	Diversity of supply to signalling /comms etc 3 different systems	Opposite interaction, rail accident causing impact on electricity (takes out power supply) impact of other trains on track or other owners	Operation of train rolling stock.	Energy required to refine petroleum products for transportation.	Energy required to distribute petroleum products to consumers.		
	Digital	Losing of social interaction	Workforce communications.	Emergency communications (e.g. Emergency Services Network)	Mobile and wifi coverage on rail lines / poor coverage in the rail corridor.	Transport bridges with co-located digital services.	Digital networks for command and control of transport infrastructure.	Shared infrastructure corridors.	GPS needed for transport systems.	Safety of life dependency on rail/road connected.	Digital required for enforcement and monitoring of tolls and emmission zones.	Railway signalling and contact systems	Rail signalling systems reliance on digital technology.
Digital	Transport	Importance of fibre optics & other digital infrastructure in transport.	Data collection at macro level about customers travel routes and locations.	Rail passenger information apps (on delays) that provide situational awareness e.g. in emergencies	General safety regulation LCAVS	Security of BIM							
	Water/Wastewater	Sharing data on vulnerable customers in Digital econonmy ACT	Control & Monitoring of assests and demand	Rapid water travelling relies on digital infrastructure	Sector becoming more digitilised which creates resilience risks	Use of digital infrastructure for precision agriculture, leading to more efficient water use.	Digital communication underpin ability to respond to or report incidents .	Could water sector become more intergrated with availability of digital software.	Negative connection to service bundling (phone and broadband and energy/water) for business retail.				
	Energy	Distributed Energy Resources (Energy/Reforce) Dispatch	Telecommunications equipment has energy demand. Smart operation & resilence also has energy demand.	Digital communications resilience.	Digital communication underpin ability to respond to or report incidents.	Ongoing study into dedicated spectrum for utilities (future).							

This example from the National Infrastructure Commission maps the 'energy trilemma'. First, it maps key policy outcomes, current policy instruments, and positive, unclear or complex, and negative causal relationships. Then it maps these factors in terms of connections.[62]

[62] Centre for Examining Complexity Across the Nexus (CECAN) (2019). 'Negotiating Complexity in Evaluation Planning: A Participatory Systems Map of the Energy Trilemma' <https://www.cecan.ac.uk/wp-content/uploads/2020/08/EPPN-No-12-Negotiating-Complexity-in-Evaluation-Planning.pdf>. This journal article unpacks the process in more detail: Barbrook-Johnson, P., & Penn, A. (2021). Participatory Systems Mapping for Complex Energy Policy Evaluation. *Evaluation*, 27:1, 57-79 <https://doi.org/10.1177/1356389020976153>.





In sum, using mapping tools provides a practical way of researching LTS that can draw on the wider set of conceptual and methodological tools in Science and Technology Studies outlined above.

PROJECT ON IRREVERSIBLE NUCLEAR DISARMAMENT

Working papers

Joelien Pretorius. **Staying the course: Lessons from South Africa for irreversibility of nuclear disarmament**. March 2023. York IND Working Paper#1.

Nick Ritchie. **Conditional Reversibility as a Condition of Irreversibility: The Case of the US and the End of Nuclear Testing.** March 2023. York IND Working Paper#2.

Mikhail Kupriyanov. **Prohibition Treaties and Irreversibility**. March 2023. York IND Working Paper#3.

James Tegnelia. **Disarmament and Reversibility: A Case Study of the Denuclearisation of the United States Army.** March 2024**.** York IND Working Paper#4.

Patrick O'Sullivan. **Irreversibility Considerations in the Decommissioning of Fissile Material Production Facilities for Nuclear Weapons: Marcoule and Pierrelatte.** March 2024**.** York IND Working Paper#5.

Nick Ritchie with Kat Lovell and Zahar Koretsky. **Researching the Decline of Large Socio-Technical Systems using Science and Technology Studies tools. March 2024.** York IND Working Paper#6.

Research Reports

Nick Ritchie. *Irreversibility and Nuclear Disarmament: Unmaking Nuclear Weapons Complexes.* March 2023. York IND Research Report#1.

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